Technical Report Documentation Page

1. Report No. SPR-UAF-92-13	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Economic Evaluation of Cold Concrete		**5. Reporting Date** September 19, 1994 **6. Performing Organization Code**
7. Author(s) F. Lawrence Bennett		**8. Performing Organization Report No.** INE/TRC 94.02
9. Performing Organization Name and Address Institute of Northern Engineering University of Alaska Fairbanks Fairbanks, AK 99775-5900		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Alaska Dept. of Transportation and Public Facilities Engineering and Operations Standards 3132 Channel Drive, Juneau, AK 99801-7898		**13. Type of Report and Period Covered.** Final, 2 years **14. Sponsoring Agency Code**

15. Supplementary Notes

16. Abstract

"Cold Concrete" is Portland cement concrete that is placed and cured at ambient temperatures below 32°F (0°C) without temporary protection or additional heating. Special admixtures are used to depress the freezing point and to allow strength build-up without detrimental effects to the concrete.

A survey of Scandinavian cold concrete was conducted. An extensive literature search resulted in a listing of 31 references. A data base was designed to provide a basis for compiling available data on material properties and costs. From several sources, data were gathered on mix components, "anti-freeze" admixtures and their proportions, water/cement ratios, curing temperatures and associated compressive strengths. The elements of an expert system were designed and demonstrated; when fully developed, this system will allow the designer, contractor and/or owner to select the optimum mix for a given set of environmental and use conditions.

The report concludes that 1) there is great potential for the economic use of cold concrete, if proper admixtures can be identified; 2) the lack of data on freeze/thaw durability characteristics limits the practical use of such mixtures at the present time; and 3) accurate data will be an essential part of a functional expert system.

17. Key Words Concrete Cold weather Construction Admixtures Expert System		**18. Distribution Statement**	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 95	**22. Price**

Form F 1700.7 (8-72) Reproduction of completed page authorized

ECONOMIC EVALUATION OF COLD CONCRETE

by

F. Lawrence Bennett, P.E.
Professor and Head, Engineering and Science Management
University of Alaska Fairbanks
Fairbanks, Alaska 99775

A report on research sponsored by
Alaska Department of Transportation and Public Facilities

September 1994

Report No. INE/TRC 94.02

TRANSPORTATION RESEARCH CENTER
INSTITUTE OF NORTHERN ENGINEERING
UNIVERSITY OF ALASKA FAIRBANKS
FAIRBANKS, ALASKA 99775

DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the date presented herein. This document is disseminated through the Transportation Research Center, University of Alaska Fairbanks. This research has been partially funded by the Alaska Department of Transportation and Public Facilities (AKDOT&PF). The contents of the report do not necessarily reflect the views or policies of AKDOT&PF or any local sponsor. This work does not constitute a standard, specification, or regulation.

ABSTRACT

"Cold concrete" is Portland cement concrete that is placed and cured at ambient temperatures below 32° F (0° C) without temporary protection or additional heating. Special admixtures are used to depress the freezing point and to allow strength build-up without detrimental effects to the concrete.

A survey of Scandinavian cold concrete practice was conducted. An extensive literature search resulted in a listing of thirty-one references. A data base was designed to provide a basis for compiling available data on material properties and costs. From several sources, data were gathered on mix components, "anti-freeze" admixtures and their proportions, water/cement ratios, curing temperatures and associated compressive strengths. The elements of an expert system were designed and demonstrated; when fully developed, this system will allow the designer, contractor and/or owner to select the optimum mix for a given set of environmental and use conditions.

The report concludes that 1) there is great potential for the economic use of cold concrete, if proper admixtures can be identified; 2) the lack of data on freeze/thaw durability characteristics limits the practical use of such mixtures at the present time; and 3) accurate cost data will be an essential part of a functional expert system.

TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

LIST OF TABLES

ACKNOWLEDGMENTS

David Esch, P.E., served as Project Manager, and Rod Platzke, P.E., served as Technical Research Advisor for this project. The efforts and interest of both are appreciated. Dr. E.R. Baker made substantial contributions as co-investigator, particularly on the database design phase. The contributions of Dr. Lutfi Raad, Director of the UAF Transportation Research Center, are also acknowledged, with thanks.

ECONOMIC EVALUATION OF COLD CONCRETE
Closure Report
September 1994

1.0 Introduction

This report has been prepared as the final report for the project "Economic Evaluation of Cold Concrete," sponsored by the Alaska Department of Transportation and Public Facilities as project SPR-UAF-92-13 under the Alaska Cooperative Transportation and Public Facilities Research Program. The project was approved in spring 1992, with funding expected for two fiscal years. Unfortunately, funding was not authorized for the second year and thus only five of the eight original work tasks could be completed. The purpose of this report is to gather the several interim reports into a single document and to suggest further necessary investigation needed to complete the original study. Other comments, additional indicated research beyond the scope of this study and a reference list covering the entire study are also included.

The original objectives of the full study were stated as follows:

1. Summarize known strength data (both short- and long-term), stability (spalling) information and corrosion performance for several design mixtures of Portland cement concrete which utilize anti-freeze admixtures and have been cured at temperatures below freezing.

2. Develop a data base that contains the available information on : 1) costs for materials, labor, equipment and other elements for mixing,

placing and protecting such mixtures; 2) short-term and long-term strength and stability; and 3) corrosion characteristics.

3. Formulate guidelines that will assist the designer, contractor and owner in determining the most appropriate types of admixtures for various concrete applications and various predicted short- and long-term environmental conditions. Develop a preliminary expert system to assist in making these determinations.

We describe each phase that was completed during the limited study and append all materials that have been prepared. These include a report on Scandinavian practice, a database design, a section on data collection and a preliminary routine that provides decision-making guidelines. We also reference a literature review that was not identified as a separate task. Sections with additional comments, further efforts needed to complete this study, additional research indicated, acknowledgments and a complete reference list complete the report.

2.0 Scandinavian Practice

The author spent the fall 1992 semester at Sweden's Luleå University of Technology and at other locations throughout Scandinavia. During that time, he gathered considerable information about cold concrete practice, which was summarized in an interim report for this project. That report is included herein as Appendix A.

3.0 Literature Review

The Scandinavian literature reports only moderate interest in the use of cold concrete. Several research projects have investigated the strength properties of such mixtures, but there has been little investigation of their freeze-thaw durability characteristics. A great deal of information is available on cold weather concrete construction methods, including various techniques for providing temporary protection and heating of fresh concrete, as well as the use of silica fume, "hot" concrete and "warm" concrete and the development of computer software to analyze the temperature versus time relationships of various mixes under a variety of environmental conditions. The report in Appendix A provides details of this literature review.

The data collection phase of the project, whose report is found in Appendix C, includes references to several sources that provide research results on three aspects of the performance of several cold concrete admixtures -- 1) compressive strength, 2) long-term freeze-thaw durability, and 3) corrosion of metals contained within the concrete.

Beach (1986) performed an extensive set of cold concrete experiments that tracked the internal concrete temperature as a function of time for a variety of mixes. The study concluded that, with proper admixtures, such concretes can gain sufficient compressive strength at ambient temperatures as low as -9° C. Consistent with other reports (Ramachandran 1984), Beach concluded that the relatively small freezing point depression of the water (about 3° C) is not the mechanism by which these concretes gain strength.

The Ramachandran (1984) Concrete Admixtures Handbook provides a small amount of information on admixtures for cold concrete. A short quotation on the anti-freezing action of calcium chloride is instructive, as follows:

> "This amount [2% calcium chloride with a water/cement ratio of 0.5], which is equivalent to 3% anhydrous calcium chloride, would lower the freezing point by approximately 1.4° C. This shows that at normal dosages the depression of the freezing point is negligible and hence calcium chloride does not act as an anti-freeze. The real effect of calcium chloride is its ability to increase the rate of reaction in the cement-water system."

Thus, according to at least two sources, the term "anti-freeze admixture" is inappropriate for the kinds of additives that were the subject of this study.

Work by Korhonen and his colleagues at the U.S. Army Cold Regions Research and Engineering Laboratory is the primary United States source of new information on the performance of such materials. His literature review (Korhonen 1990) contains excellent background information and provides a short consideration of the costs of such mixtures. Other more recent reports (Korhonen et al 1991; 1994) report research results, with the latter also presenting a short section on properties of insulation that could be used in lieu of cold concrete and would provide equivalent protection of the fresh concrete. This paper reports the interesting statistic that about $800 million is spent in the United States annually to supply heat for keeping concrete warm.

For the convenience of the reader, we list in the References section of the body of this report (section 10.0) all references cited, even though many are also included in the various individual sections and interim reports.

4.0 Database Design

In preparation for the collection and organization of data on cold concrete designs, performance and cost, a database was designed. It identifies the elements and indicates the format of each. The next step, not completed for this project, would be to program the database and populate it with data. Currently, the data that were collected are simply contained in tabular form, as shown in Appendix C.

The interim report on database design is included here as Appendix B.

5.0 Data Collection

Appendix C contains the interim report on data collection. The data collected are from literature reports of research experimentation, including 28 day compressive strength for 101 samples of varying admixture content, W/C ratio, aggregate specifications, and the like. The report also includes data on freeze-thaw durability from three sources and data on corrosive effects of different admixtures, based on two studies.

6.0 Design Guideline Development

The final effort in the abbreviated research project was to develop the framework for a set of guidelines that could assist the decision maker in selecting an appropriate and economical concrete mix for a given set of use requirements and environmental conditions. A flow chart was developed to indicate the steps in a rudimentary routine that could form the basis for an expert system. The routine was used to develop eight feasible concrete mix/construction method combinations for a very hypothetical set of conditions. Hypothetical cost data were then applied to develop overall costs for each of the combinations. That report also suggested further enhancements required to make the routine practical and indicated additional data that would be required for a "real life" application.

Appendix D contains the interim report on this phase of the project.

7.0 Additional Comments

The importance of accurate and complete cost information cannot be overemphasized. While the original intent was to include cost data in the database for each concrete mix, and while the database design provides for such a feature, it is now apparent that such an approach is likely to be impractical. Instead, as shown in the design guideline development section, it is probably more reasonable to perform the technical analysis first, utilizing mix performance information to develop all reasonable feasible mixes and construction method combinations. Then, the user can supply cost data only for the elements of cost for those options reported as feasible.

