# Durability of Portland Limestone Cement Concrete

## Testing mixtures for an infrastructure project

*by Neal S. Berke, Ali N. Inceefe, Allan Kramer, and Oscar R. Antommattei*

The cement industry in North America is making positive commitments to lower the environmental impacts of cement in several ways: by increased use of alternative fuels, increased use of supplementary cementitious materials (SCMs), the addition of limestone for blended cement production, the initiation of carbon capture technologies, and the practice of hardened concrete recarbonation accounting. All of these sustainable technologies and practices will reduce the carbon footprint of concrete. Even greater, long-term reductions in the carbon footprint of concrete are obtainable by increasing its durability so that concrete structures will not need to be repaired or replaced as frequently. Portland limestone cement (PLC) is fast becoming the main cement used in North America. PLC is included in the ASTM C595/C595M[1] blended cement standard as Type IL, which allows replacement of 5 to 15% of the portland cement clinker with natural limestone that is interground with the clinker. This results in a reduction of the carbon footprint of the cement while not impacting the performance of concrete using PLC.

Previously conducted research has shown that concrete made with PLC has good sulfate and alkali-aggregate resistance.[2] In this article, we show more data from an infrastructure project on PLC concrete durability properties, such as resistance to freezing and thawing and chloride ion ingress, for a longer service life.

Concrete for a large light-rail infrastructure project in the Northwest region of the United States was proposed to be switched from using ordinary portland cement (OPC) to PLC. This project had a design target requirement of a 100-year concrete service life. Therefore, it became very important to be able to document that the project's 100-year concrete service life specification requirement could be successfully obtained using PLC.

The work described herein shows that good concrete durability meeting a 100-year service life is obtainable with PLC concretes containing Class F fly ash as an SCM. A few experiments with PLC and ground-granulated blast-furnace slag (slag cement) also gave good concrete durability results (not included). However, because slag cement was not readily available for the project, this study concentrated on the use of Class F fly ash as an SCM.

### Experimental Work

#### Materials

PLC used in this study met the requirements for a Type IL blended cement according to ASTM C595/C595M. Fly ash used for this study met the requirements of ASTM C618[3] Class F fly ash. OPC used in this study met the requirements of ASTM C150/C150M[4] for Type I/II cement. Concrete aggregates and admixtures used in this study met the requirements of ASTM C33/C33M[5] and ASTM C494/C494M,[6] respectively. Concrete for testing was produced using a large laboratory concrete mixer at the Corliss Resources, Inc., concrete laboratory located in Sumner, WA, USA. Concrete cylinder samples for durability testing were shipped moist in insulated crates to the Tourney Consulting Group's laboratory in Kalamazoo, MI, USA.

Concrete mixture proportions, plastic properties, and compressive strengths are listed in Tables 1(a) and (b) for mixtures with PLC, and Table 2 for mixtures with Type I/II cement.

#### Durability testing

The PLC concrete was to be used in various elements of the light-rail project. The concrete mixture designs were based on exposure to chloride, concrete cover over the reinforcing steel, and freezing-and-thawing conditions for the specific elements. The aggregates used were not susceptible to alkali-silica reaction (ASR) attack, and sulfate exposure was low, so testing for resistance to these degradation mechanisms was not conducted. The PLC used had good sulfate resistance according to ASTM C1012/C1012M[7] in tests conducted by the cement producer.

The primary concern was ingress of chloride into the concrete that could result in corrosion of steel reinforcement and subsequent cracking and spalling of the concrete.

To determine the susceptibility to chloride ingress, bulk diffusion tests per ASTM C1556[8] were performed. For quality control purposes, a rapid chloride permeability test (RCPT) per ASTM C1202[9] was performed due to the shorter test duration.

