Minimizing the Risk for Portland-Limestone Cement Concrete Slabs

Best practices and strategies to reduce floor slab finishing and early-age, strength-critical challenges

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While many contractors have successfully placed and finished concrete slabs constructed using Type IL cement (portland-limestone cement [PLC]), others have struggled with project delays and unacceptable finishes. To find the root causes of unsuccessful outcomes, jobsite data such as mixture proportions, weather conditions, construction practices and equipment, and finish requirements must be evaluated.

This article discusses early-age, strength-critical construction operations such as saw cutting, cold weather protection, post-tensioning, and form removal, as well as best practices and strategies to minimize risks during floor slab finishing and early-age, strength-critical construction. This article also provides data collected on six mockups constructed with Type IL cement and one mockup constructed with Type I cement.

The authors encourage others to share their data and experiences with Type IL cement.

Concrete Finishing Challenges

The outcomes of concrete slab placements are highly dependent on the mixture constituents and the fresh concrete properties such as slump, air content, bleeding rate, and setting time. The sensitivity of the fresh concrete to the environment impacts the finisher's techniques and timing to produce a quality product. One major factor that separates slabs requiring a trowel finish from slabs designed as paving[1-4] is the length of time the fresh concrete slab is exposed to the environment. For slipform paving, Poole[5] indicated that final finishing is usually completed within a few minutes of placing the concrete, well before the time of initial setting and the end of the bleeding period. For slabs to receive a trowel finish, final finishing may occur 3 to 8 hours after placement, with the longest delays occurring in cold weather with high relative humidity. This extended exposure time poses a substantial risk to contractors who are tasked with turning a sensitive, perishable product into a quality hardened product for the owner. Thus, slipform paving and parking lot examples are not comparable to slabs specified to receive a trowel finish.

Survey on PLC Concrete

The recent Joint ACI-ASCC Survey on PLC Concrete (to be published in the February 2024 issue of *Concrete International*) posed questions to elicit user experiences with finishing and performance of slabs requiring a trowel finish. The percentages reported in the following section represent the answers from 173 respondents. As the survey shows, fresh concrete properties changed when the cement changed.

Reported changes in fresh concrete properties associated with changing from Type I cement to Type IL cement include:
- Water demand—77% reported an increase while 7% reported a decrease;
- Bleed water—14% reported an increase while 39% reported a decrease;
- Setting time—51% reported an increase while 21% reported a decrease;
- Crusting—31% reported an increase while 1% reported a decrease;
- Changes in finishing—45% reported an increase while 3% reported a decrease; and
- Need for evaporation reducer—38% reported an increase while 1% reported a decrease.

Reported PLC concrete performance characteristics (relative to concrete produced using Type I portland cement) include:
- Plastic shrinkage cracking—43% reported an increase while 6% reported a decrease;
- Scaling—13% reported an increase while 1% reported a decrease;
- Dusting—13% reported an increase while 1% reported a decrease;

- Wear resistance—4% reported an increase while 19% reported a decrease; and
- Delamination—17% reported an increase while 1% reported a decrease.

The Neuber Concrete Experience

Neuber Concrete, Phoenixville, PA, USA, was contracted to construct a 79,000 ft^2 (7340 m^2) tilt-up building including a slab-on-ground, casting slabs, and wall panels. The ready mixed concrete producer indicated that Type IL cement was the only option. Because this was Neuber Concrete's first experience with Type IL cement concrete, test slabs/mockups were used to evaluate the Type IL cement's effects on finishing. Ultimately, seven mockups were made. The ready mixed concrete producer and cement supplier made site visits during the mockups and provided recommendations. Bleeding observations, estimates of evaporation rates, and quality of the finished surfaces were recorded. While we have found no other published data correlating bleed water, evaporation rates, and surface finish with Type IL cement concrete, the Neuber experiences are instructive.

Mockup mixtures

The mixture ingredients and batch weights for the mockups are shown in Table 1. Mockup 1 had proportions of the typical concrete mixture used by Neuber Concrete. The mixture produced a slab that was good enough to use as a casting bed, but it was not up to the contractor's standards for a slab-on-ground because the bleeding rate did not offset the evaporation rate. The next five mockups were used to adjust the concrete mixture and initial curing methods to overcome this issue. For Mockup 7, the ready mixed concrete producer supplied concrete with a Type I cement.

As shown in Table 1, there were two attempts to increase the bleed water. The water content was increased by about 20 lb/yd^3 (12 kg/m^3) for Mockup 5, and a coarser sand with a higher fineness modulus was used.

Mockup parameters: The seven mockups included two for tilt-up panels at 3.5 in. (90 mm) thick and five for slab-on-ground 7 to 8 in. (178 to 230 mm) thick. The quantity of concrete ranged from 16 to 40 yd^3 (12 to 30 m^3), and the placement sizes varied from 600 to 3300 ft^2 (56 to 307 m^2). The mockups were placed in May and June 2023. Table 2 provides a summary of the measured data and observations for the mockup placements.