In terms of the performance of cold concrete mixes, the role of the admixture in the process is still not completely understood. However, most researchers now believe that the admixture serves less as a freeze point depressant and more as an accelerator of the rate of reaction.

Information on the long term freeze-thaw durability of cold concretes is lacking. Until it is better understood and those admixtures without adverse effects on such durability have been identified with confidence, it is unlikely that there will be high acceptance, at least in areas where the temperature is likely to cycle above and below freezing several times each year.

8.0 Further Efforts Needed to Complete This Study

As has been indicated earlier, this study was terminated prematurely when funding was not provided for its second year of investigation. To complete the study as originally envisioned, the following activities should be undertaken:

- At least some representative cost data should be gathered, both for the ingredients of the concrete mixes, including admixtures, and for elements of construction operations such as placement, insulation and heating.

- The database should be programmed to the point where it is ready to accept data.

- A sampling of performance and cost data should be added to the database.

- The preliminary design of an expert system should be completed.

9.0 Additional Research Indicated

Beyond the additional work required to complete the original study as proposed, noted in section 8.0, other research can help to achieve fuller understanding of the performance and cost of cold concretes. Among these topics are the following:

- Testing of mixes with other admixtures. An example is silica fume, which has gained considerable interest in Scandinavia and Russia for its ability to achieve very high compressive strengths.

- The field installation and monitoring of several cold concrete mixes under a variety of carefully recorded conditions. Various types of uses, ranging from slabs to structural members, should be studied.

- Tests of long term durability of cold concrete mixes, both in the laboratory and in the field.

- Gathering of additional data on the cost of all options

10.0 References

Beach, W.G. 1986. Cold Set Concrete: Final Report. Alaska Department of Transportation and Public Facilities Research Report AK-RD-86-28.

"BETEC Köldbetongtillsats (BETEC Cold Concrete Additive)." n.d., Finja BETEC AB, Upplands, Väsby, Sweden.

Concrete Association of Finland. 1991. "High Strength Concrete Supplementary Rules and Fire Design." RakMK B4

"ConcTrol Box." n.d. Skanska Stockholm AB, Danderyd.

Elfgren, L., V. Ronin and W. Forsling. 1992. "Concreting at Low Temperatures: Improved Methods of Using Inorganic Modifiers for High Strength Silica Fume Concrete." Tekniska Högskolan i Luleå, Division of Structural Engineering, June 10, 1992.

Elfgren, L. et al. 1992. "Mechanical Modified Cement (MMC) for Cold Concreting and Economic Evaluation of Improved Winter Concrete Technology." Tekniska Högskolan i Luleå, Division of Structural Engineering, November 11, 1992.

Fagerlund, G. 1979. "Prediction of The Service Life of Concrete Exposed to Frost Action." Studies on Concrete Technology. Swedish Cement and Concrete

Research Institute, Stockholm, 249-276.

Fagerlund, G. 1992. "Effect of The Freezing Rate on The Frost Resistance of Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 11, 20-36

Gjørv, O.E., K. Okkenhaug, E. Bathen and R. Husevåg. 1988. "Frost Resistance and Air-Void Characteristics in Hardened Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 7, 89-104.

Goncharova, L.S. and F.M. Ivanov. 1975. "The Properties of Concretes Containing Antifreeze Admixtures." Proceedings of the 2nd International Symposium on Winter Concreting, Vol. 1. October 14-16, 1975, Moscow, 69-71.

Grapp, A.A., V.B. Grapp and A.S. Kaplan. 1975. "The Structure and Cold Resistance of Concretes Containing Antifreeze Admixtures." Proceedings of the 2nd International Symposium on Winter Concreting, Vol. 1. October 14-16, 1975, Moscow, 60-68.

Hammer, T.A. and E.J. Sellevold. 1990. "Frost Resistance of High Strength Concrete." High Strength Concrete SP5 - Design Application Report 5.3. The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, Trondheim. Report No. STF65 A90013.

Hett5: Program för beräkning av temperatur-och hållfasthetsutveckling. 1991. Betong Data, Tumba, Sweden.

Jonasson, J-E. 1984. Slipform Construction -- Calculations for Assessing Protection Against Early Freezing. Cement och Betong Institutet, Stockholm, CBI Research fo 4:84.

Kilpi, E. and A. Sarja. 1983. Builder's Guide to Safe Winter Concreting. Technical Research Centre of Finland, Espoo. Research Notes 62, August 1983.

Kivekäs L., S. Huovinen and M. Leivo 1985. Concrete Under Arctic Conditions. Technical Research Centre of Finland, Espoo. Research Reports 343, March 1985

Korhonen, C.J. 1990. Antifreeze Admixtures for Cold Regions Concreting: A Literature Review. U.S Army Corps of Engineers Cold Regions Research & Engineering Laboratory. Special Report 90-32, September 1990.

Korhonen, C.J. et al. 1991. "New Admixtures for Cold Weather Concreting." in Sohdi, D.S., ed. Cold Regions Engineering. Proceedings of the Sixth International Specialty Conference, ASCE, 200-209.

Korhonen, C.J. et al. 1994. "Low-Temperature Admixtures for Concrete." in Smith, D.W. and D.C. Sego, eds. Cold Regions Engineering: A Global Perspective. Proceedings of the Seventh International Specialty Conference, Canadian Society for Civil Engineering, 87-96.

Korhonen, R. 1987. Kilpisjärvi Project: Long Transport of Frost Concrete. Technical Research Centre of Finland, Espoo. Research Notes 808, December 1987.

Kukko, H. and I. Koskinen. 1988. RILEM Recommendations for Concreting in Cold Weather. Technical Research Centre of Finland, Espoo. Research Notes 827, January 1988.

Maage, M. and S. Helland. 1988. "Cold Weather Concrete Curing Planned and Controlled by Microcomputer." Concrete International. October 1988, 34-39.

Norcem Break-Off Tester. 1983. User's Guide. Norcem Cement, Slemmestad, Norway.

Petersson, Ö. and A. Johansson. 1991. Styrning av Glättningshårdhet (Controlling Troweling Hardness). Cement och Betong Institutet, Stockholm, Rapport 1:91.

Poijärvi, H. 1991. Finnish Building: Construction Technology Developed for Cold Climates. Technical Research Centre of Finland and Rakentajain Kustannus Oy.

Ramachandran, V.S., ed. 1984. Concrete Admixtures Handbook: Properties, Science and Technology. Park Ridge, NJ: Noyes Publications.

Stormer, C. 1970. Cold Concrete. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory. DA Task 1T062112A13001, April 1970.

Swedish National Road Administration and NCC BYGG AB. 1989. "The Öland Bridge in New Clothes." Kalmar, Sweden.

"Teaching of Cold Weather Concrete Technology." n.d. Narvik College of Engineering, Narvik, Norway.

Vesikari, E. 1986. "Service Life Design of Concrete Structures with Regard to the Frost Resistance of Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 5, 215-228.

"Winter Concreting." 1992. Notes from Technical Research Centre of Finland.

Appendix A

Interim Report on Scandinavian Practice

ECONOMIC EVALUATION OF COLD CONCRETE:
An Interim Report on Scandinavian Practice

F. Lawrence Bennett, P.E.
University of Alaska Fairbanks School of Engineering
248 Duckering Building
Fairbanks, Alaska 99775
907-474-6121

September 1993

An Interim Report for the Project

Economic Evaluation of Cold Concrete
(SPR-UAF-92-13)

David Esch, P.E., Project Manager
Rod Platzke, P.E., Technical Research Advisor

ECONOMIC EVALUATION OF COLD CONCRETE
An Interim Report on Scandinavian Practice

F. Lawrence Bennett, P.E.

1.0 Introduction

This interim report is for a portion of a larger project entitled "Economic Evaluation of Cold Concrete," sponsored by the Alaska Department of Transportation and Public Facilities under the Alaska Cooperative Transportation and Public Facilities Research Program (CTPRP). The work reported herein is based on research conducted in Scandinavia in fall 1992 and subsequent acquisition of additional information. The research involved a literature review and discussions with Scandinavian engineers related to the use of cold concrete in construction operations. "Cold concrete," as used here, is Portland cement concrete that is placed and cured at ambient temperatures below 32° F (0° C), without temporary protection or additional heating; special admixtures are used to depress the freezing point and allow strength build-up without detrimental effects to the concrete.

The three research objectives of this total study are as follows:

1. Summarize known strength data (both short- and long-term), stability (spalling) information and corrosion performance for several design mixtures of Portland cement concrete which utilize anti-freeze admixtures and have been cured at temperatures below freezing.

2. Develop a data base that contains the available information on : 1) costs for materials, labor, equipment and other elements for mixing,

placing and protecting such mixtures; 2) short-term and long-term strength and stability; and 3) corrosion characteristics.

3. Formulate guidelines that will assist the designer, contractor and owner in determining the most appropriate types of admixtures for various concrete applications and various predicted short- and long-term environmental conditions. Develop a preliminary expert system to assist in making these determinations.

Thus, the scope of this project, when strictly interpreted, is confined to the effects of various anti-freezing admixtures and below-freezing curing temperatures on strength, durability (both spalling and corrosion) and costs of Portland cement concretes. Broader interests related to the project include long-term durability of various concrete mixtures cured at above-freezing temperatures, including those with a variety of admixtures, to cyclical freezing and thawing; the effect on strength of such mixtures; and methods for placing, protecting and curing concrete when the ambient temperature is below freezing.

In this interim report, we focus on Scandinavian practice related to the primary project scope but also include some information on durability to freezing and thawing and on cold weather construction methods. We begin with some general information on admixtures for freezing point depression, followed by reports of experience and practice guidelines with such mixtures in Scandinavia. We follow with a review of the literature that reports specific compressive strength data from research and practice. It will become clear that little is known about the long-term durability characteristics of such mixtures. A review of Scandinavian investigations of freeze/thaw durability of "regular" concrete is then presented, followed by a discussion of the use of "hot" concrete, insulated forms, special heating methods and other approaches to cold weather concrete construction using this "regular" concrete. In the final section, we present some conclusions and implications for the overall research project.

2.0 Admixtures for Freezing Point Depression

So-called "anti-freeze" admixtures can be used to depress the freezing point of the water in concrete and thus allow the concrete to cure. These admixtures keep at least part of the water unfrozen, and hydration of the cement continues when the temperature of the mix falls below 0°C (32°F). Both laboratory experimentation and field practice have demonstrated that satisfactory concrete can be produced in this manner.