The diffusion coefficient tests were performed on 28-day moist-cured concrete samples. In these tests, the ages of the concrete samples at the start of exposure differed from each other by a few days; thus, the apparent diffusion coefficient ($D_a$) values needed to be converted to diffusion coefficient

## Table 1(a):
**First group of concrete mixtures with PLC and Class F fly ash (FA)**

| Materials or properties | Mixtures | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1A with 30% FA | 1B with 25% FA | 1C with 25% FA | 4A with 30% FA | 4D with 30% FA | 4E with 25% FA | 4F with 25% FA |
| *w/cm* | 0.38 | 0.40 | 0.40 | 0.38 | 0.38 | 0.40 | 0.40 |
| Type IL cement,* lb/yd³ | 420 | 469 | 469 | 559 | 507 | 551 | 551 |
| Class F fly ash, lb/yd³ | 180 | 156 | 156 | 240 | 218 | 184 | 184 |
| Total cementitious, lb/yd³ | 600 | 625 | 625 | 799 | 725 | 735 | 735 |
| 3/4 in. coarse aggregate, lb/yd³ | 1399 | 1368 | 1368 | 1337 | 1349 | 1352 | 1352 |
| 3/8 in. coarse aggregate, lb/yd³ | 463 | 453 | 453 | 352 | 370 | 391 | 391 |
| Fine aggregate, lb/yd³ | 1216 | 1189 | 1216 | 1014 | 1123 | 1047 | 1047 |
| Total water, lb/yd³ | 230 | 250 | 250 | 302 | 275 | 295 | 295 |
| Air-entraining admixture | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| High-range water-reducing admixture | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Shrinkage-reducing admixture | — | — | ✓ | — | — | — | ✓ |
| Entrained-air content, % | 6.2 | 6.0 | 7.0 | 5.0 | 7.5 | 5.4 | 6.2 |
| Slump, in. | 6.25 | 5.00 | 5.25 | 6.25 | 6.00 | 7.00 | 6.00 |
| Unit weight, lb/ft³ | 144.64 | 144.48 | 142.64 | 145.28 | 140.80 | 144.64 | 143.60 |
| 28-day compressive strength, psi | 7228 | 7189 | 6439 | 7552 | 7361 | 7205 | 6574 |
| 56-day compressive strength, psi | 8294 | 7747 | 7206 | 8508 | 8075 | 7985 | 7473 |

*Lehigh NW Cement Company

Note: 1 lb/yd³ = 0.6 kg/m³; 1 in. = 25 mm; 1 lb/ft³ = 16 kg/m³; 1 psi = 0.007 MPa

## Table 1(b):
**Second group of concrete mixtures with PLC and Class F fly ash (FA)**

| Materials or properties | Mixtures | | | | | |
|---|---|---|---|---|---|---|
| | 9A with 30% FA | 9B with 25% FA | 9C with 25% FA | 10A with 30% FA | 10B with 25% FA | 10C with 25% FA |
| *w/cm* | 0.38 | 0.40 | 0.40 | 0.38 | 0.40 | 0.40 |
| Type IL cement,* lb/yd³ | 455 | 529 | 529 | 420 | 469 | 469 |
| Class F fly ash, lb/yd³ | 195 | 176 | 176 | 180 | 156 | 156 |
| Total cementitious, lb/yd³ | 650 | 705 | 705 | 600 | 625 | 625 |
| 3/4 in. coarse aggregate, lb/yd³ | 1359 | 1327 | 1327 | 0 | 0 | 0 |
| 3/8 in. coarse aggregate, lb/yd³ | 450 | 401 | 401 | 1670 | 1660 | 1660 |
| Fine aggregate, lb/yd³ | 1181 | 1129 | 1129 | 1401 | 1338 | 1338 |
| Total water, lb/yd³ | 246 | 280 | 280 | 228 | 250 | 250 |
| Air-entraining admixture | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| High-range water-reducing admixture | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Shrinkage-reducing admixture | — | — | ✓ | — | — | ✓ |
| Entrained-air content, % | 6.0 | 5.5 | 6.0 | 7.5 | 7.4 | 5.8 |
| Slump, in. | 6.00 | 6.75 | 6.50 | 4.00 | 3.50 | 3.50 |
| Unit weight, lb/ft³ | 144.88 | 143.52 | 143.36 | 142.00 | 142.08 | 144.80 |
| 28-day compressive strength, psi | 7238 | 6992 | 6529 | 6993 | 7995 | 8091 |
| 56-day compressive strength, psi | 7668 | 7686 | 7236 | 8005 | 8836 | 8995 |

*Lehigh NW Cement Company

Note: 1 lb/yd³ = 0.6 kg/m³; 1 in. = 25 mm; 1 lb/ft³ = 16 kg/m³; 1 psi = 0.007 MPa