Fresh concrete properties: Slump and air content were measured. Slumps ranged from 6.0 to 7.5 in. (152 to 190 mm), and air content ranged from 0.7 to 1.5%. Bleed water sheen was visually observed—none, little, or good. Fresh concrete properties are reported in Table 2.

Environmental factors: Table 2 summarizes the measured material and environmental conditions during concrete placements. Air and concrete temperature, relative humidity (RH), and wind speed were recorded. A Kestral Concrete Weather Pro 5200L was used to collect data and report evaporation rates on Mockups 4 and 5. The evaporation rate on the other mockups was calculated using the Uno equation provided in ACI 305R-20.[6]

Table 1:
Specified properties and proportions of non-air-entrained mixtures used for mockup placements

Mixture properties and proportions	Mockup No.						
	1	2	3	4	5	6	7
Compressive strength, psi	4000	4000	4000	4000	4000	4000	4000
Design slump, in.	6.0 ± 1.0	7.0 ± 1.0	7.0 ± 1.0	6.0 ± 1.0	6.0 ± 1.0	6.0 ± 1.0	6.0 ± 1.0
Unit weight, lb/ft^3	152.5	151.6	151.6	152.5	152.5	152.5	152.5
Steel fibers, lb/yd^3	45	0	0	0	0	0	0
Cement type[*]	IL	IL	IL	IL	IL	IL	I
Cement, lb/yd^3	530	620	620	530	530	620	530
Water, lb/yd^3	265	283	283	265	275	283	265
w/cm	0.50	0.46	0.46	0.50	0.52	0.47	0.50
Maximum aggregate size, in.	1-1/2	1	1	1-1/2	1-1/2	1-1/2	1-1/2
Coarse aggregate, lb/yd^3	1684	1446	1520	1684	1684	1684	1684
Intermediate, No. 8, lb/yd^3	400	346	240	400	400	400	400
Fine aggregate, lb/yd^3	1224	1410	1385	1224	1224[†]	1224[†]	1224
Water-reducing admixture, fl oz/cwt	6	4	6	6	6	6	6

[*] Cement mill certificates indicated limestone content and specific surface area (SSA) of 3.8% and 383 m^2/kg for Type I cement and 13% and 488 m^2/kg for Type IL cement

[†] Mockup 5 and 6 comprised a sand with a higher fineness modulus (coarser) than other mockups

Note: 100 psi = 0.7 MPa; 1 in. = 25 mm; 1 lb/ft^3 = 16 kg/m^3; 1 lb/yd^3 = 0.6 kg/m^3; 1 fl oz/100 lb = 65 mL/100 kg

Placement and finishing: All placements were executed using the following steps:

- Place—concrete was deposited directly from the chute of the concrete truck onto polyolefin sheeting;
- Strike off—concrete was leveled using a wheel-mounted, laser-guided screed;
- Wait—workers observed the concrete until bleed water and time of setting indicated finishing could commence;
- Float—concrete was worked using pans on a double-rider trowel machine; and
- Trowel—concrete was finished using combination blades on a double-rider trowel machine.

Initial curing methods and evaluation: No initial curing methods were used for the first three mockups, as this was not typically needed with Type I mixtures under the conditions at the time of placement. Because plastic shrinkage cracking, surface cracking, and crusting were observed on the first three mockups (even though evaporation rates were low), water misting and evaporation reducers were used on Mockups 4, 5, and 6. Table 3 provides the initial curing methods and the contractor's evaluation of the results. Evaporation reducers are water-based emulsions that slow evaporation rates by forming monomer films and compensating to a small degree for water lost due to evaporation.

Table 2:
Data for slab-on-ground (SOG) and tilt-up panel (Panel) mockups

	Measured data for mockup placements						
Mixture properties	1	2	3	4	5	6	7
Cement type	IL	IL	IL	IL	IL	IL	I
Placement date	5/10/23	5/15/23	5/19/23	6/5/23	6/8/23	6/16/23	6/29/23
Placement volume, yd^3	40	40	16	30	36	34	20
Placement area, ft^2	1890	3300	600	1400	1450	1421	1000
Placement thickness, in	7	3.5	3.5	7	7	8	7
Mockup type	SOG	Panel	Panel	SOG	SOG	SOG	SOG
Environmental factors							
Average air temperature, °F	65	61	63	65	55	61	72
Concrete temperature, °F	66	69	70	69	66	72	74
Average wind speed, mph	3	6	7	7	5	6	6
Average RH, %	60	54	57	50	57	80	66
Evaporation rate, lb/ft^2/h	0.03[*]	0.08[*]	0.09[*]	0.04 to 0.07[†]	0.02 to 0.09[†]	0.07[*]	0.06[*]
Fresh concrete properties							
Slump, in.	7.5	6.0	7.0	7.0	7.5	6.0	6.0
Air content, %	0.7	1.5	1.0	Not measured	1.1	1.3	1.5%
Bleed water sheen, visual	Little	None	None	None	Little	Little	Good
Observations during and after finishing							
Plastic shrinkage cracking	Yes	No	No	Yes	No	Yes	No
Surface tearing	No	Yes	Yes	Yes	Yes	Yes	No
Surface cracking	No	Yes	Yes	Yes	Yes	Yes	No
Crusting	No	Yes	Yes	Yes	Yes[‡]	Yes	No
Spotty setting	No	Yes	Yes	Yes	Yes	Yes	No
Delamination	No	No	No	No	No	Yes	No
Contractor's overall rating	OK[§]	Bad[#]	Bad[#]	Bad[#]	Bad	Repair needed	Great

