ELSEVIER

PII:S0958-9465(97)00063-2

Cement and Concrete Composites 20 (1998) 121–128

0958-9465/98/$19.00

Cold Weather Concreting Admixtures

Charles K. Nmai

Marketing Department, Master Builders, Inc., 23700 Chagrin Blvd., Cleveland, OH 44122, USA

Abstract

Significant strides have been made in the manufacture, placement, curing and protection of concrete under cold weather conditions. As a result, construction companies no longer discontinue concrete placements during cold winter months. In this paper, design considerations that need to be taken into account for the production of high-performance concrete mixtures for cold weather concreting are briefly discussed, with particular emphasis on accelerating admixtures. Performance data for high-performance cold weather concrete mixtures treated with a non-chloride accelerator that contains sodium thiocyanate and provides protection against freezing in the plastic state at ambient temperatures as low as −7°C (20°F), are presented for four projects. The data show the effectiveness of this cold weather admixture (CWA) over a range of above-freezing and subfreezing temperatures, and provide further support for the use of accelerating admixtures as a viable and economical option for cold weather concreting. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: concreting, admixtures, cold weather.

INTRODUCTION

The hydration of portland cement concrete is a chemical reaction that is affected by, among other factors, the temperature of the concrete mixture and the ambient temperature. As the temperature rises, the hydration process proceeds at a faster rate and vice versa. It is not uncommon for the set of plain concrete to be significantly delayed under cold weather conditions, defined by the American Concrete Institute's (ACI) Committee 306[1] as 'a period when for more than 3 consecutive days, the following conditions exist: (1) the average daily air temperature is less than 5°C (40°F); and (2) the air temperature is not greater than 10°C (50°F) for more than one-half of any 24-hour period'. Delayed time of setting increases the potential for freezing of the concrete before initial set, leads to low strength development, which in turn delays removal of forms, shores and reshores, and ultimately, delays construction.

Several options are available for cold weather concreting. These include: heating the water and aggregates; enclosing and heating the area in which the concrete is to be placed; the use of additional cement or Type III cement (high-early strength); the use of chemical admixtures to accelerate concrete set and increase early-age strength development; and the use of protective insulation. The objectives of these practices are to prevent damage to concrete due to freezing at early ages, assure adequate strength development for safe removal of forms, shores and reshores, reduce the potential for thermal cracking, and provide curing and protection to ensure the strength and durability of the concrete for the intended serviceability of the structure.[1]

The choice of which option or options to use is typically made after consideration of the type of structure under construction, the effectiveness of each option, and the costs and benefits involved. Concrete set and strength development often are the critical factors that control the option or options selected, and as a result, changes in concrete mixture design that affect these parameters are typically desired. Through proper selection of chemical admixtures, high-performance cold weather concrete mixtures with accelerated setting and increased early-age strength characteristics, similar to that obtained with plain concrete mixtures at higher ambient and concrete temperatures, can be produced. The use of such high-performance concrete mixtures have permitted year-round concrete construction with significant cost savings to owners and contractors.

In this paper, the parameters that need to be considered in the design of high-performance concrete mixtures for cold weather concreting, in particular the use of chemical admixtures, are discussed. Project profiles highlighting the use of these special concrete mixtures are also presented.

CONCRETE MIXTURE DESIGN CONSIDERATIONS

The primary objective in the design of mixtures for most cold weather concreting applications is to produce concrete with accelerated time of setting and increased early-age strength development characteristics. As shown in Table 1, the time of setting of concrete increases by approximately one-third for every 6°C (10°F) drop in temperature, assuming that the concrete and ambient temperature are the same down to 4°C (40°F).

Accelerated time of setting is usually achieved by increasing the heat of hydration of the concrete mixture. Concrete mixture proportions will typically be the same as that for other times of the year, with minor variations in the amounts of cementitious and pozzolanic materials used, and changes mainly in the types and dosages of chemical admixtures used. The issues that are often considered for each group of concrete mixture ingredients are discussed below.