The eutectic point of any anti-freeze admixture is the lowest temperature, and associated concentration, at which some water can be maintained in liquid form. Below this temperature, all the water freezes, and the admixture component precipitates out of the solution as crystals. In practice, a temperature somewhat above the eutectic point, such as 5°C higher, is chosen as the lowest limit of the concrete temperature. Below this point, the hydration process is considerably retarded, because the amount of chemically unbound "free" water molecules is reduced substantially in this temperature range.

Some anti-freeze admixtures are effective only because of their ability to keep at least part of the water in the concrete mix in the unfrozen state. They are either weak accelerators or weak retarders; strength development is very slow, and additional accelerators are usually used. In this group are the following:

Sodium chloride (NaCl; eutectic point -21.2°C)

Sodium nitrite ($NaNO_2$; -19..56°C)

Carbamide (urea) ($CO(NH_2)_2$); -18.0. °C)

The other group of antifreeze admixtures reacts chemically with the cement minerals or hydration products and thus accelerates the setting and hardening of the concrete. Generally these have low eutectic points.. Examples in this group are the following:

Potassium carbonate (potash) (K_2CO_3; eutectic point -36.5°C)

Calcium chloride ($CaCl_2$; -49.8°C)

Calcium nitrite ($Ca(NO_2)_2$; -17.5°C)

There are disadvantages in the use of some of these materials. For example, potash reacts very quickly after the addition of the water, causing over-acceleration and rapid setting. Thus, a retarder must also be used. A major disadvantage of the use of salts, such as calcium chloride, is the corrosive effect on steel. If calcium chloride is used, a corrosion inhibitor must also be used if the concrete contains steel. For this purpose, sodium nitrite, in a ratio of at least

1:1 by weight (sodium nitrite to calcium chloride) has been shown to be an effective corrosion inhibitor.

Helpful background information on anti-freeze admixtures can be found in Beach (1986), Kilpi and Sarja (1983), Kivekäs, Huovinen and Leivo (1985), Kukko and Koskinen (1988), Korhonen (1990), Korhonen et al (1991), and Ramachandran (1984).

It should be noted that other types of admixtures can be used in concrete, such as air entrainment compounds, plasticizers, water reducers, retarders and accelerators. Such mixtures may also depress the freezing point of the water. For purposes of this investigation, we confine our study to those compounds used primarily as anti-freeze admixtures.

3.0 Use of Cold Concrete in Scandinavia

The use of cold concrete, as defined herein, varies in the different countries of Scandinavia. In Sweden, one contractor confines its use to the joints between precast panels. Although this mortar contains chlorides, the joints contain no steel, and thus no corrosion problems have been encountered. Such mortars provide a quick set with no temporary protection and no extra heating. SKANSKA, Sweden's largest contractor, suspended its use of chloride admixtures in 1987. They warn that some other additives may produce chlorides during the curing process. Their general approach is to utilize the heat of hydration wherever possible.

The Swedish National Road Administration points with considerable embarrassment to an unfortunate experience with its Öland Bridge. Completed in 1972, the 6,072 meter (19,920 feet) bridge cost 65,000,000 Swedish kronor (approximately $US 10,000,000 at the 1993 exchange rate). Early in the 1980's, corrosion damage to the reinforcing steel in the piers was detected. A combination of factors was cited, including aggregate taken from salt water, salt water used as mixing water, and porosity of the sandstone aggregate that permitted seawater intrusion to the reinforcement. Between 1990 and 1995, a total of 105 piers will be renovated, at a cost of about 250,000,000 Swedish kronor ($US 40,000,000). (Swedish National Road Administration 1989) Even though this was not "cold" concrete, the road administration decided that chloride admixtures would henceforth not be permitted in any of its concretes.

In Norway, cold concrete is not used except for brick mortar. Low air temperature limits are in the -25° C (-13° F) range. For practical purposes, temperatures as low as -10° to -15° C (+14° to +5° F) present no problems for such work; at lower temperatures, the limitation is due more to working conditions than to mortar properties.

There seems to be a disagreement between Swedish and Norwegian engineers as to the primary long-term durability problems due to anti-freeze admixtures. In general, Norway believes the problem is with corrosion and not with freeze/thaw scaling, whereas Sweden claims there is a problem with both.

Cold concrete in Finland is used primarily for joints, as in Sweden, although small footings sometimes also use anti-freeze admixtures. Nitrates and nitrites are common chloride-free admixtures. -15° C (+5° F) is considered too low an air temperature; the recommended lower temperature limit is -5° C (+23° F), since the rate of curing becomes too slow at temperatures below this limit. An experimental building project at Kilpisjärvi utilized transit mix concrete for the foundations both with and without anti-freeze admixtures. Two different cold concrete mixes were used; one load (5.5 m^3, or 7.2 yd^3) of one type and two loads of another type were transported distances of 465 km (290 miles) at outside temperatures ranging between -1° and -8° C (+30° and +18° F). Two loads of regular concrete were transported 270 km (170 miles) under similar conditions. Plasticizers of different types, plus additional water, were added after arrival at the work site. All could be pumped and cast for the foundations. (Korhonen 1987) Performance of these concretes will be reported in section 4.0.

In Finland, such concretes are not permitted for use in structures located in salt water. No problems with durability of cold concretes have been reported in Finland. The Finnish specifications for high strength contain the following stipulation in the section on admixtures:

> "In the production of high strength concrete it is not allowed to use admixtures containing more than 0.5% of chlorides by the weight of the mixture." (Concrete Association of Finland 1991)

There is much interest in Scandinavia in the use of silica fume as an admixture to produce concretes of very high compressive strength (on the order of 110 to 150 MPa (16,000 to 21,500 psi), with some experimental results with cement paste as high as 180 MPa (26,000 psi).) (Elfgren, Ronin and Forsling 1992) Whereas Sweden requires water/cement ratios of 0.45 or lower for its bridge structure concrete, the use of silica fume has permitted satisfactory concretes with such ratios as low as 0.28. (Hammer and Sellevold 1990) Although such mixtures attain high strength, durability problems can arise after about one hundred freeze-thaw cycles. A suspected cause is a lack of dispersion of the silica particles. Special mixing procedures are being developed; one approach is to prepare a water/fume slurry first and then add cement and aggregate. Research is being proposed to investigate the impact of anti-freeze admixtures on compressive strength, durability and economy of silica fume concrete. (Elfgren et al 1992)

While they are not "anti-freeze" additives, air entraining admixtures must be mentioned. Their importance is recognized throughout Scandinavia for the prevention of scaling from freeze/thaw. For concrete that will be exposed to such conditions, between 4 and 6% air is the standard. Superplasticizers are sometimes used, but it is important to recognize that some may retard the initial curing process and delay the attainment of 5 MPa strength.

4.0 Compressive Strength Data for Cold Concrete

We now turn to some research and field results from the use of cold concrete. As might be expected, the data are not in consistent form. We have gathered data on 28 day compressive strength from a number of sources; the information is presented in tabular form in Table A.1.

The first four and one-half pages of Table A.1 are from an extensive experimental program conducted in Finland. Many more results are available in Kivekäs, Huovinen and Leivo (1985) than are shown in our Table A.1. For example, compression strength tests were also performed after one, three and seven days, and after a combination of twenty-eight days at below freezing temperatures followed by an equal time at +20° C.

At a curing temperature of -10° C, the admixtures with the greatest potential for strength development were those shown in Table A.2. That study also compression tested air-entrained, non-air-entrained and "microsphered" concretes that had been cured at +20 ° C; the tests were conducted at various ambient temperatures between +20° C and -70° C. Also, a series of freeze/thaw durability tests was conducted, but none of those samples were of cold concrete.

The second set of data, on the fifth and sixth pages of Table A.1, were published in Finland but were taken from some work conducted in Russia. That work seems to have been theoretical, with a lack of laboratory or field experimentation. In some cases, it appears that the results are quite consistent with the recommendations in our Table A.2.

The next four entries in Table A.1 are from the Kilpisjärvi experiment described in section 3.0. The primary purpose of that experiment was to ascertain the feasibility of transporting cold transit mix long distances in below-freezing temperatures. It appears that no temperature records were kept during the curing of either the samples or the foundations themselves. In any case, one of the cold mixes performed extremely well, when compared to "normal" concrete. It should be noted that this "normal" concrete contained a retarder, a "pore-forming agent," and a plasticizer (in different proportions than the cold concrete) but no anti-freeze agent; its ratio of cement to aggregate was 1:6.07, and its water/cement ratio was 0.67. Samples of the normal concrete were cured at room temperature.

Finally, the last six entries in Table A.1 are for a commercial admixture produced in Sweden called BETEC. ("BETEC Köldbetongtillsats" n.d.) Since it is a proprietary product, its chemical composition could not be ascertained. Product literature says that it "consists partly of inorganic salts and is free from chlorides." Test results show that it lowers the freezing point of concrete and mortar and also increases resistance to frost damage. The normal dosage is 5% of the weight of cement. At this rate, samples with a water/cement ratio of 0.55 attained 44% of the control sample (no BETEC; +20° C curing temperature) 28 day compressive strength when cured at -10° C; similar samples cured at -20° C attained 13% of the control sample strength.

We have included, as Table A.3, a copy of a table from Kukko and Koskinen (1988) that gives guidelines for the use of various admixtures under a variety of conditions of service. The importance of avoiding those admixtures which tend to cause corrosion in certain conditions is evident in this table.

5.0 Freeze/Thaw Durability

No information was found on the freeze/thaw durability of cold concretes. Apparently no research has been conducted on this topic in Scandinavia. A great deal of information is available on freeze/thaw durability of a variety of concretes cured above freezing. We present a summary of some of that information in this section. It would seem that the durability of cold concrete must be assured before it can be adopted for use in Alaska; perhaps this in an area where some basic research could provide major technical and economic benefits.

General recommendations for improved frost resistance of concrete, as practiced in Norway, include the following ("Teaching of Cold Weather Concrete Technology" n.d.):

- Low water/cement ratio

  < 0.60 when exposed to fresh water only

  < 0.45 when exposed to water and salt (as in de-icing)

- Good pore-distribution

  Distance factor < 0.25 mm for fresh water exposure

  Distance factor < 0.18 mm for water and salt exposure

- Good compaction and curing

- Design to minimize moisture exposure

At the end of section 3.0, we noted the importance of air entrainment for freeze/thaw durability. A paper by Fagerlund (1979) provides a thorough theoretical background for predicting the service life of concrete exposed to frost action. It describes the use of an "air pore spacing factor" and methods for determining the critical spacing. The basic mechanism providing resistance to freezing and cracking is the cushioning effects of the voids to water expansion as it freezes. Above a certain limit, however, excess permeability leads to excessive water absorption, resulting in undesirable cracking when it freezes.