[*] Evaporation rate calculated using the Uno equation provided in ACI 305R-20

[†] Measured with Kestrel Concrete Weather Pro 5200L

[‡] Water comes up through cracks when troweled concrete surface is pushed down

[§] Good enough to use as a casting bed, not up to contractor standards for slab-on-ground

[#] Not good enough to use as a casting bed, removed and disposed off site

Note: 1 yd^3 = 0.8 m^3; 1 ft^2 = 0.09 m^2; 1 in. = 25 mm; °C = 5/9 × (°F – 32); 1 mph = 1.6 km/h; 1 lb/ft^2/h = 4.9 kg/m^2/h

Table 3:
Initial curing methods and contractor evaluation

Mockup No.	Initial curing methods	Contractor evaluation
1	No misting or evaporation reducer used	Some bleed water Surface OK
2	No misting or evaporation reducer used	Crusting, spongy, surface tearing
3	No misting or evaporation reducer used	Soft, spongy with hard surface
4	Truck 1: Applied evaporation reducer directly from pan machine on first pass Truck 2: Applied evaporation reducer from backpack sprayer directly after laser screed	No bleed water on any surface Crusting and cracking
5	1/4 area—no water misting or evaporation reducer 1/4 area—misted directly after laser screed strike-off 1/2 area—applied evaporation reducer directly after laser screed	Small amount of bleed water Not as effective as evaporation reducer Surface water longer than other areas but crusted and cracked
6	Applied evaporation reducer directly after laser screed with a power drum sprayer	Soft, spongy, and cracking
7	No misting or evaporation reducer used	Good amount of bleed water Finished great

Surface evaluation during finishing: Figures 1, 2, and 3 show examples of plastic shrinkage cracking, surface tearing, and surface cracking observed on Mockups 4, 5, and 6. The occurrence of these issues and the contractor's overall evaluation of the finishing are provided in Table 2. Crusting was evident in most of the Type IL cement concrete mockups. The crusting was evident as water was pushed to the surface of the slab when finishers applied pressure on the slab. Only Mockup 7, the slab constructed with Type I cement, was given a good rating by the contractor.

Project construction: The project was successfully constructed with Type I cement.

Bleeding Rate and Capacity, Evaporation Rate, and Setting Time

Poole[5] indicates that loss of water due to evaporation is particularly critical during the initial curing period. Under climatic conditions favorable to drying, evaporation of bleed water can be quite rapid. When evaporation exceeds bleeding, the near-surface zone of the cement paste dries, resulting in shrinkage and development of tensile strains. Because tensile strength at such early ages is very low, fresh concrete develops plastic shrinkage cracks.

Thus, a finisher's most critical objectives are accurately anticipating the evaporation-to-bleed water balance and taking adequate steps to shift that balance to a favorable position. Current guidance suggests either limiting the time concrete is left in an unprotected condition or limiting evaporation rates.

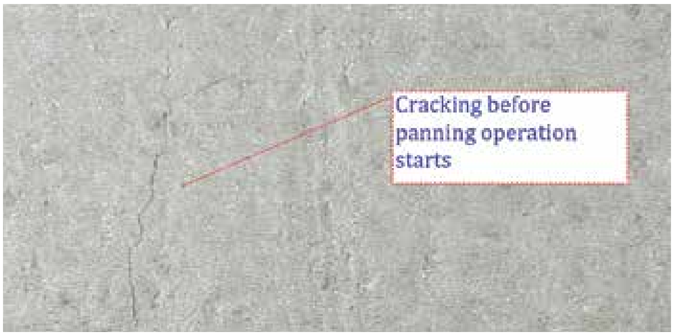

Fig. 1: Plastic shrinkage cracking prior to finishing operations

Fig. 2: Surface tearing during troweling

Fig. 3: Surface cracking during troweling operation, concrete below surface is still plastic

Neuber's mockup information suggests a critical evaporation rate of about 0.05 lb/ft^2/h (0.24 kg/m^2/h)—identical to the allowable evaporation rate specified for silica fume concrete bridge deck overlays.[6] And Neuber's experience relates to a comment from the ACI-ASCC Survey: "…have to use evaporation retarder [reducer], no matter the evaporation rate." The use of an evaporation reducer, however, does not guarantee success. In the Neuber mockups, the application of an evaporation reducer did not result in adequate finishability or overall success.

Critical points during construction: Comparing bleeding behavior with probable drying conditions will identify potential critical periods prior to the time of initial setting. Figure 4 provides a hypothetical plot of evaporation and bleeding for a Type I cement concrete pavement placement.[5] For the first 1/2 hour, and again after about 4 hours, evaporation can exceed bleeding. The two periods, marked with red ovals, represent critical time periods for plastic shrinkage cracking. In the first critical period, the mixture will be plastic and can adjust to evaporative losses by shrinking into a thinner placement. However, cracking may occur during the second period because the concrete will have developed some stiffness and cannot adjust to the loss of water by simply reducing volume.