Table 1. Effect of temperature on the time of setting of concrete

Temperature, °C (°F)	*Approximate time of setting (h)*
21 (70)	6
16 (60)	8
10 (50)	10 2/3
4 (40)	14 1/3
−1 (30)	19
−7 (20)	Set does not occur (concrete will freeze)

Chemical admixtures

Concrete that will be exposed to cyclic freezing and thawing in service should be air entrained. While this provides protection for hardened concrete, it is imperative that protection is also provided for the plastic concrete to ensure adequate development of strength and durability properties. In this regard, chemical admixtures, specifically accelerators, can be used to significantly increase the rate of hydration of portland cement concrete, thereby reducing the need for some of the other considerations discussed later in this paper. ACI Committee 212 defines an accelerating admixture as 'a material added to concrete for the purpose of reducing the time of setting and accelerating early strength development'.[2] Accelerating admixtures are designated as either Type C, Accelerating, or Type E, Water-reducing and Accelerating, in the American Society for Testing and Materials' 'Standard Specification for Chemical Admixtures for Concrete' (ASTM C 494),[3] where their performance requirements in portland cement concrete are also specified.

There are many chemical substances that act as accelerators for concrete. They include soluble inorganic salts, soluble organic compounds, quick-setting admixtures that are used primarily in shotcrete applications, and miscellaneous solid admixtures.[2]

One of the most effective and commonly used accelerators in the construction industry is the inorganic salt, calcium chloride. Consequently, it has been researched extensively and information on its effects on the hydration of cement minerals, the plastic, hardened and durability properties of concrete can be found in the literature.[4,5] However, because under certain conditions it promotes corrosion of embedded reinforcing steel, maximum chloride ion contents have been established for new reinforced concrete structures.[6] This has resulted in the development of non-chloride, non-corrosive accelerating admixtures containing salts of formates, nitrates, nitrites, and thiocyanates.[7–10] These non-chloride, non-corrosive accelerators are effective for set acceleration and strength development; however, the degree of effectiveness of some of these products is dependent on the ambient temperature at the time of placement.

Figure 1 illustrates the effect of a 650 ml/100 kg (10 fl oz/cwt) dose of a non-chloride

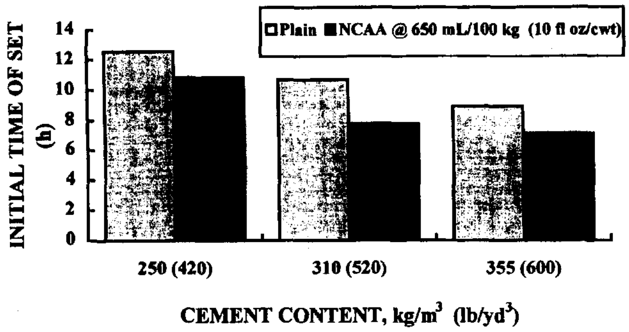

Fig. 1. Effect of cement content and a non-chloride accelerating admixture (NCAA) on initial time of set, at concrete and ambient temperatures of 10°C (50°F).

accelerating admixture (NCAA) on initial time of setting at an ambient and concrete temperature of 10°C (50°F). It can be seen from the figure that a 250 kg/m^3 (420 lb/yd^3) cement factor concrete mixture that was treated with the NCAA had an initial set time approximately equal to that for a plain concrete mixture containing 310 kg/m^3 (520 lb/yd^3) of cement. Similarly, slightly better performance was obtained with an admixture-treated concrete mixture containing 310 kg/m^3 (520 lb/yd^3) of cement compared with a plain concrete mixture with a cement content of 355 kg/m^3 (600 lb/yd^3). For the concrete mixtures evaluated, a 650 ml/100 kg (10 fl oz/cwt) dosage of the NCAA was as effective as a 45 kg (100 lb) increase in cement content. More significant reductions in time of setting can be obtained by increasing the dosage of the accelerator.

In a paper published in 1989, Scanlon and Ryan[11] classified accelerating admixtures into four categories, namely:

(1) Calcium chloride
(2) Accelerating admixtures containing calcium chloride
(3) Non-chloride accelerating admixtures
(4) Non-chloride accelerating admixtures for use in subfreezing ambient temperatures.