Many methods have been developed to measure concrete durability. In Sweden, concrete for bridges is subjected to Swedish Standard 137244. The cut face of a concrete sample is exposed to a 3% sodium chloride solution and then subjected to freezing/thawing cycles of twenty-four hours each. The decrease in weight of the sample is measured after specified numbers of cycles. Other similar tests use pure water. (Vesikari 1986) A Finnish test measures ultra sound velocity in a beam during the water absorption phase that follows the freeze/thaw phase. (Kivekäs, Huovinen and Leivo 1985) A vacuum pull method is also used in Finland, whereas Denmark utilizes a process wherein thin ground sections are examined with a microscope.

The study by Kivekäs, Huovinen and Leivo (1985) that conducted compressive strength tests on several types of cold concrete, as reported in section 4.0, also investigated the durability of regular concretes with different strength grades and water/cement ratios, with air entrainment, without air entrainment and with "microspheres." Durability factor was measured by the ultra sound method. All concretes without air entrainment lost durability strength after as little as eight freeze/thaw cycles, as did the microsphere concrete. No loss was observed in the air entrained concrete samples. After eight cycles, another set of samples was subjected to moist curing and then seven more freeze/thaw cycles. Again, the air entrained samples did not suffer durability loss, whereas the other samples did, even though they had gained most of their original durability during the moist curing.

The use of BETEC, which was reported in section 4.0 to be an effective anti-freeze admixture, has been shown to be effective in frost resistance, when used at the recommended rate of 5% of the weight of cement. Once again, these samples were not cured at below freezing temperatures. In Table A.4, we show the results of the test program. ("BETEC Köldbetongtillsats" n.d.) After the standard fifty-six cycles in a scaling test, concrete with no BETEC and 0.045% air entraining admixture had lost 0.26 kilograms per square meter, whereas concrete with 5% BETEC and 0.05% air entraining admixture had lost 0.08 kg/m^2, or less than one-third of the loss for the control sample. With 10% BETEC, however, the loss was 1.36 kg/m^2.

Hammer and Sellevold (1990) studied the frost resistance of high strength concrete with and without silica fume. Results from two different testing methods were somewhat inconsistent, with one showing acceptable resistance for water-to-binder ratios [= water/(cement + silica fume)] below about 0.37 for both air entrained and non air entrained concretes. In the other test, relatively severe damage to non air entrained concretes was observed down to w/b ratios of 0.28.

Gjørv and others (1988) in Norway introduced a "frost resistance number" that is a function of compressive strength, water/cement ratio, paste fraction, and amount of air voids smaller than 0.3 mm. From limited data, they proposed that adequate frost resistance can be obtained from concrete whose number is at least 1500. An earlier "frost resistance index," dependent on the type of cement, compressive strength and "protection porosity" percentage, was utilized by

Vesikari (1986), in combination with an environmental factor based on type of use, to determine service life of concrete components.

Fagerlund (1992) studied the effect of the rate of freezing on frost resistance of concrete. Theoretical analysis and two types of laboratory tests showed no correlation between this rate and the concrete's frost resistance properties.

6.0 Cold Weather Concrete Construction Methods

The topic of construction methods for mixing, placing and curing concrete during cold weather is one that could fill several volumes! We want to give here some basic highlights of methods used and provide a small selection of references. At the outset, we note two excellent references, in English, published by the Technical Research Centre of Finland. First, the RILEM Recommendations for Concreting in Cold Weather (Kukko and Koskinen 1988) is the result of efforts by a committee representing the countries of Scandinavia and northern Europe, the former USSR, Canada and the United States. In addition to information on concrete materials, which we have discussed in previous sections of this report, the publication includes guidelines for planning, mixing, transporting, placing and curing concrete under cold conditions. Builder's Guide to Safe Winter Concreting (Kilpi and Sarja 1983) is a concise guide oriented toward occupational safety; it includes sections on choice of concrete, material factors, strength development, heating and insulation, and stripping strength and form removal.

The Technical Research Centre of Finland and Rakentajain Kustannus Oy have published a lovely full color book entitled Finnish Building: Construction Technology Developed for Cold Climates. (1991) A short section gives a good introduction to cold weather concreting as practiced in Finland.

> "A concreting job that is carried out in the winter must be carefully prepared, paying particular attention to the demands that the cold season brings. These requirements concern the compatibility of the formwork and the heating method, the possibilities for the removal and elimination of snow and ice, the implementation and control of heating measures, the concreting equipment together with the concrete grade and its admixtures, the duration and timing of the concreting work, the curing of casts and quality control, insulating quilts, and the final stripping of weather protection and formwork.
>
> When a warm concrete mass is to be brought to the work location, its initial temperature is determined by the outdoor air temperature, the distance over which it must be transported, the casting time and the time necessary for sealing and protecting. When the concreting work has been completed, the temperature of the concrete mass should be between +5 and +40° C.
>
> Cast concrete must be kept warm during the hardening process. It is possible to utilize the heat generated by the setting process for this purpose. Measurements have shown that the temperature of a concrete slab compacted in its formwork and left uninsulated will fall in each hour by 15 percent of the difference between the temperature of the concrete

and that of the surrounding air. It therefore pays to insulate both the formwork and the concrete.

If the heat of the concrete itself will not suffice, additional heating must be employed. There are several ways in which this can be done: electrical heating installed in the falsework, infrared heating and hot air heating. The heating effect is improved by good thermal insulation, so that the frequently set target of a one day formwork turnover can be achieved even in the winter.

The most recently developed techniques of winter concreting include the use of hot concrete and special "frost concrete." The temperature of hot concrete when it leaves the plant is 40-50° C, the idea being that after it has been poured into the formwork and thermally insulated, it will harden sufficiently quickly without any heating. Frost concrete is a product developed specially for jointing prefabricated units and for small scale casting work. The admixtures used in this concrete allow its strength development to continue even at sub-zero temperatures."

A basic guideline observed throughout Scandinavia is that concrete must not be allowed to freeze until its attains a compressive strength of at least 5 MPa (725 psi). Heated concrete, application of heat after placing, heating of falsework and reinforcement prior to placement of concrete, insulation, anti-freeze admixtures, accelerators, rapid hardening cements or a combination of these approaches are used to achieve this over-riding objective. "Winter" concreting techniques are utilized for any air temperatures below +5° C. In Norway, concreting operations occur regularly at temperatures as low as -15 to -20° C in coastal areas and -30°

C in inland areas, the difference being attributed to winds in coastal areas. Norway reports successful concrete pumping at temperatures as low as -15° C.

We have already mentioned the use of silica fume concretes for attaining high strength. CEMENTA, Sweden's largest cement producer, recommends 5% silica (of the total of cement and silica) as the optimum quantity, if no fly ash is used. With fly ash, the optimum percentage of silica fume will vary. A Swedish contractor reported that it has ended its use of fly ash, citing unreasonable variations in fly ash characteristics.

The use of "warm" and "hot" concretes is recommended for some applications, by heating the aggregate and/or mixing water. The former is defined by a temperature of 25 to 30° C, whereas the latter has a temperature above 30° C. In Finland, some concretes as "hot" as +60° C have been used successfully. A Swedish contractor reports good results with hot concrete at 30 to 35° C; proper selection of admixtures permits these high temperatures with no premature set. This same contractor uses warm concrete only for components less than about 40 mm thick. Above this thickness, the fresh concrete generates sufficient heat from the hydration process, although care must be taken to protect corners and other vulnerable portions. In Norway, one experiment started with 30° C concrete which, after transportation and placement, was at 6° C.

A guide for use in northern Norway lists the following "main checkpoints" during concrete mixing and placing in cold conditions: 1) thawing and cleaning of forms before casting; 2) temperature of fresh concrete, both at the mixer and at the site; 3) time-temperature control during the first few days; 4) strength at form

C in inland areas, the difference being attributed to winds in coastal areas. Norway reports successful concrete pumping at temperatures as low as -15° C.

We have already mentioned the use of silica fume concretes for attaining high strength. CEMENTA, Sweden's largest cement producer, recommends 5% silica (of the total of cement and silica) as the optimum quantity, if no fly ash is used. With fly ash, the optimum percentage of silica fume will vary. A Swedish contractor reported that it has ended its use of fly ash, citing unreasonable variations in fly ash characteristics.

The use of "warm" and "hot" concretes is recommended for some applications, by heating the aggregate and/or mixing water. The former is defined by a temperature of 25 to 30° C, whereas the latter has a temperature above 30° C. In Finland, some concretes as "hot" as +60° C have been used successfully. A Swedish contractor reports good results with hot concrete at 30 to 35° C; proper selection of admixtures permits these high temperatures with no premature set. This same contractor uses warm concrete only for components less than about 40 mm thick. Above this thickness, the fresh concrete generates sufficient heat from the hydration process, although care must be taken to protect corners and other vulnerable portions. In Norway, one experiment started with 30° C concrete which, after transportation and placement, was at 6° C.

A guide for use in northern Norway lists the following "main checkpoints" during concrete mixing and placing in cold conditions: 1) thawing and cleaning of forms before casting; 2) temperature of fresh concrete, both at the mixer and at the site; 3) time-temperature control during the first few days; 4) strength at form removal. ("Teaching of Cold Weather Concrete Technology" n.d.) This same guide lists five main factors in winter concrete curing technology, as follows:

1. Initial temperature of fresh concrete

2. Mix design

   Cement content

   Cement type

3. Admixtures

4. Temperature loss to the surroundings

   Geometry and dimensions of structure

   Form materials

   Insulation measures

   Weather conditions

5. Moisture loss (premature drying prevents further curing and strength gain)

Methods for testing and controlling concrete strength include various maturity methods, which utilize relationships between time and temperature; a break-off test using a device and procedure developed in Norway (<u>Norcem Break-Off Tester</u> 1983); a pull-out test; surface hardness tests and an ultrasound test. In the county surrounding Trondheim, Norway, flat slabs are insulated for a minimum of one week, except that, if temperature sensors are embedded in the new concrete, the insulation is removed when the temperature difference between the concrete and the air reaches 18° C.