Figure 5 provides a hypothetical plot of evaporation and bleeding for Type I cement concrete pavement treated with an evaporation reducer shortly after strike-off.[5] The evaporation reducer shifts the cumulative evaporation curve, keeping the cumulative evaporation below the cumulative bleeding until final setting at 5 hours. This shift effectively eliminates any critical periods for plastic shrinkage cracking.

Figure 6 provides a hypothetical plot of evaporation and bleeding for a Type IL cement concrete slab placement treated with an evaporation reducer. Although the reducer shifts the cumulative evaporation curve, evaporation exceeds bleeding throughout the initial curing period. Such a scenario would expose the fresh concrete to conditions suitable for crusting and plastic shrinkage cracking. Both outcomes were observed in the Neuber mockups.

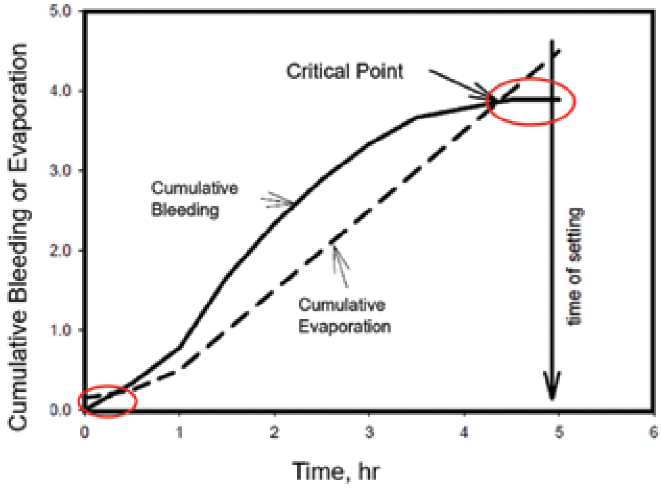

Fig. 4: Hypothetical plot of cumulative bleeding and evaporation versus time for a concrete mixture prepared with Type I portland cement. The red circles indicate critical periods in which evaporation exceeds bleeding (after Reference 5)

Bleeding rate and capacity: Poole[5] reported that 12 in. (300 mm) pavements placed using concretes with a water-cementitious material ratio (*w/cm*) ranging from 0.38 to 0.48 had bleeding rates ranging from 0.03 to 0.06 lb/ft^2/h (0.15 to 0.30 kg/m^2/h). These rates are much lower than those observed in slab-on-ground concretes. For slab-on-ground

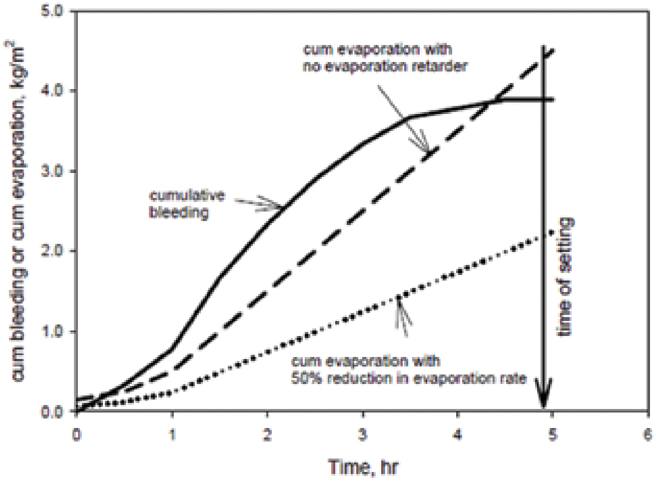

Fig. 5: Hypothetical plot of cumulative bleed and evaporation versus time for a concrete mixture prepared with Type I cement and finished using an evaporation reducer immediately after strike-off. By lowering cumulative evaporation, the surface treatment eliminates critical periods for plastic shrinkage cracking (after Reference 5)

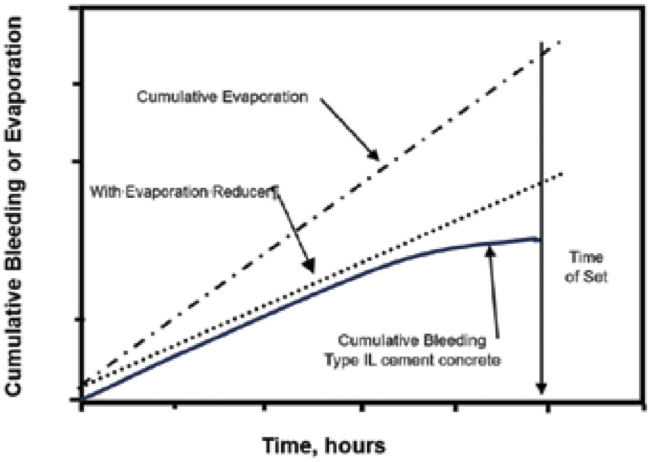

Fig. 6: Schematic plot of cumulative bleeding and evaporation versus time for a concrete mixture prepared with Type IL cement. Based on observations, the cumulative bleeding of PLC concrete is lower than the cumulative evaporation, even though a slab has been treated with an evaporation reducer. PLC concrete is therefore susceptible to plastic shrinkage cracking throughout the entire placement (after Reference 5)