Accelerating admixtures with year-round versatility, that is, those that fall into the fourth category listed above, offer the most benefits for cold weather concreting. Ratinov and Rozenberg[4] reported that over 40 years of experience has been gained in Russia on the use of antifreeze admixtures in unheated concrete at ambient air or ground temperatures below 5°C (41°F), and minimum daily temperatures below 0°C (32°F) and down to −30°C (−22°F). Chemical substances listed as antifreeze admixtures in Russia include sodium chloride, calcium chloride, potash, sodium nitrite, calcium nitrate, urea, calcium nitrite–nitrate, and calcium chloride–nitrite–nitrate. However, only calcium nitrite–nitrate and calcium chloride–nitrite–nitrate are, reportedly, specially formulated for use as antifreeze admixtures in Russia.[4]

Antifreeze admixtures are believed to function in two ways:[4,7] first, by lowering the freezing point of the liquid phase of concrete; and second, by accelerating the hydration of cement. The mechanism of ice formation in a normal salt solution can be used to illustrate how antifreeze admixtures lower the freezing point of the pore solution. During cooling of a normal salt solution, pure ice forms leading to an increase in the concentration of the solution. At a critical concentration, the eutectic point, the solution freezes. Data reported by Ratinov and Rozenberg[4] show that for a given antifreeze admixture the freezing point is a function of the solution concentration; the higher the solution concentration, the lower the freezing point. As would be expected also, the eutectic point is dependent on the type of antifreeze admixture; hence, the differences in effectiveness. Table 2 summarizes the eutectic point characteristics reported[4] for some of the antifreeze admixtures used in Russia.

Similarly, in freshly mixed concrete the presence of dissolved calcium, sodium, potassium and sulfate ions lowers slightly the freezing point of pore water, which begins to crystallize as ice at a concrete temperature of about −2°C (28°F).[7] The addition of the proper combination of dissolved solids can further reduce the temperature at which ice formation begins.

Table 2. Eutectic point characteristics for some Russian antifreeze admixtures[4]

Antifreeze admixture	*Eutectic point characteristics*	
	Solution concentration, %	*Freezing point, °C (°F)*
Sodium chloride	23	−21.2 (−6.2)
Calcium chloride	31	−55.0 (−67.0)
Sodium nitrite	28	−19.6 (−3.2)
Calcium nitrate	35	−18.5 (−1.3)
Urea	31	−8.4 (16.9)
Calcium nitrite−Nitrate	35	−29.4 (−20.9)
Calcium chloride-Nitrite-Nitrate	30	−48.0 (−54.4)

Until recently, only one commercially available non-chloride accelerator in North America was reported to be effective at subfreezing temperatures, specifically, at ambient temperatures as low as −7°C (20°F).[7] This multi-component cold weather admixture (CWA) contains sodium thiocyanate as an ingredient. Freezing point data published by Brook *et al.*[7] indicate that the temperature for ice formation in synthetic pore water containing the CWA at a solids concentration of 47.4% was −19.1°C (−24°F). They concluded from the data that for a 10% solids solution of the CWA, ice formation could be prevented down to −7°C (20°F).

The second mechanism by which antifreeze admixtures function, acceleration of cement hydration, was verified through calorimetry tests reported by Brook *et al.*[7] The data (Fig. 2) show that the CWA accelerated the time to maximum heat generation by 8–10 h. Brook *et al.*[7] also reported that, relative to plain cement, the high and low doses of the CWA increased the total amount of heat generated by 625 and 569%, respectively, at −7°C (20°F). The increases in total heat generated comparing the high and low admixture treatments at −7°C (20°F) with the plain cement at 10°C (50°F) were 132 and 120%, respectively.