**Table 2:**
**Concrete mixtures with Type I/II cement and Class F fly ash (FA)**

| Materials or properties | Mixtures | |
|---|---|---|
| | 4G with 30% FA | 4I with 25% FA |
| *w/cm* | 0.38 | 0.40 |
| Type I/II cement, lb/yd³ | 507 | 551 |
| Class F fly ash, lb/yd³ | 218 | 184 |
| Total cementitious, lb/yd³ | 725 | 735 |
| 3/4 in. coarse aggregate, lb/yd³ | 1349 | 1352 |
| 3/8 in. coarse aggregate, lb/yd³ | 370 | 391 |
| Fine aggregate, lb/yd³ | 1123 | 1047 |
| Total water, lb/yd³ | 275 | 295 |
| Air-entraining admixture | ✓ | ✓ |
| High-range water-reducing admixture | ✓ | ✓ |
| Shrinkage-reducing admixture | — | ✓ |
| Entrained air content, % | 6.6 | 5.6 |
| Slump, in. | 6.00 | 6.50 |
| Unit weight, lb/ft³ | 142.32 | 142.88 |
| 28-day compressive strength, psi | 7087 | 6548 |
| 56-day compressive strength, psi | 7872 | 7515 |

Note: 1 lb/yd³ = 0.6 kg/m³; 1 in. = 25 mm; 1 lb/ft³ = 16 kg/m³; 1 psi = 0.007 MPa

values at a reference time for comparison purposes. The $D_a$ calculated by fitting the ASTM C1556 results to the well-known solution of Fick's Second Law is the average of the changing diffusion coefficient over the test period. To make this conversion, one first needs to determine the time at which $D_a$ occurs, which can be done using Eq. (1).[10] Then, Eq. (2) is used to calculate the diffusion coefficients at the reference time. In this study, a reference time of 28 days was used, as in the most common service-life prediction models.

$$t_{eff} = \left[ \frac{(1-m)(t_2 - t_1)}{t_2^{1-m} - t_1^{1-m}} \right]^{1/m} \quad m \neq 0.1 \qquad (1)$$

$$D_{28} = \frac{D_a}{\left( \frac{28}{t_{eff}} \right)^m} \qquad (2)$$

where $t_{eff}$ is the effective time in days at which the $D_a$ occurs; $m$ is the aging factor; $t_1$ is the age of the concrete at the start of the exposure; $t_2$ is the age of the concrete at the end of the exposure; and $D_{28}$ is the 28-day diffusion coefficient.

Aging factors were determined by plotting bulk conductivity results at various ages obtained from ASTM C1760[11] on a log-log scale and fitting a power function. Figure 1 shows the test results for various concrete mixtures; the negative slopes correspond to aging factors. The following sections provide the conductivity and calculated $m$ values for the tested concrete mixtures.

ASTM C457/C457M[12] hardened concrete air void analysis was performed to estimate freezing-and-thawing resistance.

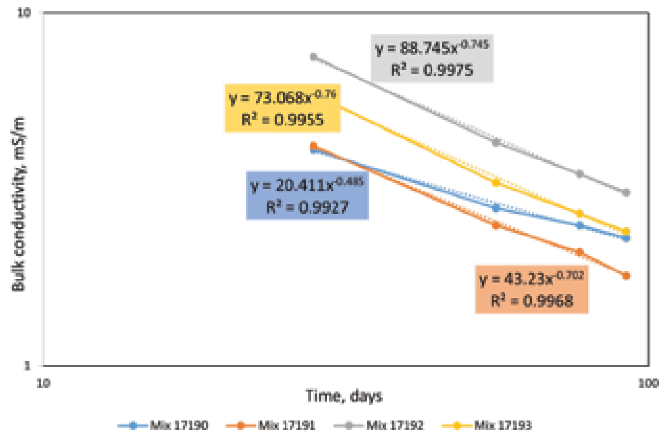



**Fig. 1: Example bulk conductivity results versus time, plotted on a log-log scale. Aging factors are defined by the slopes (the power terms) for the fitted functions**

If spacing factors were above 0.008 in. (0.2 mm), then ASTM C666/C666M, Procedure A,[13] was performed.