To secure an adequate curing temperature, the Narvik guide ("Teaching of Cold Weather Concrete Technology" n.d.) provides for the following basic measures: 1) Warm concrete from the mixer; 2) Insulation of forms and covering of concrete surfaces with "winter mats;" 3) Covering and heating immediately after casting, using external and/or internal heating; 4) Use of the heat of hydration, increased cement content, accelerating admixtures, and rapid-hardening cement. Since we have already discussed items 1 and 4, we shall now consider briefly both protection and heating methods.

Practices vary with respect to the use of insulated formwork. In Sweden, a popular method for walls is to use insulated sandwich panels made of plywood, cellular plastic insulation and a galvanized steel frame. Heating devices can be embedded in this formwork. Norwegian and Finnish engineers advise that the use of insulated forms cannot be justified economically; one said that such forms would have to be reused thirty times in order for such a practice to be feasible. In central Norway, wall forms are generally removed after one day for reuse elsewhere; this practice is being questioned, since hairline cracks tend to develop in some situations. Alternatives would be to insulate the wall after form removal or leave the forms in place for a longer period. In all of Scandinavia, many above-ground slabs are cured by placing an insulation mat on top and heat underneath; in central Norway, mats consisting of a 10 mm thickness of foam or 50 mm thickness of rockwool are used.

For maintaining the temperature of the fresh concrete, electrical heating is used to a greater extent in Scandinavia than in Alaska. One method is to include electrical resistance units in the formwork; the insulated sandwich panels described in the previous paragraph utilize 80 watt per meter units for those panels located at the corners of components. Embedding heating wires in the fresh concrete also provides heat during curing; this practice seems to be quite prevalent in Finland. Throughout Scandinavia, the use of infrared radiation for heating fresh concrete is popular. Units can heat entire spaces or be directed toward particular cold spots such as corners or wall bottoms. Hot air from gas-fired or other units is also used, although many contractors contend that large volumes of air are heated unnecessarily. Some information from Finland indicates that hot air heating utilizes two to three times as much energy as does infrared radiation to heat an equivalent volume of concrete. ("Winter Concreting" 1992) For all types of heating, users stress the importance of paying attention to corners, edges and other locations where heat loss is likely to be greatest.

A great deal of use has been made in Scandinavia of computer programs for assessing temperature versus strength characteristics of various cold weather concreting operations. By incorporating such parameters as concrete qualities, heating and protection methods, desired strength, and predicted air temperature and wind information, the programs can be used for calculating the risk of damage as a result of early freezing, assessing form stripping times, determining when troweling of slabs should commence, and the like. Thus, a number of alternative schemes can be compared, and the most desirable chosen.

At Sweden's Cement and Concrete Research Institute and Luleå Institute of Technology, such a program was developed, under the designation HETT, where H = "strength," ET = "equivalent time," and T = "temperature." This program utilizes a one-dimensional heat flow analysis and is valid for timeframes after the first ten hours following concrete placement. (Hett5 1991) A similar program in Norway is designated HERD. ("Teaching of Cold Weather Concrete Technology" n.d.) An extension of the basic HETT program, called PLAGLID, can be used for slipform construction of flat walls. (Jonasson 1984) For assessing early concrete characteristics, within the first ten hours, a program called GLATT is under development. With this program, builders will be able to determine the optimum timing for troweling of flat slabs placed in cold conditions. (Petersson and Johansson 1991)

The Danish "Curing Technology" system provides a similar approach. There are five modules -- 1) development of the concrete's mechanical properties, such as strength and elastic modulus at constant temperature; 2) adiabatic evolution of the heat of reaction between water and cement at constant temperature; 3) effect of the curing temperature on 1 and 2, based on a maturity function; 4) heat balance of the concrete inside the construction and against the environment; and 5) a combination of the first four modules. One example of the successful use of this program was on a housing compound in Oslo. The analysis of one scheme, utilizing rapid hardening cement, air heaters beneath the slab and insulation mats above, showed that the concrete would attain its required stripping strength after about 36 hours, thus indicating a two-day pour-and-strip cycle. An alternative approach using insulated formwork indicated a one-day cycle. The manager was then able to evaluate the economics of both schemes. Another application, on a heavily reinforced free cantilever bridge in the Norwegian mountains, resulted in the use of insulated formwork and insulating mats on top of the fresh concrete, rather than an air heater in a "tent," as had originally been proposed. (Maage and Helland 1988)

The Swedish contractor SKANSKA has carried this computerized approach even further, with its ConcTrol Box. The system consists of temperature probes cast into the concrete, a data logger, a hand computer for calculating the degree of maturity and current strength and a printer for displaying concrete temperature and strength at desired intervals. The system is used for decisions about the timing of form removal and prestressing of cables. ("ConcTrol Box" n.d.)

To summarize this discussion of winter concreting methods, we list a series of "obligatory" and "alternative" protective measures, as practiced in Norway.

<u>Obligatory Measures</u>

- Placing concrete at the site without delay
- Protective coverage of newly placed concrete
- Heat insulation of forms
- Protect and heat lower parts of columns and walls
- Protect exposed edges of slabs
- Avoid the use of retarders

- Avoid the use of Pozzolanic additives, unless special precautions are taken

<u>Alternative Measures (in addition to above list)</u>

- Raised concrete strength class
- Rapid hardening cement
- Special high-insulated forms
- Accelerators
- Infrared radiation heaters
- Cast-in electrical heating wires
- Air heaters
- Heated sheds
- Warm concrete
- Hot concrete

7.0 Conclusions and Implications

This investigation has found that cold concrete is being used in Scandinavia, although to a limited extent. Primary uses confined to joints between precast componets, brick mortar and footings. We can conclude that sufficient data are available on the performance of such concretes to begin to build a data base that will combine information from Scandinavia with similar performance data from other areas.

What is lacking is cost data. At this point in the research, it appears that the data base should be designed to include cost data but that such factors will have to be location and project specific, to be provided by the user for any particular application.

Concern with the corrosion effects of chlorides has led Scandinavian engineers to utilize non-chloride anti-freeze admixtures in any application where steel is present in the concrete.

No information could be found in the long term durability of cold concretes when subjected to freezing and thawing, although much information is available on such performance of regular concretes.

It appears that there could be rather substantial value to some investigation of the long-term durability of such concretes. Perhaps a project that evaluates the freeze/thaw performance of cold concretes both with and without silica fume would be appropriate.

8.0 Acknowledgments

I am grateful to Mr. Joachim Hammersland, a UAF exchange student from Sweden's Tekniska Högskolan i Luleå, and Dr. Nils I. Johansen of the UAF School of Mineral Engineering for assistance in translating Swedish and Norwegian materials, respectively, for use in this report.

9.0 References

Beach, W.G. 1986. Cold Set Concrete: Final Report. Alaska Department of Transportation and Public Facilities Research Report AK-RD-86-28.

"BETEC Köldbetongtillsats (BETEC Cold Concrete Additive)." n.d., Finja BETEC AB, Upplands, Väsby, Sweden.

Concrete Association of Finland. 1991. "High Strength Concrete Supplementary Rules and Fire Design." RakMK B4

"ConcTrol Box." n.d. Skanska Stockholm AB, Danderyd.

Elfgren, L., V. Ronin and W. Forsling. 1992. "Concreting at Low Temperatures: Improved Methods of Using Inorganic Modifiers for High Strength Silica Fume Concrete." Tekniska Högskolan i Luleå, Division of Structural Engineering, June 10, 1992.

Elfgren, L. et al. 1992. "Mechanical Modified Cement (MMC) for Cold Concreting and Economic Evaluation of Improved Winter Concrete Technology." Tekniska Högskolan i Luleå, Division of Structural Engineering, November 11, 1992.

Fagerlund, G. 1979. "Prediction of The Service Life of Concrete Exposed to Frost Action." Studies on Concrete Technology. Swedish Cement and Concrete Research Institute, Stockholm, 249-276.

Fagerlund, G. 1992. "Effect of The Freezing Rate on The Frost Resistance of Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 11, 20-36

Gjørv, O.E., K. Okkenhaug, E. Bathen and R. Husevåg. 1988. "Frost Resistance and Air-Void Characteristics in Hardened Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 7, 89-104.

Hammer, T.A. and E.J. Sellevold. 1990. "Frost Resistance of High Strength Concrete." High Strength Concrete SP5 - Design Application Report 5.3. The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, Trondheim. Report No. STF65 A90013.

Hett5: Program för beräkning av temperatur-och hållfasthetsutveckling. 1991. Betong Data, Tumba, Sweden.

Jonasson, J-E. 1984. Slipform Construction -- Calculations for Assessing Protection Against Early Freezing. Cement och Betong Institutet, Stockholm, CBI

Research fo 4:84.

Kilpi, E. and A. Sarja. 1983. Builder's Guide to Safe Winter Concreting. Technical Research Centre of Finland, Espoo. Research Notes 62, August 1983.

Kivekäs L., S. Huovinen and M. Leivo 1985. Concrete Under Arctic Conditions. Technical Research Centre of Finland, Espoo. Research Reports 343, March 1985

Korhonen, C.J. 1990. Antifreeze Admixtures for Cold Regions Concreting: A Literature Review. U.S Army Corps of Engineers Cold Regions Research & Engineering Laboratory. Special Report 90-32, September 1990.

Korhonen, C.J. et al. 1991. "New Admixtures for Cold Weather Concreting." in Sohdi, D.S., ed. Cold Regions Engineering. Proceedings of the Sixth International Specialty Conference, ASCE, 200-209.

Korhonen, R. 1987. Kilpisjärvi Project: Long Transport of Frost Concrete. Technical Research Centre of Finland, Espoo. Research Notes 808, December 1987.

Kukko, H. and I. Koskinen. 1988. RILEM Recommendations for Concreting in Cold Weather. Technical Research Centre of Finland, Espoo. Research Notes 827, January 1988.

Maage, M. and S. Helland. 1988. "Cold Weather Concrete Curing Planned and Controlled by Microcomputer." Concrete International. October 1988, 34-39.

Norcem Break-Off Tester. 1983. User's Guide. Norcem Cement, Slemmestad, Norway.

Petersson, Ö. and A. Johansson. 1991. Styrning av Glättningshårdhet (Controlling Troweling Hardness). Cement och Betong Institutet, Stockholm, Rapport 1:91.