The CWA is used at dosages ranging from 325 to 5860 ml/100 kg (5–90 fl oz/cwt). For acceleration benefits, dosages ranging from 325 to 3840 ml/100 kg (5–59 fl oz/cwt) are recommended. The higher dosages of 3910–5860 ml/100 kg (60–90 fl oz/cwt) are recommended for concrete placements in subfreezing temperatures for early protection against freezing, in addition to the acceleration benefits. In Ref. 7, it was shown that the time of setting of 4.4°C (40°F) and 10°C (50°F) concrete treated with the CWA, at an ambient temperature of −7°C (20°F), was comparable with that for plain concrete at an ambient and concrete temperature of 21°C (70°F). The companion 10°C (50°F) plain concretes froze in the −7°C (20°F) ambient temperature environment.

The effectiveness of the CWA with regard to set acceleration is also illustrated in Fig. 3 for concrete containing 30% Class C fly ash, at concrete and ambient temperatures of 10°C (50°F). Additional data highlighting the benefits of this admixture at subfreezing temperatures can be found in Ref. 11.

Since the introduction of the CWA, other admixture formulations that depress the freezing point of mix water and accelerate the hydration of portland cement at low temperatures have been investigated.[12,13] As a result of these efforts, in 1992 the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) embarked on separate joint ventures with two major admixture manufacturers in the United States to develop other antifreeze admixtures for commercial applications. These joint ventures were part of the Construction Productivity Advancement Research (CPAR) initiative of the U.S. Army Corps of Engineers.

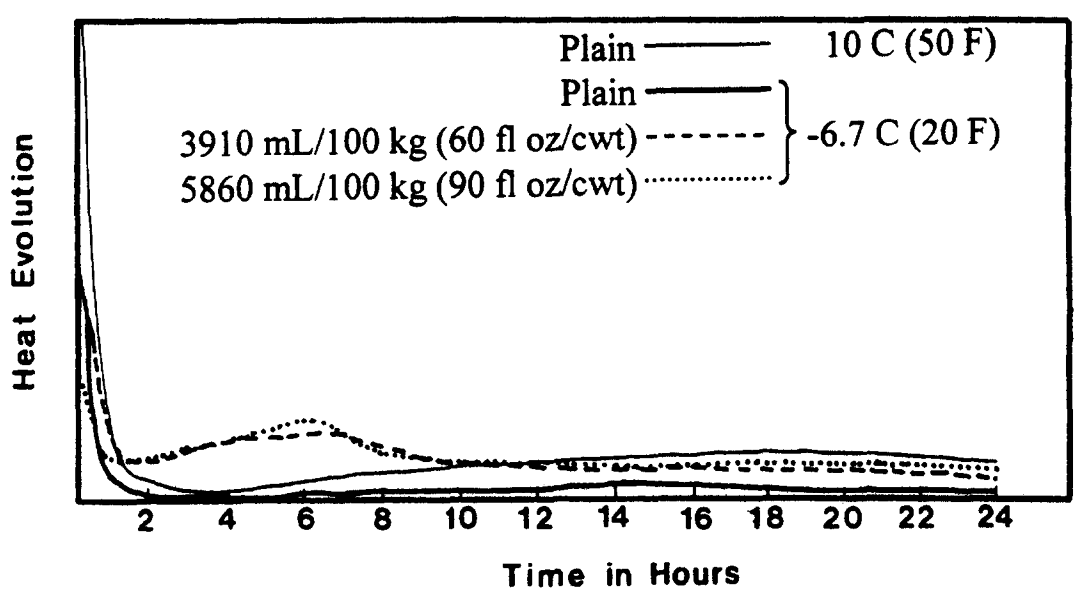

Fig. 2. Calorimetry test data for CWA-treated cement hydrated at −6.7°C and plain cement hydrated at −7 and 10°C [7].