placements for mixtures with *w/cm* ranging from 0.47 to 0.52, for example, bleeding rates of 0.10 to 0.30 lb/ ft^2/h (0.5 to 1.5 kg/m^2/h) were observed for a 6 in. (150 mm) thick slab.[7] Thomas and Hooton,[8] for study 2, reported that the mixtures without supplementary cementitious materials (SCMs) showed reduced bleeding for PLC compared with ordinary portland cement (OPC). In some mixtures with SCMs, no bleed water was observed.

Figure 7 illustrates the bleeding capacity of concrete with *w/cm* = 0.50 at a cement content of 350 kg/m^3 (600 lb/yd^3).[9] Mixture C0 was produced with Type I portland cement, and Mixtures C10 and C20 were produced using PLC. The bleeding rates of the PLC mixtures were about half that of Mixture C0. Because the PLC mixtures essentially stopped bleeding hours prior to Mixture C0, the total bleed water for the PLC mixtures was about 75% of the total bleed water for the portland cement mixture.

Tennis et al.[2] verified that the bleeding rate is influenced primarily by the specific surface area (SSA) and not necessarily the amount of limestone in the cement (refer to Fig. 8). While the authors conclude that "In general, there appears to be no concern with bleeding for mixtures containing cements with limestone,"[2] they fail to emphasize the sensitivity of bleeding rate to SSA. For example, the SSA values for the Type I and Type IL cements used in the Neuber mockup slabs (383 and 488 m^2/kg, respectively) correlate with bleeding rates of 7.3 x 10^{-4} and 17.8 x 10^{-4} cm/min (Fig. 8). Reference 2 would therefore indicate that the bleeding rate for the Type IL cement is less than half the bleeding rate for Type I cement.

As previously noted, data for bleeding rate of PLC concretes used for slabs-on-ground is scarce. Contractors are currently requesting data from ready mixed concrete producers. Neuber requested bleed data for both the PLC and Type I cement mixtures. While bleed data was not available for the mockup mixtures, Fig. 8 shows a significant effect based on the cement fineness. Further, the ACI-ASCC Survey showed that 39% of the respondents observed less bleed water with PLC concrete than with Type I portland cement concrete.

Evaporation rate: ACI 305R-20 provides some advice on measuring evaporation rates. Many contractors, including Neuber, use Kestral weather stations that can calculate evaporation rates based on measurements of air temperature, RH, wind speed, and concrete temperature. It should be noted, however, that the provided rates are estimates based on a study of evaporation rates from a lake. Further, the estimates do not account for the significant effect of solar heat gain.[6]

Setting time: Many factors affect setting time. While the greater fineness of Type IL cement relative to Type I cement can reduce the setting time, SCMs will decrease the setting time. The setting time must therefore be measured for any new combinations.

Time of initial setting is important because it indicates when bleeding is complete and final curing procedures can be initiated. However, the time of initial setting measured by ASTM C403/C403M,[10] at a penetration resistance of 500 psi,

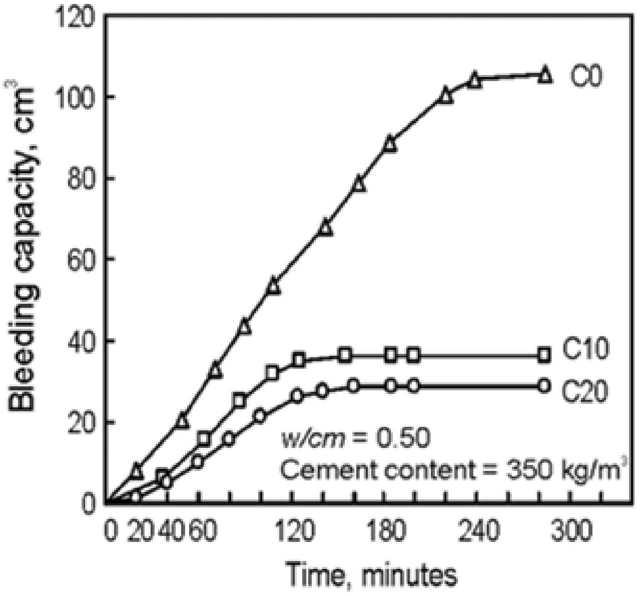

Fig. 7: Bleeding capacity of concrete with *w/cm* = 0.50 at a cement content of 350 kg/m^3 (600 lb/yd^3). One portland cement, C0, and two portland limestone cements, C10 and C20, were used.[9] Over the initial 120 minutes, the bleeding rates for concrete produced using C10 and C20 cements (with limestone) were about half the rate for concrete produced using C0 cement. Further, the bleeding capacity was reduced by about 75% (Note: 1 cm^3 = 0.06 in.^{3})