Poijärvi, H. 1991. Finnish Building: Construction Technology Developed for Cold Climates. Technical Research Centre of Finland and Rakentajain Kustannus Oy.

Ramachandran, V.S., ed. 1984. Concrete Admixtures Handbook: Properties, Science and Technology. Park Ridge, NJ: Noyes Publications.

Swedish National Road Administration and NCC BYGG AB. 1989. "The Öland Bridge in New Clothes." Kalmar, Sweden.

"Teaching of Cold Weather Concrete Technology." n.d. Narvik College of Engineering, Narvik, Norway.

Vesikari, E. 1986. "Service Life Design of Concrete Structures with Regard to the Frost Resistance of Concrete." Nordic Concrete Research. The Nordic Concrete Federation, Norske Betongforening, Oslo, Publication No. 5, 215-228.

"Winter Concreting." 1992. Notes from Technical Research Centre of Finland.

Table A.1 Compressive Strength Data for Cold Concrete, gathered from Scandinavian Sources

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (10.4% by weight of cement) + Na_2SO_4 (3%)	0.65	-30° C	0.2 MPa (0.7% of strength of control sample)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (13%) + Na_2SO_4 (3%)	0.65	-17.5° C	3.8 MPa (13%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (16.3%) + Na_2SO_4 (3%)	0.65	-17.5° C	2.2 MPa (7.5%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (3.5%) + Na_2SO_4 (3%	0.65	-10° C	12.6 MPa (33%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (3.5%) + Na_2SO_4 (3%	0.65	24 hours @ +20° C; then -10° C	22.4 MPa (58%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (3.6%) + $CO(NH_2)_2$ (5.2%)	0.65	-10°C	8.5 MPa (29%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (3.6%) + Na_2SO_4 (3%)	0.65	-10°C	16.3 MPa (56%)	1, App. 4
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (5%) + Na_2SO_4 (3%)	0.66	-10° C	10.1 MPa (27%)	1, App 8

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (8.8%) + $CO(NH_2)_2$ (4.2%)	0.65	-17.5° C	3.7 MPa (9.6%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (9%) + Na_2SO_4 (3%)	0.65	-17.5° C	6.6 MPa (17%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7	$Ca(NO_3)_2$ (9%) + Na_2SO_4 (3%)	0.65	24 hours @ +20° C; then -17.5° C	19.3 MPa (50%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (9.8%) + Na_2SO_4 (3%)	0.65	-17.5° C	2.7 MPa (9.2%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	K_2CO_3 (15.8%)	0.65	-10°C	4.1 MPa (14%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (5.8%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.75%)	0.65	-10° C	15.6 MPa (41%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (5.8%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.75%)	0.65	24 hours @ +20° C; then -10° C	26.7 MPa (70%)	1, App 7

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	K_2CO_3 (8.3%) + ligno-sulfonate-based plasticizing retarder (3%)	0.65	-10° C	17.8 MPa (61%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (9.1%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.5%)	0.65	-17.5° C	6.6 MPa (17%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (9.1%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.5%)	0.65	24 hours @ +20° C; then -17.5° C	12.5 MPa (33%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (4.9%) + $Ca(NO_3)_2$ (1.7%) + $CaCl_2$ (4.9%)	0.65	-10° C	10.5 MPa (36%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (4.9%) + $CaCl_2$ (4.9%)	0.65	-10° C	15.3 MPa (52%)	1, App. 4
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (5%) + $CaCl_2$ (5%)	0.66	-10° C	18.2 MPa (49%)	1, App 8
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (5%) + $CaCl_2$ (5%) + super-plasticizer (4%)	0.59	-10° C	22.0 MPa (59%)	1, App 8

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + $CaCl_2$ (1.5%)	0.65	-10° C	20.7 MPa (54%)	1, App 7
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.64	-10° C	13.8 MPa (37%)	1, App 8
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	-10°C	18.2 MPa (62%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	-10° C	21.4 MPa (56%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	24 hours @ +20° C; then -10° C	22.0 MPa (58%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (7%)	0.65	-10°C	16.3 MPa (55%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (8.5%) + $CaCl_2$ (8.5%)	0.65	-17.5°C	3.3 MPa (11%)	1, App 5

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	None	0.65	-17.5° C	1.5 MPa (3.9%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	None	0.65	24 hours @ +20° C; then -17.5° C	17.3 MPa (45%)	1, App 6
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-5° C	70% of nominal	2, Table 1, page 11/5
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-10° C	55%	2, Table 1, page 11/5
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-15° C	35%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-5° C	80%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-10° C	45%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-15° C	35%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-5° C	80%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-10° C	50%	2, Table 1, page 11/5

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
	50% $NaNO_2$ + 50% $CaCl_2$		-15° C	45%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-20° C	40%	2, Table 1, page 11/5
	100% K_2CO_3		-5° C	75%	2, Table 1, page 11/5
	100% K_2CO_3		-10° C	70%	2, Table 1, page 11/5
	100% K_2CO_3		-15° C	65%	2, Table 1, page 11/5
	100% K_2CO_3		-20° C	55%	2, Table 1, page 11/5
	100% K_2CO_3		-25° C	50%	2, Table 1, page 11/5
Cement:Aggregate = 1:4.39;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.54%); Pore-forming agent (0.05%); "Frost additive #2" (7.8%); "Plasticizer #2" (0.32%)	0.41	(outside at Tornio, March 1986)	30.7 MPa (138% of strength of control sample (different mix))	3, Table 5, page 19 (Samples left at factory)
Cement:Aggregate = 1:4.39;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.54%); Pore-forming agent (0.05%); "Frost additive #2" (7.8%); "Plasticizer #2" (0.32%)	0.41	(outside at Kilpisjärvi, March 1986)	30.8 MPa (138%)	3, Table 5, page 19 (Samples after 465 km transport)

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:4.1;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.58%); Pore-forming agent (0.06%); "Frost additive #1" (5.5%); "Plasticizer #1" (3.1%)	0.41	(outside at Tornio, March 1986)	35.5 MPa (159%)	3, Table 5, page 19 (Samples left at factory)
Cement:Aggregate = 1:4.1;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.58%); Pore-forming agent (0.06%); "Frost additive #1" (5.5%); "Plasticizer #1" (3.1%)	0.41	(outside at Kilpisjärvi, March 1986)	19.2 MPa (86%)	3, Table 5, page 19 (Samples after 465 km transport)
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.65	-5° C	28.5 MPa (81% of strength of 5% BETEC sample cured at +20° C)	4, Figure 1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.55	-10° C	21.3 MPa (44% of strength of control sample with no BETEC cured at +20° C)	4, Table 1.1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	10% BETEC Cold Concrete Additive per weight of cement	0.55	-10° C	22.8 MPa (47%)	4, Table 1.1

Table A.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.65	-15° C	14 MPa (40% of strength of 5% BETEC sample cured at +20° C)	4, Figure 1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.55	-20° C	6.1 MPa (13% of strength of control sample with no BETEC cured at +20° C)	4, Table 1.1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	10% BETEC Cold Concrete Additive per weight of cement	0.55	-20° C	7.5 MPa (16%)	4, Table 1.1

Information sources: 1: Kivekäs, Huovinen and Leivo (1985); 2: Kukko and Koskinen (1988); 3: Korhonen (1987); 4: "BETEC Köldbetongtillsats" (n.d.)

Admixture Combination	Ordinary Portland Cement	Rapid Hardening Portland Cement
$NaNO_2 + Na_2SO_4$	85%	70%
$NaNO_2 + CaCl_2$	63%	63%
K_2CO_3 + retarder	94%	48%
$Ca(NO)_3)_2 + Na_2SO_4$	75%	43%

Table A.2 Strengths of Concrete with Admixtures with Greatest Potential for Strength Development at -10° C, expressed as % of 28 day strength at +20° C. (Kivekäs, Huovinen and Leivo 1985)

Nos.	Types of members and conditions of service	ADMIXTURES $CaCl_2$ / $NaCl + CaCl_2$	Na_2SO_4	$Ca(NO_3)_2$ / $Ca(NO_3)_2 + CO(NH_2)_2$	$NaNO_2 + CaCl_2$	$NaNO_2$ / $NaNO_3$	$KsCO_3$
1	2	3	4	5	6	7	8
1	Prestressed members expect those indicated in item 2, joints (ducts) in cast-in-situ and precast units with stressed steel	-	+	(+)	-	+	-
2	Prestressed members reinforced with toughened steel	-	+	-	-	-	-
3	Concrete components reinforced with non-stressed structural steel bars of diameters:						
	a) over 5 mm	(+)	+	+	+	+	+
	b) 5 mm and less	-	+	+	(+)	+	+
4	Reinforced concrete members and joints without stressed steel in cast-precast and precast units with protruding reinforcement or inserts:						
	a) without special protection for steel	-	+	+	-	+	+
	b) with zinc coating steel	-	-	-	-	+	-
	c) with aluminium coating on steel	-	-	(+)	-	-	-
	d) with composite coatings (alkali-resistant paints or other coatings on metallised backing) and joints without inserts or designed reinforcement	(+)	+	+	(+)	+	+
5	Cast-in-situ components made from edging clocks 30 cm thick or more and surrounding a cast-in-place core	-	+	+	+	+	+
6	Reinforced concrete members designed for:						
	a) non-corrosive gas environments	(+)	+	+	+	+	+
	b) corrosive gas environments	-	+	+	(+)	+	+*
	c) non-corrosive and corrosive water environments except those indicated in item 6d	+	+	+	+	+	+*
	d) corrosive sulphate waters and solutions of salts and caustic alkalis where there are evaporating surfaces	-	+	-	-	+	-
	e) areas of variable water level	-	+	+	-	+	-
	f) water and gas environments with relative humidity over 60 %, aggregate containing inclusions of reactive alumina	-**	-	+	-	-	-
	g) areas of stray direct currents from outside sources	-	+	+	-	+	+
7	Reinforced concrete members for electric transport and factories using direct current	-	-	-	-	-	-

* Allowed in combination with a retarder
** Not allowed except $CaCl_2$ in plain concrete members

Notes: 1. The possibility of using admixtures for items 1 to 4 should be checked considering the requirements of item 6 and for items 1 to 3 with protective coating of steel, requirements of item 4.

2. The restrictions on the use of concrete with admixtures as indicated in item 4 and items 6d and 6f, and in items 6c for potash-containing concretes are applicable to plain concrete members.