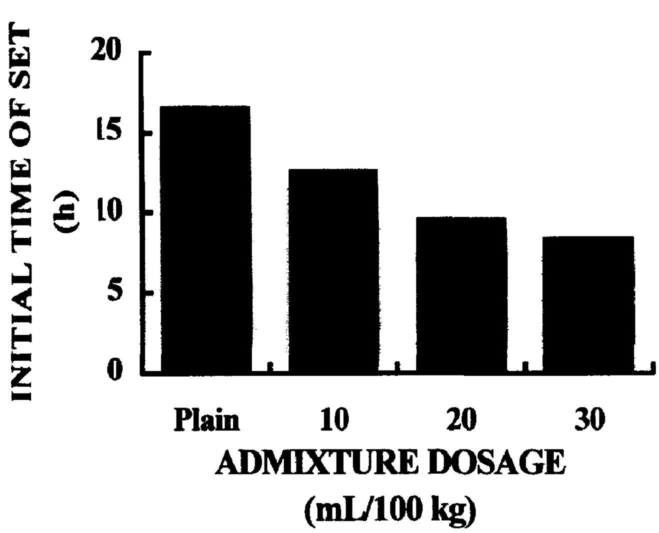

Fig. 3. Effect of CWA dosage on initial set of concrete. [Non-air-entrained with 30% Class C fly ash; concrete and ambient temperatures of 10°C (50°F); 1 fl oz/cwt = 65.1 ml/100 kg.]

Mid-range and high-range water reducing admixtures

The primary benefit of antifreeze admixtures with regard to plastic concrete is the ability to prevent ice formation, especially prior to setting, while accelerating setting and early-age strength development. The two mechanisms by which antifreeze admixture work are both beneficial in this regard. Conceivably, the formation of ice, and any subsequent damage that can be caused as a result, can also be minimized by significantly reducing the amount of pore water. This can be achieved in part by reducing the amount of mixing water through the use of a low water–cementitious materials ratio and a mid-range or high-range water-reducing admixture. It should be noted, however, that these types of water-reducing admixtures will typically not accelerate the setting of concrete. Therefore, for maximum benefit they should be used in combination with an accelerating admixture. Conversely, the accelerating admixture can be formulated to provide water reduction. The CWA described earlier is formulated to provide water reduction and it meets ASTM C 494 requirements for a Type E, Water-reducing and Accelerating, admixture.

Cementitious and pozzolanic materials

Adjustments can be made in the amounts and types of cementitious and pozzolanic materials used in order to increase the rate of hydration, and consequently, the heat of hydration. For straight cement mixes, either the amount of cement can be increased or Type III cement can be substituted for other types of cement to accelerate concrete set. As shown in Fig. 1, initial times of setting for plain concretes placed at an ambient temperature of 10°C (50°F) were reduced by approximately 1 h 55 min and 3 h 40 min, by increasing the cement content by 59 and 107 kg/m^3 (100 and 180 lb/yd^3), respectively.

For mixes containing pozzolanic materials, the percentage of the pozzolan, as a partial replacement for cement, can be reduced and the amount of cement increased accordingly. In all cases, trial mixes should be made to ensure that the desired setting and strength development characteristics are obtained.

Mixing water

The amount of mixing water should be consistent with the specified or desired water–cementitious materials (w/cm) ratio. For flatwork, ACI 306[1] recommends the use of concrete with a slump lower than normal (less than 100 mm (4 in.)), to minimize bleeding and thereby permit proper finishing. For concrete mixtures batched to a specified slump, the amount of mixing water will decrease with a decrease in concrete temperature, as shown in Fig. 4. The temperature of the mixing water is the easiest means of adjusting the temperature of the concrete mixture, and for concrete placed in cold weather, it is not uncommon to heat the mixing water to 60°C (140°F) or higher.

Fine and coarse aggregates

No significant adjustments are made in the amounts of fine and coarse aggregates used,

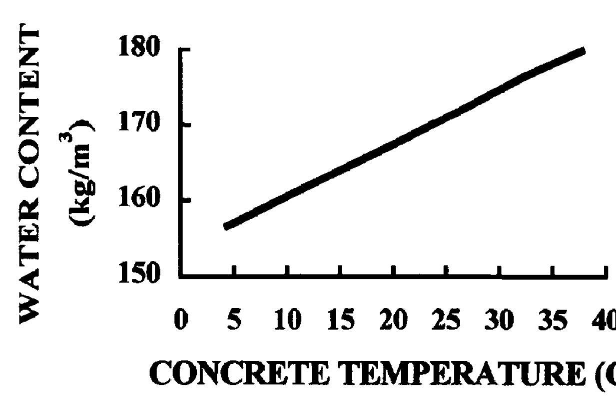

Fig. 4. Effect of concrete temperature on mixing water content to produce a slump of 75 mm (3 in.) [1 kg/m^3 = 1.686 lb/yd^3; °F = 1.8°C +32.]