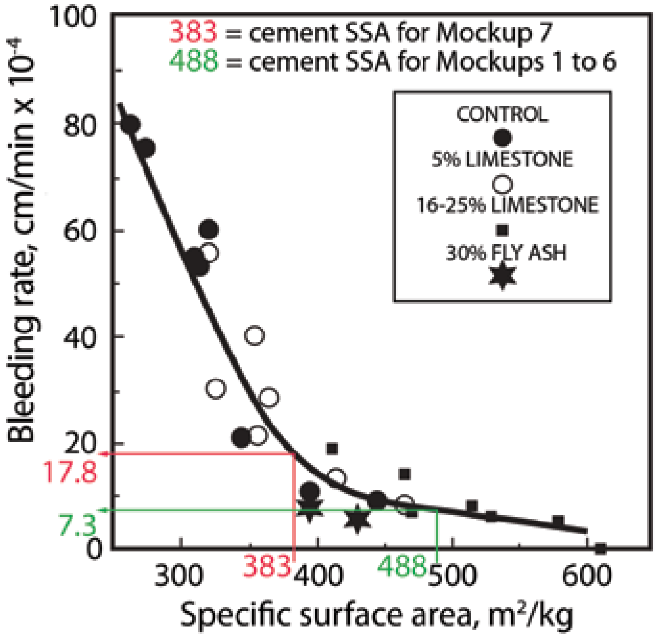

Fig. 8: The influence of specific surface area (SSA) of cementitious material on the bleeding rate (after Reference 2). We have indicated the SSA values (refer to Table 1) and associated bleeding rates for the cements used in the Neuber placements (Note: 1 cm/min = 0.4 in./min; 1 m^2/kg = 4.9 ft^2/lb)

is not the correct time to initiate final curing procedures. Bury et al.,[11] Suprenant and Malisch,[12] Lee and Hover,[13] and Dodson[14] showed that power floating should start at a penetration resistance of about 50 to 150 psi (0.3 to 1.0 MPa). Calorimetry per ASTM C1753/C1753M[15] can be used to estimate setting time, but the final curing time must be calibrated with the 50 to 150 psi penetration resistance.

Application and Effectiveness of Evaporation Reducers

A major difference between concrete slabs-on-ground and most other concrete structures is the large surface area-to-volume ratio. This makes slabs-on-ground highly susceptible to environmental effects such as drying or temperature extremes. Compounding this is the relatively large amount of such concrete that can be placed in a single workday, resulting in a large surface area that must be managed without delay. For example, based on owners' demands for cost and schedule, the current slab placement for an industrial slab is 40,000 ft^2 (1700 m^2) that is exposed to prevailing climatic conditions. As a matter of economics, this amount of surface area strongly affects choices for initial curing methods and materials.

Access: A 40,000 ft^2 industrial slab would be roughly 275 ft long by 150 ft wide (84 m long by 46 m wide). Such large areas will allow only limited access for initial curing during the 3 to 8 hours the fresh concrete will be exposed to the environment. Figure 4 shows the critical point when cumulative evaporation exceeds cumulative bleed, which is when power trowels are on the slab. Modern power trowels are equipped with containers capable of holding about 5 gal. (19 L) of evaporation reducer. Based on a typical manufacturer's recommended average application rate of 300 ft^2/gal. (7.4 m^2/L), a trowel will have enough reducer to cover about 1500 ft^2 (140 m^2) of slab area. For concretes produced using Type I cement, application of evaporation reducer using power trowels has worked well.

Wheel-mounted, laser-guided screeds provide another opportunity for applying evaporation reducer. A commonly used laser screed carries a 16 gal. (61 L) capacity storage container that can apply evaporation reducer at a rate of 150 to 450 ft^2 (14 to 42 m^2), and the screed can apply reducer only at the start of the placement.

Multiple applications: Water (in the form of mist) or evaporation reducers can be used to prevent excessive loss of bleed water. Water application generally faces no serious specification compliance issues and may be a reasonable option when evaporation rates are such that one or two passes by the application equipment are sufficient to protect the concrete. Poole[16] reports that for an application rate of 0.04 lb/ft^2/h (0.20 kg/m^2/h) and an evaporation rate of 0.20 lb/ft^2/h (1.00 kg/m^2/h), water would need to be applied every 12 minutes to avoid loss of mixing water.

Evaporation reducers are a very practical option for extending this period between required applications. Depending on the conditions, multiple applications may be needed. Equation (1) yields a conservative estimate of the frequency of the application of an evaporation reducer for a given condition

$$F = \frac{AR}{ER(1-0.4)-BR} \tag{1}$$

where F is the frequency of application in hours; AR is the application rate; ER is the evaporation rate; and BR is the bleeding rate of concrete, with AR, ER, and BR in lb/ft^2/h or kg/m^2/h.

The constant, 0.4, is taken to be the reduction in evaporation rate caused by an evaporation reducer. Most manufacturers claim at least a 50% reduction in evaporation rate, so this equation is probably conservative. A commonly recommended AR is 0.04 lb/ft^2 (0.2 kg/m^2), also expressed as 200 ft^2/gal. (5 m^2/L), and this rate is near the maximum that can be applied practically without ponding or runoff.

