Breaking the *Freeze* Barrier

A new ASTM standard helps extend the construction season

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The conventional wisdom is that portland cement concrete placed in below-freezing temperatures requires thermal protection. A new ASTM document, however, will force industry professionals to adjust their thinking. ASTM C 1622, "Standard Specification for Cold-Weather Admixture Systems,"[1] provides specifications for chemical admixtures that help protect concrete and maintain productivity, even when the temperature of concrete is expected to fall as low as –5 °C (23 °F) soon after mixing.

Research dating back to the early 1990s clearly demonstrates the technical feasibility of using chemicals to depress the freezing point and accelerate the curing of concrete. However, cold-weather admixture systems (CWAS) are rarely, if ever, specified, and few concrete practitioners have been willing to develop their own CWAS. This reluctance is a direct consequence of the lack of formal industry acceptance standards.

The new specification, when coupled with forthcoming updates to the ACI guides for chemical admixtures[2] and cold-weather concreting,[3] should therefore increase cold-weather concreting options. In this article, we'll review the work leading up to the adoption of this specification, discuss the main features of the specification itself (along with their impacts on concrete and the concrete industry), and present a synopsis of a recent project that used a CWAS comprising a combination of commercially-available chemical admixtures.

EXPERIENCE WITH CWAS

A survey of the literature dealing with admixtures for cold-weather concrete indicates that these systems were used in the early 1950s in the former Soviet Union and, by the mid-1980s, they were reported in international literature. Except for a few studies,[4,5] domestic literature was quiet on the topic.[6] The first commercial interest in the U.S. occurred in 1992, when two major admixture manufacturers, W.R. Grace & Co. and Master Builders Technologies (now Degussa), partnered with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) to study the performance of chemical admixtures in concrete cured at low temperatures (down to –5 °C [23 °F]) under a Corps of Engineers Construction Productivity Advancement Research (CPAR) program. Two prototype CWAS were successfully field tested as part of this program, but were never commercialized, for reasons explained previously.[7,8]

In 1997, a CWAS was developed from commercial, off-the-shelf admixtures for the Sequoyah Nuclear Power Plant of the Tennessee Valley Authority (TVA). This led to the realization that it was possible to specify and use CWAS from commercially available admixtures without requiring special acceptance standards.[9]

For the Department of Defense (DoD), a clear need existed for being able to place concrete regardless of the weather, even though insulation or heated enclosures

TABLE 1:
SUMMARY OF U.S. FIELD EXPERIENCE WITH CWAS

User/Sponsor	Location	Project date	Purpose
CPAR	Hanover, NH	Feb. 17-18, 1994	Slab and wall
	Sault Ste. Marie, MI	Mar. 15-17, 1994	Road pavement
TVA	Chattanooga, TN	Apr. 14, 1997	Floor of refrigerated room
DoD	Fort Carson, CO	Jan. 28, 2000	Slab-on-ground
	Grand Forks AFB, ND	Feb. 23, 2004	Airfield pavement
FHWA	Littleton, NH	Dec. 10, 2001	Bridge curbing
	Rhinelander, WI	Feb. 27, 2002	Highway pavement
	North Woodstock, NH	Dec.12, 2002	Bridge footing
	West Lebanon, NH	Dec. 18, 2002	Bridge curbing
	Concord, NH	Feb. 14, 2003	Sidewalk
Others	New York , NY	Feb. 18, 2004	Streets and sidewalks
	Bath, ME	Feb. 20, 2000	Shipyard structural concrete

might not always be available. Further, because long-term performance is of less importance in battlefield or emergency operations, a wider scope of additives that might not otherwise be acceptable for commercial application could be used. Various everyday chemicals were found to be useful for making cold-weather concrete not required to last more than 5 years,[10] and the U.S. Army 52nd Engineer Battalion from Fort Carson, CO, successfully tested one of these CWAS in 2000.

More interest in CWAS was generated when others, including the City of New York Department of Design and Construction and Atkinson Construction in Bath, ME, requested CRREL's assistance in selecting their own admixture combination from off-the-shelf products. The City of New York wanted to be able to extend their repair season for streets and sidewalks, while Atkinson Construction wanted to continue concreting operations during the winter to complete a naval shipyard project. Although, in each case, mild weather made use of this technology unnecessary, each entity was better equipped for future needs.