other than that necessary to adjust for yield if changes are made in the total volume of cementitious and pozzolanic materials. However, it may be necessary to heat the aggregates if the ambient temperatures are consistently below −4°C (25°F).[1] Depending on the temperature of the heated mixing water and the condition of the coarse aggregate, heating may be necessary for only the fine aggregate to obtain the desired freshly mixed concrete temperature. Further details may be found in ACI 306R-88.[1]

HIGH-PERFORMANCE COLD WEATHER CONCRETE MIXTURES

The advent of specialty chemical and mineral admixtures has facilitated the development and use of concrete mixtures with properties that cannot be obtained routinely using only conventional constituents. These mixtures have been termed 'high-performance concretes' because of the enhanced fresh/plastic, mechanical and durability properties that they possess. For example, if a concrete mixture typically used at an ambient temperature of 21°C (70°F) is placed at −7°C (20°F), its time of setting and strength development would be delayed significantly. However, by simply adding an accelerating admixture with antifreeze properties to the mixture, faster setting and improved strength development characteristics could be obtained. In this regard, concrete mixtures used in cold weather applications can be termed 'high performance', especially when their economic impact is taken into consideration.

Numerous projects have benefited from high-performance cold weather concrete mixtures incorporating some of the design considerations discussed above, in particular, non-chloride accelerating admixtures. In this section, a few of these projects are profiled. All the concrete mixtures described below were treated with a Class 4 accelerator, specifically, the CWA mentioned earlier. These projects have also been selected to illustrate the impact of this admixture on normal concrete mixtures containing Class C fly ash or ground granulated blast-furnace slag. These mineral admixtures typically delay time of setting and, hence, would not be logical choices for a cold weather concrete mixture.

Project No. 1: Freezer concrete floor, Little Rock, Arkansas

A rather unique application of a high-performance cold weather concrete mixture occurred in the summer of 1986 in Little Rock, Arkansas, even though the ambient temperature was about 28°C (82°F). The project was a 9.2 m^3 (12 yd^3) concrete floor placement for a freezer at a dairy food manufacturing plant. At the time of placement, the concrete temperature was 27°C (80°F) and the temperature in the freezer was −4°C (25°F). As shown in Table 3, the CWA was used at a dosage of 3910 ml/100 kg (60 fl oz/cwt) and the design strength of 27.6 MPa (4000 psi) at 28 days was achieved. The concrete contained approximately 23% Class C fly ash by mass of cement.

Project No. 2: Parking garage, Detroit, Michigan

This project involved the construction of a 62 710 m^2 (675 000 ft^2), 30 580 m^3 (40 000 yd^3) parking garage to serve the Chrysler Technology Center. The critical performance requirement, to meet the contractor's needs, was the production of high plasticity, pumpable concrete that set in 4 h throughout the year, regardless of the ambient conditions. In addition, the concrete had to develop 75% of the specified 28-day compressive strength of 34 MPa (5000 psi) in 3 days. These requirements were achieved by using the CWA in combination with a third-generation high-range water-reducer (HRWR) as shown in Table 4.