## Concrete Permeability and Bulk Diffusion Results

### PLC and Class F fly ash mixtures

The RCPT results are shown in Fig. 2. They are for normal-temperature curing and accelerated curing (7 days at normal curing followed by 21 days moist curing at 100°F [38°C]), which is used for concrete mixtures containing SCMs.

The RCPT results for accelerated-curing PLC concrete mixtures were near or below 1500 coulombs in most cases, with the best performers in general being at a water-cementitious materials ratio (*w/cm*) of 0.38 with 30% Class F fly ash replacement.

The bulk conductivity results are shown in Fig. 3. As this is a nondestructive test, the same concrete cylinders can be tested multiple times, reducing variability. In all cases, there was a significant decrease in conductivity between 28 and 56 days. The 28-day conductivity values show less variation than the rapid chloride permeability values as the concrete does not heat up in the ASTM C1760 test method, which causes the current to rise in time in the RCPT.[15]

The data shown in Fig. 3 were used to calculate the $m$ value, which relates to the reduction in concrete permeability with time. These values were used, as noted earlier, to convert the ASTM C1556 bulk diffusion coefficients from an average value determined over the course of the test to the value at 28 days. $D_{28}$ and $m$ values were then used to predict chloride ingress into concrete in conjunction with the exposure conditions. Figure 4 shows $D_{28}$ and $m$ values for the tested PLC and fly ash concretes.

The 28-day diffusion coefficients for concrete mixtures with PLC and fly ash in Fig. 4 were lower than those predicted in Life-365™ for concrete mixtures with portland cement and fly ash.[15]