Between 2000 and 2003, eight CWAS were developed from existing commercial admixtures, and five successful field studies were carried out to demonstrate the freeze-protection capability of these products for the Federal Highway Administration (FHWA). This work established the feasibility of mixing, transporting, placing, and finishing concrete made with CWAS at low temperature in full-scale operations using conventional materials, techniques, and equipment. The results indicated that, if this technology were adopted, about 3 to 4 months could be added to a typical construction season and in-place costs could be reduced by about 1/3 of those for projects using conventional cold-weather techniques.[11]

Finally, in February 2004, the U.S. Air Force 319th Civil Engineering Squadron completed a full-depth repair of a 610-mm (24-in.) thick airfield pavement section in Grand Forks, ND, using one of the CWAS developed in the FHWA project mentioned previously. This work demonstrated that U.S. Air Force civil engineering squadrons and contractors alike could place concrete made with CWAS in winter conditions.[12] This work is highlighted at the end of this article.

The use of CWAS technology for various field applications is summarized in Table 1.

OVERVIEW OF ASTM C 1622

The new ASTM specification was justified by an increasing need to place concrete under conditions where freezing temperatures were expected prior to significant strength gain. Although CWAS can be developed from existing admixtures on a case-by-case basis, industry accepted criteria had not been established to qualify their performance under a set of standard test conditions. Thus, a new specification was needed to assure concrete producers and specifiers that selected commercially available admixture systems, used over appropriate dosage ranges, can both protect fresh concrete against freezing and help maintain a productive pace of construction when concrete is expected to be cured under sub-freezing conditions.

According to ASTM C 1622, a CWAS is any combination of commercial chemical admixtures that either depresses the freezing point of mixing water or accelerates the hydration rate of portland cement in concrete, and thereby allows the mixture to eventually achieve normal strength while its internal temperature is as low as –5 °C (23 °F). In addition to these attributes, the new standard requires that concrete mixtures dosed with the CWAS achieve specified ranges of slump and air content.

A highly critical component of the test protocol is that all concrete specimens are to be cooled to –5 °C (23 °F) before the time of initial setting. Thus, essentially all of the cement in these specimens is required to hydrate at low temperature.

Because the degree of workability determines whether the concrete can be properly placed and finished, the rate at which concrete stiffens is important to handling operations. Concrete that loses workability too quickly can be difficult to handle, while concrete mixtures with prolonged setting times can slow down progress and increase the cost of construction. Invariably, the time of setting is extended significantly at low temperatures. For example, an industry rule of thumb suggests that setting time doubles for each 10 °C (18 °F) drop in temperature. The specification requires that the CWAS not allow set retardation, when concrete is held at –5 °C (23 °F), by more than twice that of control concrete held at 20 °C (68 °F). In effect, concrete made with a CWAS is required to act as if it was at 10 °C (50 °F), even though the temperature might be as cold as –5 °C (23 °F).

The time of setting is also used to prove whether the CWAS is able to prevent ice from forming inside the concrete. This is verified by requiring that a replicate specimen be transferred from the –5 °C (23 °F) curing room to a 20 °C (68 °F) room at the time companion specimens reach initial setting. If resistance-to-penetration readings continue to increase over the ensuing 2 hours, the replicate specimen is considered not to have frozen.

The rate at which concrete hardens dictates how rapidly forms can be reused. The specification requires that concrete made with a CWAS, when held at –5 °C (23 °F) for 7 days, attain a compressive strength equal to or greater than 40% of the control concrete cured at 23 °C (73.5 °F) for 7 days. This requires concrete made with a CWAS, as a minimum, to