Table 3. Concrete performance data: Project No. 1

Mixture ingredient	*lb/yd³*	*kg/m³*
Cement	440	260
Class C Fly Ash	100	59
Fine Aggregate	1385	820
Coarse Aggregate	1900	1125
Water	200	118
CWA dosage:	60 fl oz/cwt	3910 ml/100 kg
Concrete temperature	80°F	27°C
Ambient temperature		
Air	82°F	28°C
Freezer	25°F	−4°C
Slump	8.5 in.	215 mm
Compressive strength		
3-day	3470 psi	24 MPa
7-day	4030 psi	28 MPa
28-day	4370 psi	30 MPa

Table 4. Concrete performance data: Project No. 2

Mixture ingredient	*lb/yd³*	*kg/m³*
Cement	520	310
Class C fly ash	100	59
Fine aggregate	1300	790
Coarse aggregate	1710	1015
Water	240	142
CWA dosage	5–20 fl oz/cwt	325–1300 ml/100 kg
Third generation HRWR	18 fl oz/cwt	1170 ml/100 kg
Air-entraining admixture	1 fl oz/cwt	65 ml/100 kg
Air content	6.5%	6.5%
Slump	8.0 in.	200 mm
Compressive strength		
3-day	4470 psi	31 MPa
7-day	5100 psi	35 MPa
28-day	6790 psi	47 MPa

To meet the 4 h time-of-set requirement, the dosage of the CWA was varied as shown in the chart below:

Ambient temperature, °C (°F)	*Accelerator dosage, ml/100 kg (fl oz/cwt)*
16–21 (60–69)	325 (5)
10–15 (50–59)	650 (10)
4–9 (40–49)	975 (15)
0–4* (32–39*)	1300 (20)

*Concrete required to be protected after placement.

Project No. 3: Pile caps for fishing pier, Gloucester, Massachusetts

Approximately 153 m³ (200 yd³) of concrete containing a mixture of Type II cement and ground granulated blast-furnace slag were treated with 3910 ml/100 kg (60 fl oz/cwt) of the CWA, for protection against freezing in the plastic state, during the construction of a fishing pier in Gloucester, Massachusetts. Concrete performance data for this project are given in Table 5. The design compressive strength at 28 days was 28 MPa (4000 psi).

Project No. 4: Society tower, Cleveland, Ohio

Several high-performance concrete mixtures were used in the construction of this 64-storey high-rise building in downtown Cleveland, Ohio. One of these mixtures, which was used for the floor slabs, contained 267 and 59 kg/m³ (450 and 100 lb/yd³) of Type I cement and Class C fly ash, respectively, and a water–cementitious materials ratio of about 0.55. During the winter months, 980–3910 ml/100 kg (15 to 60 fl oz/cwt) of the CWA was used in this mixture to enhance concrete set and early-age strength development. The 3910 ml/100 kg (60 fl oz/cwt) dosage was used in subfreezing temperatures and enabled placement of the upper floor slabs under construction at the time without the need for heaters on the floors immediately beneath them, which were tarped. Ambient temperatures ranged from −7 to −3°C (20–27°F).

ECONOMIC BENEFITS OF COLD WEATHER CONCRETING ADMIXTURES

The economic benefits of cold weather concreting admixtures, in particular, accelerating admixtures with antifreeze properties, are basically derived from their ability to extend the

Table 5. Concrete performance data: Project No. 3

Mixture ingredient	*lb/yd³*	*kg/m³*
Type II cement	508	300
Granulated slag	218	129
Fine aggregate	1015	602
Coarse aggregate	1750	1038
CWA dosage	60 fl oz/cwt	3910 ml/100 kg
Air-entraining admixture	1.5 fl oz/cwt	100 ml/100 kg
Concrete temperature	60°F	16°C
Ambient temperature	26°F	−3°C
Air content	approx. 7%	approx. 7%
Slump	4.25 in.	110 mm
Compressive strength		
7-day	5190 psi	36 MPa
28-day	7090 psi	49 MPa

construction season. In this regard, the ready-mixed concrete producer, the contractor and, more importantly, the owner benefit. The specific benefits include:

For the Ready-Mixed Concrete Producer

(1) Ability to provide concrete for use in subfreezing ambient temperatures
(2) A viable, economic alternative to other cold weather concreting options
(3) (increased cement content and hot water)
(4) Accelerated setting and increased early-age strength development
(5) Increased productivity and profitability