3. For item 6b, admixtures, except $NaNO_2$, are allowed for the environment containing chlorine or hydrogen chloride only after a special feasibility study.

4. Concrete of the members which are regularly wetted with water, condensate or industrial fluids should meet the same requirements as concrete of the members that are exposed to a relative humidity of air in excess of 60 per cent.

Table A.3 Applications of Admixtures to Concretes. "+" = advisable; "(+)" = advisable as an accelerator only; "-" = must not be used. (Kukko and Koskinen 1988)

	0% BETEC	5% BETEC (by weight of cement)	10% BETEC (by weight of cement)
	0.045% Air Entraining Admixture	0.04% Air Entraining Admixture	0.01% Air Entraining Admixture
28 day Compressive Strength, MPa	43	36	32
Frost Resistance, kg/m^2 loss in scale test			
7 cycles	0.08	0.03	0.35
14 cycles	0.14	0.04	0.68
28 cycles	0.20	0.06	1.11
42 cycles	0.24	0.07	1.27
56 cycles	0.26	0.08	1.36
70 cycles	0.28	0.09	1.42
84 cycles	0.29	0.10	1.47
98 cycles	0.31	0.11	1.51
112 cycles	0.32	0.13	1.53

Table A.4 Frost Resistance of Concrete Samples Using BETEC Anti-Freeze Admixture and Air Entraining Admixture, based on Scaling Test. ("BETEC Köldbetongtillsats" n.d.)

Appendix B

Database Design

Cold Concrete Project
Database Schema

The database under development for the DOT/PF Cold Concrete Project is intended for use by both designers and contractors. The purpose is to provide a single source of information from which a protocol for the placement of concrete can be developed. The proposed database design includes several different schemas. Note that in many cases, the data required to populate this database is not available. It is assumed that missing information can be gathered and/or specific experimental exercises conducted to complete the population.

The database is open. That is, the proposed design assumes that new concrete mixes will be developed and the appropriate information added to the database after testing. The primary access mode is the concrete mix type to be used. Secondary access will be through air temperature at time of placement.

The data fields defined below include the following format codes:

- n.m F, is a fixed decimal with n digits to the left and m digits to the right of the decimal point.
- n I, is an integer of length n digits.
  n S, is a signed integer of length n digits.
- l C, is a character string of length l characters.
- w R, is a pointer to a record in a different database.

Concrete Mix Schema

Cement Type	2C	Alphanumeric code for mix type.
Cement Quantity	2.2F	Percent of cement by weight of final mix.
Aggregate Gradation		
10 sieves	2.2F	Percent passing sieve *S*.
or		
3 types	2.2F	Percent of Fine, Medium and Coarse in mix.
Aggregate Quantity	2.2F	Percent by weight of final mix.
Water Quantity	2.2F	Percent by weight of final mix.
Freeze Point Depressant type	2C	Alphanumeric code for depressant type
Freeze Point Depressant Qt.	2.2F	Percent of final mix by weight.
Air Entraining Type	2C	Alphanumeric Code for Entraining type.
Air Entraining Quantity	2.2F	Percent of final mix by weight.
Water Reducer Type	2C	Alphanumeric code for reducer type.
Water Reducer Quantity	2.2F	Percent of final mix by weight.
Air Temperature	2I	Temperature in degrees Celsius of air at placement.
Concrete Temperature	2I	Temperature in degrees Celsius of concrete at placement.
Curing Maximum	2I	Maximum temperature during curing.
Curing Minimum	2I	Minimum temperature during curing.
Tempeature Class 1	2C	Alphanumeric classification scheme 1.
Temperature Class 2	2C	Alphanumeric classification scheme 2.
Comments	8R	Pointer to a comments record of variable length.

Temperature Database

Air Temperature	2S	Temperature in degrees Celsius of air at placement.
Concrete Temperature	2S	Temperature in degrees Celsius of concrete at placement.
Curing Maximum	2S	Maximum temperature during curing.
Curing Minimum	2S	Minimum temperature during curing.
Tempeature Class 1	2C	Alphanumeric classification scheme 1.
Temperature Class 2	2C	Alphanumeric classification scheme 2.
Concrete Mixes	n*8R	Pointers to concrete mixes used in these classes.

Compressive Strength

1 day	3.3f	Compressive Strength in psi after 1 day of curing.
3 day	3.3f	Compressive Strength in psi after 1 day of curing.
7 day	3.3f	Compressive Strength in psi after 1 day of curing.
14 day	3.3f	Compressive Strength in psi after 1 day of curing.
28 day	3.3f	Compressive Strength in psi after 1 day of curing.
Other Period Length	2I	Curing time in days.
Other Period	3.3f	Compressive Strength in psi after 1 day of curing.
Other Period Length	2I	Curing time in days.
Other Period	3.3f	Compressive Strength in psi after 1 day of curing.
Other Period Length	2I	Curing time in days.
Other Period	3.3f	Compressive Strength in psi after 1 day of curing.
Concrete Mix 8R	Pointer to concrete mix tested.	

Durability

Mix	1R	Pointer to concrete mix commented on.
Durability Comments	nnC	Variable length text record.

Costs

Cement Costs	3I	Cost in dollars per cubic yard placed.
Aggregate Costs	3I	Cost in dollars per cubic yard placed.
Additive 1 Type	2C	Alphanumeric code of first additive.
Additive Costs	3I	Cost in dollars per cubic yard placed.
Additive 2 Type	2C	Alphanumeric code of second additive.
Additive Costs	3I	Cost in dollars per cubic yard placed.
Additive 3 Type	2C	Alphanumeric code of third additive.
Additive Costs	3I	Cost in dollars per cubic yard placed.
Additive 4 Type	2C	Alphanumeric code of fourth additive.
Additive Costs	3I	Cost in dollars per cubic yard placed.
Water Costs	3I	Cost in dollars per cubic yard placed.
Equipment Costs	3I	Cost in dollars per cubic yard placed.
Transportation Costs	3I	Cost in dollars per cubic yard placed.
Concrete Mix	1R	Pointer to concrete mix reported.

Other Costs

Forms Materials	3I	Cost per cubic yard of forming the placement.
Total Forms Cost	6I	Total forming cost of placement.
Forming Labor	3I	Cost per cubic yard of forming the placement.
Total Labor	6I	Total forming labor cost of placement.
Protection Materials	6I	Total cost of protective materials for placement.
Protection Labor	6I	Total cost of protection labor for placement.
Install Labor	6I	Total cost of protection installation.
Maintenance Labor	6I	Total cost of maintaining the protection.
Heating Labor	6I	Total cost of heating related labor.
Heating Equipment	6I	Total cost of heating equipment used.
Energy Costs	6I	Total cost of heating related energy.
Miscellaneous Supplies	6I	Total cost of miscellaneous heating related supplies.
Concrete Mix	1R	Pointer to the concrete mix reported.

Appendix C

Data Collection Report

ECONOMIC EVALUATION OF COLD CONCRETE
A Report on <u>Data Collection</u> for Project SPR-UAF-92-13

F. Lawrence Bennett, P.E.
UAF School of Engineering

June 1994

This portion of the project collected compressive strength data from all identified sources for concrete, containing anti-freeze admixtures, that was cured at temperatures below 0° C, as well as information on long-term durability and corrosive effects of such mixes. The sources, some of which have been used in reports on previous phases of the study, include the following:

1. Beach, W.G. 1986. Cold Set Concrete: Final Report. Alaska Department of Transportation and Public Facilities Research Report AK-RD-86-28.

2. "BETEC Köldbetongtillsats (BETEC Cold Concrete Additive)." n.d., Finja BETEC AB, Upplands, Väsby, Sweden.

3. Goncharova, L.S. and F.M. Ivanov. 1975. "The Properties of Concretes Containing Antifreeze Admixtures." Proceedings of the 2nd International Symposium on Winter Concreting, Vol. 1. October 14-16, 1975, Moscow, 69-71.

4. Grapp, A.A., V.B. Grapp and A.S. Kaplan. 1975. "The Structure and Cold Resistance of Concretes Containing Antifreeze Admixtures." Proceedings of the 2nd International Symposium on Winter Concreting, Vol. 1. October 14-16, 1975, Moscow, 60-68.

5. Kivekäs L., S. Huovinen and M. Leivo 1985. Concrete Under Arctic Conditions. Technical Research Centre of Finland, Espoo. Research Reports 343, March 1985

6. Korhonen, C.J. 1990. Antifreeze Admixtures for Cold Regions Concreting: A Literature Review. U.S Army Corps of Engineers Cold Regions Research & Engineering Laboratory. Special Report 90-32, September 1990.

7. Korhonen, C.J. et al. 1991. "New Admixtures for Cold Weather Concreting." in Sohdi, D.S., ed. Cold Regions Engineering. Proceedings of the Sixth International Specialty Conference, ASCE, 200-209.

8. Korhonen, C.J. et al. 1994. "Low-Temperature Admixtures for Concrete." in Smith, D.W. and D.C. Sego, eds. Cold Regions Engineering: A Global Perspective. Proceedings of the Seventh International Specialty Conference, Canadian Society for Civil Engineering, 87-96.

9. Korhonen, R. 1987. Kilpisjärvi Project: Long Transport of Frost Concrete. Technical Research Centre of Finland, Espoo. Research Notes 808, December 1987.

10. Kukko, H. and I. Koskinen. 1988. RILEM Recommendations for Concreting in Cold Weather. Technical Research Centre of Finland, Espoo. Research Notes 827, January 1988.

11. Ramachandran, V.S. 1984. Concrete Admixtures Handbook: Properties, Science and Technology. Park Ridge, NJ: Noyes Publications.

12. Stormer, C. 1970. Cold Concrete. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory. DA Task 1T062112A13001, April 1970.

Citations 2, 3, 7 and 8 were used to compile Table A.1 in "Economic Evaluation of Cold Concrete: An Interim Report on Scandinavian Practice" submitted in September 1993.

We present here Table C.1, which is a duplicate of that Table A.1. In the same format, we present other research results on compressive strength taken from the Korhonen (1994) and Stormer (1970) references, shown here as Table C.2.

Another important aspect of cold concrete performance is its long-term freeze-thaw durability. While several studies have evaluated the effects of admixtures on such durability ("BETEC Köldbetongtillsats" n.d.; Ramachandran 1984), most of this research has focused on samples cured at temperatures above 0° C. We show in Tables C.3, C.4 and C.5 a compilation of the results from the limited testing that has been completed on admixture-containing concretes that have been cured at temperatures below 0° C. Note that these tests utilized standard laboratory freeze-thaw cycling methods; no documented long-term field observations and/or testing of such in-place concretes were found in the literature.