Effectiveness of evaporation reducers: As there is no standard specification for evaporation reducers, contractors must follow manufacturer's guidelines. A review of 14 evaporation reducers listed in AIA MasterSpec 03000 cast-in-place concrete[17] indicates that nine provide data on the amount of moisture reduction. However, the data these manufacturers provided for reduction in moisture loss associated with wind (80% reduction) and sunlight (40% reduction) were the values originally reported by Cordon and Thorpe in 1965.[18]

Poole[16] investigated three evaporation reducers in a limited testing program. Mortars were prepared according to ASTM C156,[19] and evaporation reducers were applied at the manufacturer's recommended rate 200 ft^2/gal. (5 m^2/L) immediately after molding. The specimens were then placed in a walk-in environmental room at 100°F (38°C), 30% RH, with a fan directed on the surface at a speed of 6.7 mph (11 km/h). Specimens were weighed periodically, and evaporation rates were calculated. Control specimens had no evaporation reducer applied. The test ran for 2.5 hours.

Cordon and Thorpe[18] tested evaporation reducers in either wind or sunlight but not in combination. Poole[16] tested evaporation reducers with air temperature, RH, and wind—anticipated weather conditions in the field. Poole's test values are lower than those observed by Thorpe and Cordon, which is understandable due to the different environmental conditions. What is not understandable, however, is the range of the test results—23, 44, and 65% reduction in moisture (Table 4). In other words, not all evaporation reducers are equal. The best product was found to be two to three times better than the other two products. These are disturbing results for concrete contractors using evaporation reducers to minimize plastic shrinkage cracking and surface crusting. Some contractors indicate that water misting works better using an evaporation reducer—a plausible conclusion if the evaporation reducer they evaluated provided a low reduction in moisture.

From Poole's limited investigation,[16] it appears as though

Table 4:
Effect of evaporation reducers on evaporation of bleed water from mortar specimens

Evaporation reducer	Mass loss, $kg/m^2/h$		Evaporation reduction, %
	With evaporation reducer	Control	
Product A	0.58	0.75	23
Product B	0.49	0.88	44
Product C	0.42	1.19	65

Note: 1 $kg/m^2/h$ = 0.2 $lb/ft^2/h$

protecting concrete during the period between placing and applying final curing using evaporation reducers might require repeated applications, depending on conditions. This would particularly apply if the time of initial setting was several hours after placement, which occurs for slabs to receive a trowel finish.

The limited test results presented herein suggest a wide variation in performance among products. These products are in common use and potentially have a role to play in minimizing early drying problems for PLC concretes. Although the use of an evaporation reducer did not prove effective in the Neuber mockups produced using Type IL cement, it is clear that the industry needs to develop test methods and a specification for evaporation reducers.

Best Practices and Strategies to Minimize Slab Finishing Challenges

The following recommended processes, even though they don't guarantee success as the Neuber mockups illustrate, provide the best solution to minimize slab finishing challenges:

- During the trial batch process, acquire data from a bleed test in accordance with ASTM C232/C232M[20] and a setting time test in accordance with ASTM C403/C403M. For ASTM C232/C232M, obtain the bleeding rate and the accumulated volume of bleed water versus elapsed time. For ASTM C403/C403M, obtain the setting time for 150 psi penetration resistance. This information is needed to develop an initial curing plan for the mockup;
- Based on the anticipated weather, develop an initial curing plan using bleeding and setting time data. Evaluate options for access and techniques for spraying multiple applications of evaporation reducer. Use this plan on the mockup;
- Perform a mockup using the anticipated tools and techniques, and incorporate the initial curing plan. Some Type IL cement concrete mixtures are sensitive to environmental changes, so there is a need for mockups representing both cold (50°F [10°C]) and hot (90°F [32°C]) weather. Adjust the plan based on the mockup, and, if necessary, perform another mockup; and
- Because trial batch data and mockup information might not be available until after the contract is awarded, qualify bid proposals based on anticipated timing of finishing and initial curing. If the planned construction operations require more time, the concrete mixture needs to be adjusted to achieve desired bleeding and setting time, or the anticipated initial curing plan changes, a change order would be appropriate to cover the added costs.

Early-Age, Strength-Critical Concrete Challenges

Construction operations, and thus cost and schedule, are highly dependent on early-age concrete strength. Compressive strength requirements are specified for cold-weather protection (500 psi before first freeze and 3500 psi before multiple freezing-and-thawing cycles per ACI 306R-16[21]), stressing post-tensioning (2500 psi per ACI CODE-318-(19)22)[22], and form removal (75% f_c' per ACI 347R-14(21)).[23] Saw-cut joint timing is also correlated with compressive strength, depending on the aggregate type, ranging from 500 to 1000 psi.[24] Thus, any reduction in strength or delay in early-age strength gain can dramatically affect construction cost and schedule.

The recent Joint ACI-ASCC Survey on PLC Concrete posed questions to elicit user experiences with the performance of early-age concrete in various strength-critical construction operations. The percentages reported as follows represent the answers from 173 respondents. According to the survey, construction operations have been affected by difficulties in achieving early-age strength for PLC concrete.