For the Contractor
(1) Ability to place concrete in subfreezing ambient temperatures
(2) Accelerated setting
(3) Earlier finishing of slabs
(4) Reduced heating and protection costs (insulating blankets, heaters, etc.)
(5) Increased early-age strength development
(6) Earlier stripping and re-use of forms of forms
(7) Faster construction, increased productivity and greater flexibility in scheduling work
(8) Overall reduction in construction costs (especially, for labor)
(9) Reduced construction loan finance charges and increased profitability

For the Owner

(1) Earlier use of structure
(2) Reduced loan interest payments

SUMMARY

The information presented in this paper show that high-performance concrete mixtures that permit concreting in cold weather can be produced with the use of specialty non-chloride accelerating admixtures. These admixtures accelerate the setting and early-age strength development of concrete and, as in the case of the CWA, also provide protection against freezing in the plastic state.

Significant benefits are derived from the use of high-performance concretes that contain cold weather concreting admixtures. For the ready-mixed concrete producer, the use of the CWA will reduce hot water heating costs and the need to increase cementitious materials contents. Benefits for contractors include the ability to place concrete in subfreezing temperatures, reduced in-place concrete costs, earlier stripping of forms and, ultimately, faster and earlier completion of construction, and an overall reduction in construction costs. For the owner, the main benefit is earlier use of the structure, and possibly, a reduction in loan interest payments.

REFERENCES

1. ACI Committee 306, ACI 306.R-88, Cold Weather Concreting. American Concrete Institute, Detroit, Michigan, 1988.
2. ACI Committee 212, ACI 212.3-91, Chemical Admixtures. American Concrete Institute, Detroit, Michigan, 1991.
3. ASTM C 494, Standard Specification for Chemical Admixtures for Concrete. Annual Book of ASTM Standards, Vol. 04.02, Concrete and Aggregates, 1993, pp. 260–268.
4. Ramachandran, V. S., Chapter 5: Accelerators; Chapter 11: Antifreezing admixtures. In: Ratinov, V. B., Rozenberg, T. I. and Ramachandran, V. S. (Eds), Concrete Admixtures Handbook — Properties, Science, and Technology, 2nd edn. Noyes Publications, New Jersey, 1995, 1153 pp.
5. Rixom, M. R. and Mailvaganam, N.P., Chemical Admixtures for Concrete, 2nd edn. E. and F.N. Spon, London, 1986, 306 pp.
6. ACI Committee 318, ACI 318 (Revised 1992), Building Code Requirements for Reinforced Concrete. American Concrete Institute, Detroit, MI, 1992.
7. Brook, J. W., Factor, D. F., Kinney, F. D. and Sarkar, A. K., Cold weather admixture. In: Concrete International — Design and Construction, Vol. 10, No. 10, Oct. 1988, pp. 44–49.
8. Smith, P., Effects of two non-chloride accelerating agents on setting characteristics of portland cement mortars. Corrosion, Concrete, and Chlorides, Steel Corrosion in Concrete: Causes and Restraints, SP-102, American Concrete Institute, 1987, pp. 25–34.
9. Chin, D., A calcium nitrite-based, non-corrosive, non-chloride accelerator. Corrosion, Concrete, and Chlorides, Steel Corrosion in Concrete: Causes and Restraints, SP-102. American Concrete Institute, 1987, pp. 49–77.
10. Popovics, S., Strength-increasing effects of a chloride-free accelerator. Corrosion, Concrete, and Chlorides, Steel Corrosion in Concrete: Causes and Restraints, SP-102. American Concrete Institute, 1987, pp. 79–106.
11. Scanlon, J. M. and Ryan, R., Placing cold weather concrete. The Construction Specifier, December 1989, pp. 58–65.
12. Korhonen, C. J., Cortez, E. R., and Smith C. E., New admixtures for cold weather concreting. Cold Regions Engineering, 6th International Specialty Conference TCCR-ASCE. West Lebanon, NH, 26-28 February 1991, pp. 200–209.
13. Korhonen, C. J., Cortez, E. R., Charest, B. A. and Smith C. E., Low-temperature admixtures for concrete. Proceedings of the 7th International Cold Regions Engineering Specialty Conference, Edmonton, Alberta, Canada, 7–9 March 1994, pp. 87–96.