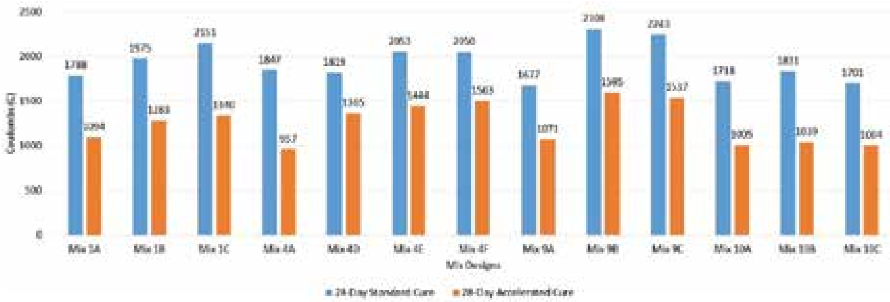



**Fig. 2: ASTM C1202 RCPT results for PLC concretes containing Class F fly ash**

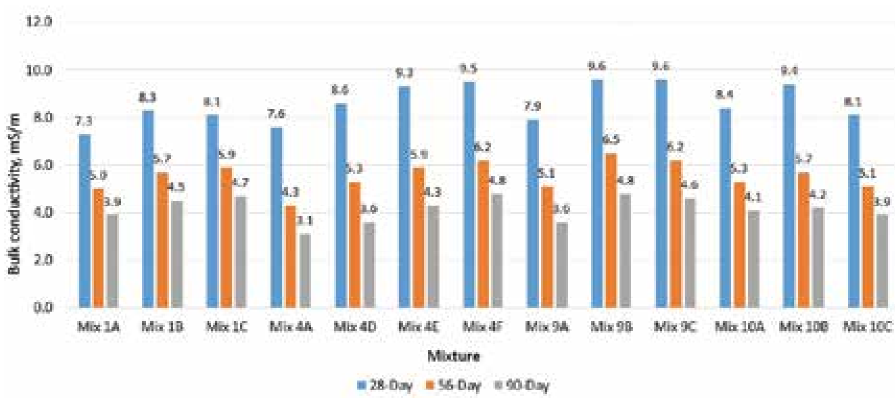



**Fig. 3: ASTM C1760 bulk conductivity results over time for PLC concrete mixtures containing Class F fly ash**

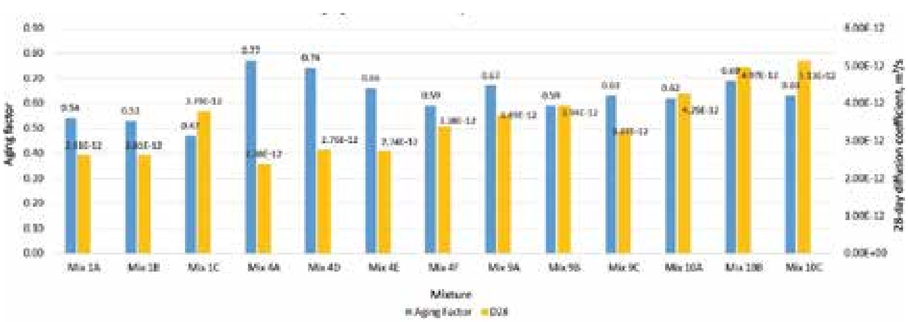



**Fig. 4: Aging factors and 28-day diffusion coefficients for concrete mixtures containing PLC and Class F fly ash**

## Comparison of PLC and Type I/II cement mixtures

Two of the mixtures with PLC and Class F fly ash were compared to two mixtures with Type I/II portland cement and Class F fly ash. Figure 5 shows the RCPT for these mixtures; Fig. 6 shows the bulk conductivities; and Fig. 7 shows the diffusion coefficients and aging factors.

The RCP (normal cure), bulk conductivity, and diffusion coefficient values for the PLC concrete specimens were all lower than those of the Type I/II concrete specimens, indicating that PLC improves resistance to chloride penetration. The RCP (accelerated cure) appeared to have been more effective with the Type I/II concrete specimens as those specimens had a lower RCP value.

# Air Entrainment and Freezing-and-Thawing Results

## PLC and fly ash mixtures

Figure 8 shows the plastic air, hardened air, and spacing factor data for the PLC concrete specimens containing Class F fly ash. All concretes had good air systems, as can be seen in Fig. 8. Specimens from Mixture 10C were tested for ASTM C666/C666M, Procedure A, because the spacing factor was at the upper specified limit. The relative dynamic modulus of elasticity (RDME) factor at 300 cycles was 96.5%, indicating good concrete durability against freezing and thawing.

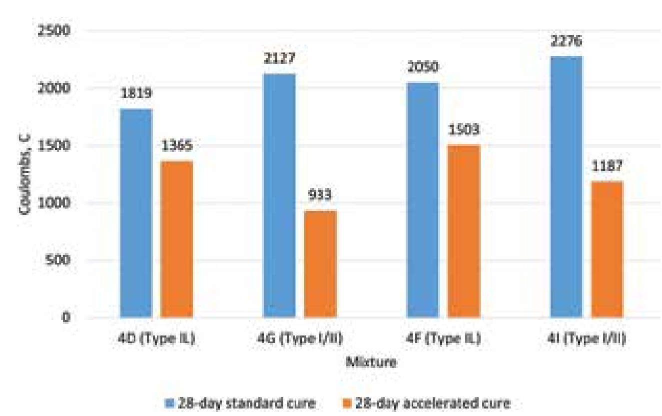



**Fig. 5: Comparison of RCP results for PLC (Type IL) and Type I/II concretes containing Class F fly ash**

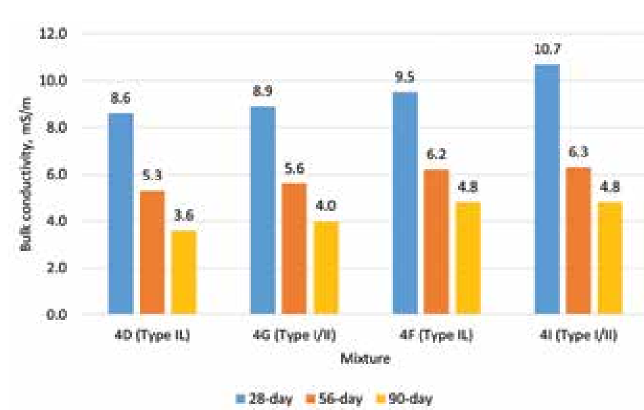



**Fig. 6: Comparison of bulk conductivity results for PLC (Type IL) and Type I/II concretes containing Class F fly ash**

## Comparison of PLC and Type I/II concretes with fly ash

The air-void data comparisons between the PLC with Class F fly ash concretes and Type I/II portland cement with Class F fly ash concretes are shown in Fig. 9. The spacing factors were identical, and the air contents were similar.