TABLE 2:
CONCRETE MIXTURE PROPORTIONS AND BATCHING LOCATIONS

Location	Ingredient	Batch			
		1	2	3	4
Concrete plant	Type I/II cement, kg/m³	362	366	362	364
	19 mm (3/4 in.) maximum size coarse aggregate, kg/m³	1099	1145	1143	1145
	Fine aggregate, kg/m³	811	842	832	838
	Water, kg/m³	87	87	88	88
	ASTM C 260[13] air-entraining admixture, mL/m³	99	99	62	68
	ASTM C 494[14] Type A water-reducing admixture, mL/100 kg	916	907	920	913
	Water-cement ratio*	0.31	0.31	0.31	0.31
Job site	ASTM C 494[14] Type C accelerating admixture, L/100 kg	6.8	7.1	5.9	6.2
	Calcium nitrite corrosion inhibitor, L/m³	21.3	21.3	24.8	23.5
	Added water, kg/m³	0	5.3	0	0
	ASTM C 494[14] Type F high-range, water-reducing admixture, mL/100 kg	0	0	84	0
	Water-cement ratio*	0.41	0.43	0.42	0.42
	Concrete temperature† (°C)	‡	8	7	11

* Apparent ratio, based on water metered into the batch, water in the admixtures, and estimated water in the aggregates.

† Temperature of outer surface of mixing drum, taken using a non-contact infrared thermometer.

‡ Not measured.

Note: 1 kg/m³ = 1.69 lb/yd³; 1 mL/m³ = 0.0259 oz/yd³; 1 mL/100 kg = 0.0153 oz/100 lb; 1 L/100 kg = 15.2 oz/100 lb; l L/m³ = 25.9 oz/yd³.

behave as if held at 5 °C (40 °F), which is the lowest concrete curing temperature allowed by current standards.[3]

For long-term performance considerations, CWAS must also meet the requirements for shrinkage and resistance to freezing and thawing similar to those found in the ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete."[13]

FIELD APPLICATION

In February 2004, at Grand Forks Air Force Base in North Dakota, CRREL worked with the U.S. Air Force 319th Civil Engineering Squadron to replace an airfield pavement slab using a CWAS produced from three commercial admixtures. The following synopsis of the project is based on the project report prepared for the Air Force.[12]

To allow the concrete producer time to adjust the individual admixture dosages and overall dosing sequence to produce a concrete mixture that behaved like normal concrete at the time of placement, trial batches of concrete were made the day before the airfield was prepared. Because the job site was at least a half hour away from the concrete plant and gaining access through Base security could be slow, the trial batching simulated job-site addition of some of the admixtures. Past experience with CWAS made by combining commercial off-the-shelf admixtures has shown that the resulting concrete tends to lose slump 30 to 40 minutes after batching.

Figure 1 shows the repair section prepared to receive the concrete. It was an unreinforced concrete pavement located in a nontrafficked area of a parking apron. It was approximately 4.25 x 7 m (14 x 23 ft) and 0.6 m (2 ft) deep. Three locations were instrumented with thermocouples at three depths: 25 mm (1 in.) below the finished surface, at mid-depth, and directly on the base course. The three thermocouple strings were located at the edge, corner, and center of the slab. The edge and corner strings measured temperatures about 25 mm (1 in.) inboard of the existing concrete.

Table 2 shows the mixture proportions and batching locations for the four truckloads of concrete necessary for the job. The CWAS consisted of an accelerating admixture, a corrosion inhibitor, and a water-reducing admixture. The accelerating admixture was used to reduce the time of setting and to speed up strength development

Fig. 1: View of the section of airfield pavement prior to repair. The three thermocouple locations where concrete temperatures were monitored are numbered (from Ref. 12)