The following construction operations were influenced by the early-age PLC concrete strength:

- Cold weather protection—49% reported changes;
- Post-tensioning—11% reported delays;
- Form removal—18% reported delays;
- Saw-cut joints—70% reported changes in timing; and
- Compressive strength—30% reported decrease at 3 days while 40% reported decrease at 7 days.

Cold weather protection: Risks include early freezing before concrete reaches 500 psi and multiple freezing-and-thawing cycles before concrete reaches 3500 psi (24 MPa). Low or delayed early-age strength increases the length of cold weather protection, increasing costs and delaying schedule.

Saw-cut joints: Risks include early sawing that causes joint raveling (Fig. 9) and late sawing that causes the concrete to crack outside the joint (Fig. 10). Joint raveling makes it more difficult to fill joints, and the raveled edges may create an undesirable aesthetic. Cracking outside the joint may lead to crack repair or diminished load transfer. Figure 11[25] illustrates the sawing window for which contractors may need to adjust for some Type IL cement concrete slabs. ACI-ASCC Survey comments include: (a) "Some have seen cracking before early entry sawcuts could be cut," (b) "Intermittent setting and unpredictable set times of the concrete made timing the sawcuts difficult. Material sets faster in hot weather and slower in cold weather than equivalent I/II cement," and (c) "There is a need to be very strict about timing for sawcuts."

Stressing post-tensioning: Risks include slab blowouts when stressing and cracking prior to stressing, both due to low strength. On one project, the ready mixed concrete producer told the contractor to use the same maturity curve for Type IL cement concrete as that developed for Type I cement concrete. As Fig. 12 illustrates, the maturity curve for Type I cement over predicted the strength for Type IL, resulting in slab blowouts during stressing; ACI-ASCC Survey comment: "Issue with accuracy of maturity meter readings at early stages of curing of air-entrained mixes with IL cement. Maturity meter readings overpredicted strength. Resulted in PT anchor blowouts. Utilized Windsor probes to assist in determination of concrete strength."

Form removal: Risks include cracking and increased deflection due to early form removal when concrete strength is low, and increased cost and schedule for delayed form removal due to low strength; ACI-ASCC Survey comment: "The last three (cold weather, stressing, and form removal) are most problematic and uniform across the Type IL footprint...reduced 18 hr to 36 hr strengths resulting in delayed post tensioning, form removal, and construction time."

Fig. 9: Saw cutting too early results in raveled joint edges *(photo courtesy of Scott Metzger, Metzger/McGuire)*

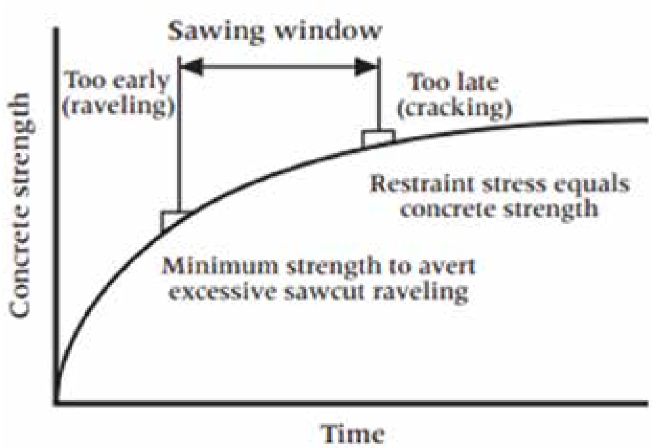

Fig. 11: The sawing window for some Type IL cement concrete slabs is very sensitive to the environment, making it difficult to avoid raveling or cracking[25]

Fig. 10: Saw cutting too late results in cracking *(photo courtesy of Scott Metzger, Metzger/McGuire)*

Fig. 12: Tendons in a concrete slab constructed with Type IL concrete were stressed based on a maturity calibration for Type I cement concrete. The strength of the Type IL cement concrete was overestimated, resulting in slab blowouts

Minimizing Early-Age Strength Challenges

Recommended best practices and strategies to minimize early-age strength challenges include:

- Develop a new trial batch for each Type IL cement concrete mixture, measuring early-age strength at 1, 3, and 7 days. Alternatively, develop a maturity curve on the trial batch in accordance with ASTM C1074.[26] Prior to performing strength-critical operations, such as formwork removal or post-tensioning, ASTM C1074 requires supplementing determination of concrete maturity with other tests;
- Ensure saw cuts are incorporated into slab mockups. Some Type IL cement concrete mixtures are sensitive to environmental changes, resulting in the need for mockups representing both cold (50°F) and hot (90°F) weather; and
- Because trial batch data and mockup information might not be available until after contract award, qualify bid proposals based on anticipated timing of cold weather protection, stressing post-tensioning tendons, and form removal. If the planned construction operations require more time or if the concrete mixture needs to be adjusted to achieve desired early-age strengths, a change order would be appropriate to cover these costs.

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Selected for reader interest by the editors.

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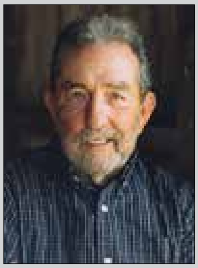

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