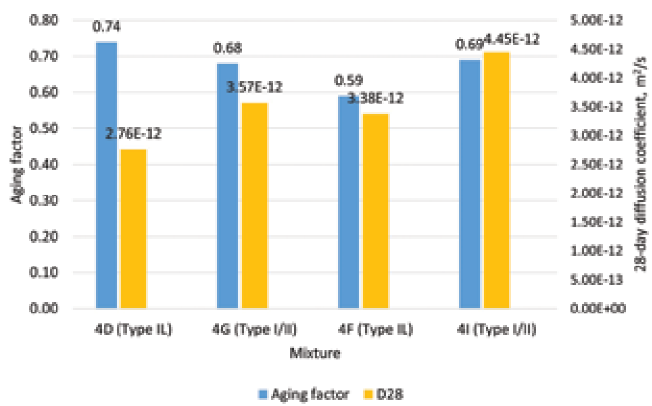



**Fig. 7: Comparison of aging factor and 28-day diffusion coefficient values for PLC (Type IL) and Type I/II concretes containing Class F fly ash**

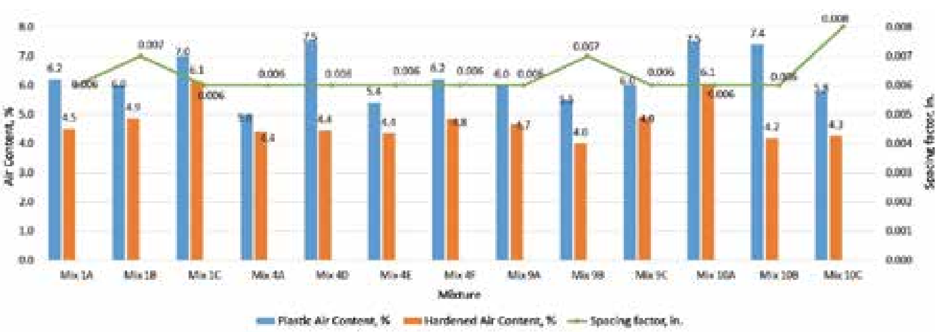



**Fig. 8: Air-entrainment parameters for PLC concretes containing Class F fly ash**

## Conclusions

Concrete mixtures containing ASTM Type IL PLC and ASTM Class F fly ash were proposed for a large light-rail infrastructure project in the Pacific Northwest. The test program described in this article showed that the PLC concrete mixtures met the project's concrete durability plan's specific 100-year service-life parameters.

Limited tests of concrete containing PLC and slag cement (not presented in this article) indicated that this mixture also would have met the project's durability plan and 100-year service-life parameters.

Additional tests showed that the PLC concretes had lower permeability to chloride ingress than concretes produced with Type I/II OPC and that air entrainment was comparable between the two.

Based on the concrete testing performed, PLC concrete with Class F fly ash can provide better performance related to chloride ingress than Type I/II OPC concrete with Class F fly ash.


## Acknowledgments

The authors wish to thank Lehigh NW Cement Company, Kiewit Construction, and Corliss Resources, Inc., for making this study possible.


## References


1. ASTM C595/C595M-20, "Standard Specification for Blended Hydraulic Cements," ASTM International, West Conshohocken, PA, 2020, 10 pp.
2. Thomas, M.D.A.; Delagrave, A.; Blair, B.; and Barcelo, L., "Equivalent Durability Performance of Portland Limestone Cement," *Concrete International*, V. 35, No. 12, 2013, pp. 39-45.