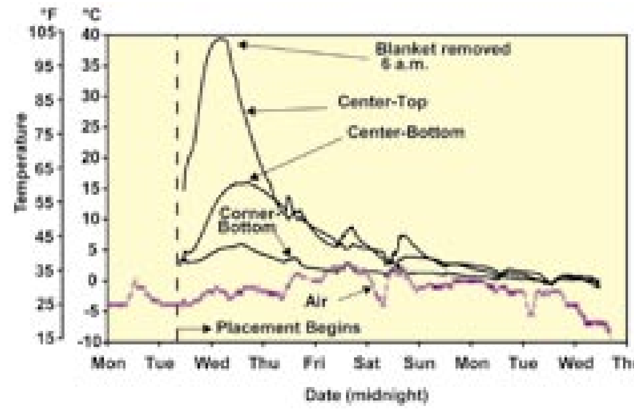

Fig. 2: Temperatures from three locations in the slab and the ambient air

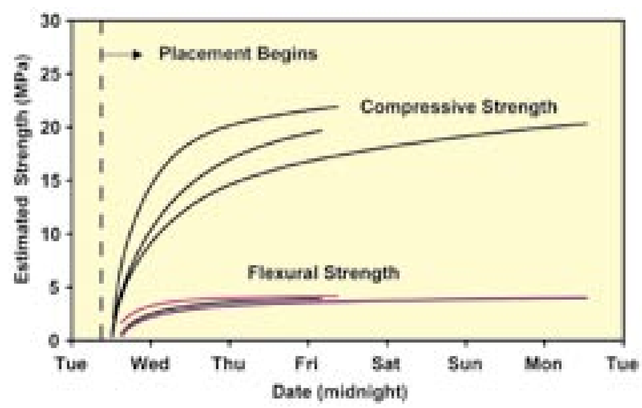

Fig. 3: Compressive strength in the slab was estimated using maturity calculations, and flexural strength was estimated from compressive strength. For the compressive or flexural strength groupings, the top line represents the values for the top surface at the center of the slab, the middle line represents the values for the bottom surface at the center of the slab, and the bottom line represents the values for the bottom surface at the corner of the slab (1 MPa = 145 psi)

at low temperature in addition to its contribution to depressing the freezing point of the concrete. The corrosion inhibitor was used not for its implied property, but for the extra freezing point depression it imparted to the concrete. The water-reducing admixture reduced the amount of mixing water that needed protection from freezing. As can be seen, except for the accelerating admixture and the corrosion inhibitor, the main ingredients were batched at the concrete plant. The dosages of several admixtures were adjusted slightly from batch to batch to make small improvements in properties measured from the preceding loads.

The four truckloads of concrete were sequentially batched at the concrete plant in Grand Forks and driven about 40 km (25 miles) east to a hangar on the Air Base, where they were dosed with the accelerator and corrosion inhibitor before proceeding the final 2 km (1.25 miles) to the job site. The concrete was layered truckload by truckload into the repair section. Thus, the work consisted of placing each layer with the truck's chute, raking it into place, and consolidating it with a vibrator. The surface was later smoothed with a magnesium float, broomed, and edged. After finishing, the slab was covered with insulation blankets, not for thermal protection but to minimize evaporation caused by the windy conditions.

In general, the concrete behaved like normal fast-setting concrete during mixing, placing, and finishing with the exception of the second truckload. Its concrete started out very stiff, even with the full complement of admixtures, and it remained fairly stiff even after extra water was added at the hangar. Initially, the concern was that the mixture might be hydrating rapidly, but a temperature reading quickly revealed that the concrete temperature was low. It was later determined that the fins inside the truck's drum were damaged and the mixing was severely affected. Thus, the poor workability of this load was attributed to the inefficient mixing action of the truck, as opposed to something caused by the admixtures. The other three loads met expectations for workability.

The concrete for this project was designed to resist freezing down to –5 °C (23 °F) and gain appreciable strength while at that temperature. Even though air temperatures cycled between 0 and –5 °C (32 and 23 °F) (Fig. 2), the concrete was never in danger of freezing—even when in direct contact with the frozen substrate. Typically, normal concrete should not be placed on a frozen substrate, but with CWAS, even that is now possible.

Figure 3 shows the development of strength in the slab based on temperature-time factors calculated according to ASTM C 1074[15] from cylinders stored in insulated plywood boxes placed near the repaired section or in water baths at a local testing laboratory. The flexural strength was estimated with an empirical relationship between compressive and flexural strengths.[16] As a rule of thumb, pavements must attain a flexural strength of at least 3.5 to 4.5 MPa (500 to 650 psi) before they are opened to traffic. As Fig. 3 shows, this slab reached a flexural strength of 3.5 MPa (500 psi) within 2 days and was therefore ready for traffic.

ACCEPTANCE INCREASES CAPABILITIES

For the past 25 years, the capability has existed to develop cold-weather admixture systems from existing off-the-shelf admixtures. However, because no acceptance standards existed to qualify their performance, these systems have not been widely used. The new ASTM C 1622 standard, based in part on critical setting and strength performance criteria at –5 °C (23 °F), provides assurance that qualified chemical admixture systems are effective in producing workable and durable concrete mixtures. We expect this new standard will allow wide acceptance of CWAS and enable greater flexibility for placing and curing concrete in below-freezing conditions.

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Selected for reader interest by the editors.

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