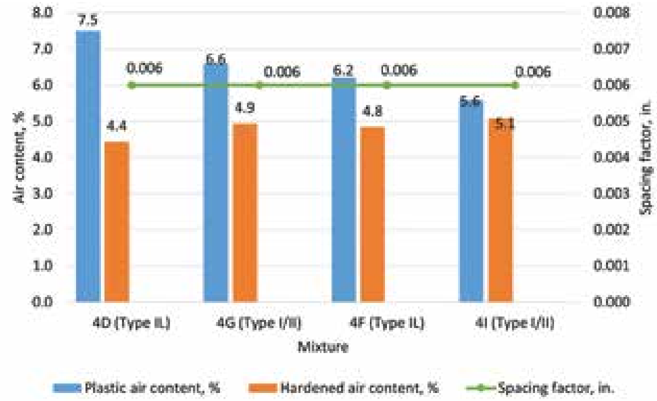


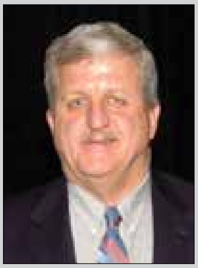

**Fig. 9: Air-void system comparison of PLC (Type IL) and Type I/II concretes with Class F fly ash**

3. ASTM C618-19, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," ASTM International, West Conshohocken, PA, 2019, 5 pp.
4. ASTM C150/C150M-21, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 2021, 9 pp.
5. ASTM C33/C33M-18, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2018, 8 pp.
6. ASTM C494/C494M-19, "Standard Specification for Chemical Admixtures for Concrete," ASTM International, West Conshohocken, PA, 2019, 15 pp.
7. ASTM C1012/C1012M-18B, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," ASTM International, West Conshohocken, PA, 2018, 9 pp.
8. ASTM C1556-11A, "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion," ASTM International, West Conshohocken, PA, 2016, 7 pp.
9. ASTM C1202-19, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 2019, 8 pp.
10. Stanish, K., and Thomas, M., "The Use of Bulk Diffusion Tests to Establish Time-Dependent Chloride Diffusion Coefficients," *Cement and Concrete Research*, V. 33, No. 1, 2003, pp. 55-62.
11. ASTM C1760-12, "Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete (Withdrawn 2021)," ASTM International, West Conshohocken, PA, 2012, 5 pp.
12. ASTM C457/C457M-16, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," ASTM International, West Conshohocken, PA, 2016, 18 pp.
13. ASTM C666/C666M-15, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," ASTM International, West Conshohocken, PA, 2015, 7 pp.
14. Hope, B.B.; Ip, A.K.; and Manning, D.G., "Corrosion and Electrical Impedance in Concrete," *Cement and Concrete Research*, V. 15, No. 3, 1985, pp. 523-534.
15. Ehlen, M.A., and Kojundic, A.N., "Life-365™ v2.2," *Concrete International*, V. 36, No. 5, May 2014, pp. 41-44.

Selected for reader interest by the editors.

**Neal S. Berke**, FACI, is Vice President of Research at Tourney Consulting Group, LLC, in Kalamazoo, MI, USA. He has extensive experience in the development and application of concrete admixtures and materials as well as corrosion and durability of concrete. He is a member of ACI Committees 212, Chemical Admixtures; 222, Corrosion of Metals in Concrete; 224, Cracking; and 365, Service Life Prediction. He received the 2012 ACI Jean-Claude Roumain Innovation in Concrete Award. He received his PhD from the University of Illinois at Urbana-Champaign, Urbana, IL, USA.

ACI member **Ali N. Inceefe** is a civil engineer with Tourney Consulting Group. He is a member of ACI Committee 365, Service Life Prediction. He received his MS in structural engineering from Western Michigan University, Kalamazoo, MI, USA.



**Allan Kramer** is the Technical Service Manager for the Lehigh NW Cement Company in Seattle, WA, USA. He has over 40 years of extensive concrete and cement industry experience. His expertise includes forensic investigation, analysis, and resolution of hardened concrete problems, and developing high-performance and high-strength concrete mixtures for the Seattle and Puget Sound region of Washington State. He received his BS in industrial engineering from Fairleigh Dickinson University, Teaneck, NJ, USA, and is a National Ready Mixed Concrete Association (NRMCA) Certified Concrete Technologist – Level 4.

**Oscar R. Antommattei**, FACI, is Chief Concrete Engineer and Engineering Manager with Kiewit Engineering Group Inc., Lone Tree, CO, USA. He has 20 years of industry experience in concrete materials with focuses that range from technical support to infrastructure design and heavy-civil construction projects. His technical interests are performance-based concrete, long-term durability, constructability, and mass concrete. He is Chair of the ACI Construction Liaison Committee, and a member of ACI Committees 134, Concrete Constructability; 201, Durability of Concrete; 207, Mass and Thermally Controlled Concrete; 305, Hot Weather Concreting; 308, Curing Concrete; and 321, Concrete Durability Code; and a member of ACI Subcommittee 301-H, Mass Concrete—Section 8.