In Table C.3, the measure of effectiveness is the change in compressive strength after 400 freeze-thaw cycles. Table C.4 reports results based on ultra-sound wave velocity measurements, in which the durability is related directly to velocity (higher velocities indicate greater durability). Table C.5 summarizes results from testing by Stormer (1970) in which all phases of the freeze thaw cycles were conducted in air, with no immersion in water. Here the measure of loss of durability is percent weight loss.

A further important consideration in concrete containing any kind of admixture is the possible corrosive effect on metals contained within the concrete. Salts are well-known for such effects, while other admixtures, such as calcium nitrite and sodium nitrite, are corrosion inhibitors. Table C.6, taken from Korhonen (1990) and Korhonen et al (1994), summarizes important findings in this regard.

Table C.1 Compressive Strength Data for Cold Concrete, gathered from Scandinavian Sources

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (10.4% by weight of cement) + Na_2SO_4 (3%)	0.65	-30° C	0.2 MPa (0.7% of strength of control sample)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (13%) + Na_2SO_4 (3%)	0.65	-17.5° C	3.8 MPa (13%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (16.3%) + Na_2SO_4 (3%)	0.65	-17.5° C	2.2 MPa (7.5%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (3.5%) + Na_2SO_4 (3%	0.65	-10° C	12.6 MPa (33%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (3.5%) + Na_2SO_4 (3%	0.65	24 hours @ +20° C; then -10° C	22.4 MPa (58%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (3.6%) + $CO(NH_2)_2$ (5.2%)	0.65	-10°C	8.5 MPa (29%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (3.6%) + Na_2SO_4 (3%)	0.65	-10°C	16.3 MPa (56%)	1, App. 4
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (5%) + Na_2SO_4 (3%)	0.66	-10° C	10.1 MPa (27%)	1, App 8

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (8.8%) + $CO(NH_2)_2$ (4.2%)	0.65	-17.5° C	3.7 MPa (9.6%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$Ca(NO_3)_2$ (9%) + Na_2SO_4 (3%)	0.65	-17.5° C	6.6 MPa (17%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7	$Ca(NO_3)_2$ (9%) + Na_2SO_4 (3%)	0.65	24 hours @ +20° C; then -17.5° C	19.3 MPa (50%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$Ca(NO_3)_2$ (9.8%) + Na_2SO_4 (3%)	0.65	-17.5° C	2.7 MPa (9.2%)	1, App 5
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	K_2CO_3 (15.8%)	0.65	-10°C	4.1 MPa (14%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (5.8%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.75%)	0.65	-10° C	15.6 MPa (41%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (5.8%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.75%)	0.65	24 hours @ +20° C; then -10° C	26.7 MPa (70%)	1, App 7

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	K_2CO_3 (8.3%) + ligno-sulfonate-based plasticizing retarder (3%)	0.65	-10° C	17.8 MPa (61%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (9.1%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.5%)	0.65	-17.5° C	6.6 MPa (17%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	K_2CO_3 (9.1%) + plasticizing retarder based on salt of polyhydroxy-carboxylic acid (0.5%)	0.65	24 hours @ +20° C; then -17.5° C	12.5 MPa (33%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (4.9%) + $Ca(NO_3)_2$ (1.7%) + $CaCl_2$ (4.9%)	0.65	-10° C	10.5 MPa (36%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (4.9%) + $CaCl_2$ (4.9%)	0.65	-10° C	15.3 MPa (52%)	1, App. 4
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (5%) + $CaCl_2$ (5%)	0.66	-10° C	18.2 MPa (49%)	1, App 8
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (5%) + $CaCl_2$ (5%) + super-plasticizer (4%)	0.59	-10° C	22.0 MPa (59%)	1, App 8

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + $CaCl_2$ (1.5%)	0.65	-10° C	20.7 MPa (54%)	1, App 7
Cement:Aggregate = 1:7.4;max aggregate size = 16 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.64	-10° C	13.8 MPa (37%)	1, App 8
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	-10°C	18.2 MPa (62%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	-10° C	21.4 MPa (56%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	$NaNO_2$ (6%) + Na_2SO_4 (3%)	0.65	24 hours @ +20° C; then -10° C	22.0 MPa (58%)	1, App 7
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (7%)	0.65	-10°C	16.3 MPa (55%)	1, App. 4
Cement:Aggregate = 1:7;max aggregate size = 8 mm; ordinary Portland cement (S40/28)	$NaNO_2$ (8.5%) + $CaCl_2$ (8.5%)	0.65	-17.5°C	3.3 MPa (11%)	1, App 5

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	None	0.65	-17.5° C	1.5 MPa (3.9%)	1, App 6
Cement:Aggregate = 1:7;max aggregate size = 8 mm; rapid hardening Portland cement (S40/7)	None	0.65	24 hours @ +20° C; then -17.5° C	17.3 MPa (45%)	1, App 6
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-5° C	70% of nominal	2, Table 1, page 11/5
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-10° C	55%	2, Table 1, page 11/5
	100% $NaNO_2$ or 75% $Ca(NO_3)_2$ + 25% $CO(NH_2)_2$		-15° C	35%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-5° C	80%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-10° C	45%	2, Table 1, page 11/5
	100% NaCl or 70% NaCl + 30% $CaCl_2$ or 40% NaCl + 60% $CaCl_2$		-15° C	35%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-5° C	80%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-10° C	50%	2, Table 1, page 11/5

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
	50% $NaNO_2$ + 50% $CaCl_2$		-15° C	45%	2, Table 1, page 11/5
	50% $NaNO_2$ + 50% $CaCl_2$		-20° C	40%	2, Table 1, page 11/5
	100% K_2CO_3		-5° C	75%	2, Table 1, page 11/5
	100% K_2CO_3		-10° C	70%	2, Table 1, page 11/5
	100% K_2CO_3		-15° C	65%	2, Table 1, page 11/5
	100% K_2CO_3		-20° C	55%	2, Table 1, page 11/5
	100% K_2CO_3		-25° C	50%	2, Table 1, page 11/5
Cement:Aggregate = 1:4.39;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.54%); Pore-forming agent (0.05%); "Frost additive #2" (7.8%); "Plasticizer #2" (0.32%)	0.41	(outside at Tornio, March 1986)	30.7 MPa (138% of strength of control sample (different mix))	3, Table 5, page 19 (Samples left at factory)
Cement:Aggregate = 1:4.39;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.54%); Pore-forming agent (0.05%); "Frost additive #2" (7.8%); "Plasticizer #2" (0.32%)	0.41	(outside at Kilpisjärvi, March 1986)	30.8 MPa (138%)	3, Table 5, page 19 (Samples after 465 km transport)

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
Cement:Aggregate = 1:4.1;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.58%); Pore-forming agent (0.06%); "Frost additive #1" (5.5%); "Plasticizer #1" (3.1%)	0.41	(outside at Tornio, March 1986)	35.5 MPa (159%)	3, Table 5, page 19 (Samples left at factory)
Cement:Aggregate = 1:4.1;max aggregate size = 16 mm; Portland cement	"Retarder #1" (0.58%); Pore-forming agent (0.06%); "Frost additive #1" (5.5%); "Plasticizer #1" (3.1%)	0.41	(outside at Kilpisjärvi, March 1986)	19.2 MPa (86%)	3, Table 5, page 19 (Samples after 465 km transport)
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.65	-5° C	28.5 MPa (81% of strength of 5% BETEC sample cured at +20° C)	4, Figure 1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.55	-10° C	21.3 MPa (44% of strength of control sample with no BETEC cured at +20° C)	4, Table 1.1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	10% BETEC Cold Concrete Additive per weight of cement	0.55	-10° C	22.8 MPa (47%)	4, Table 1.1

Table C.1, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.65	-15° C	14 MPa (40% of strength of 5% BETEC sample cured at +20° C)	4, Figure 1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	5% BETEC Cold Concrete Additive per weight of cement	0.55	-20° C	6.1 MPa (13% of strength of control sample with no BETEC cured at +20° C)	4, Table 1.1
400 kg cement + 10 kg silica per cubic meter; max aggregate size = 8 mm.	10% BETEC Cold Concrete Additive per weight of cement	0.55	-20° C	7.5 MPa (16%)	4, Table 1.1

Information sources: 1: Kivekäs, Huovinen and Leivo (1985); 2: Kukko and Koskinen (1988); 3: Korhonen (1987); 4: "BETEC Köldbetongtillsats" (n.d.)

Table C.2 Compressive Strength Data for Cold Concrete, from U.S. Research

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information (see key at end of table)
	3% sodium nitrite (% of cement weight)	0.45	+20° C	97% of control sample cured at +20° C	A, Table 1
	3% sodium nitrite	0.45	-5° C	112%	A, Table 1
	3% sodium nitrite	0.45	-10° C	39%	A, Table 1
	3% sodium nitrite	0.45	-20° C	11%	A, Table 1
	6% sodium nitrite	0.45	+20° C	89%	A, Table 1
	6% sodium nitrite	0.45	-5° C	100%	A, Table 1
	6% sodium nitrite	0.45	-10° C	82%	A, Table 1
	6% sodium nitrite	0.45	-20° C	23%	A, Table 1
	9% sodium nitrite	0.45	+20° C	81%	A, Table 1
	9% sodium nitrite	0.45	-5° C	90%	A, Table 1
	9% sodium nitrite	0.45	-10° C	93%	A, Table 1
	9% sodium nitrite	0.45	-20° C	22%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% calcium nitrite	0.39	+20° C	135 %	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% calcium nitrite	0.39	-5° C	120%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% calcium nitrite	0.39	-10° C	42%	A, Table 1
	3% calcium nitrite	0.45	+20° C	136%	A, Table 1
	3% calcium nitrite	0.45	-5° C	105%	A, Table 1
	3% calcium nitrite	0.45	-10° C	29%	A, Table 1
	3% calcium nitrite	0.45	-20° C	4%	A, Table 1
	9% calcium nitrite	0.45	+20° C	151%	A, Table 1
	9% calcium nitrite	0.45	-5° C	116%	A, Table 1

Table C.2, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information (see key at end of table)
	6% sodium nitrite + 2% calcium nitrite	0.45	-10° C	100%	A, Table 1
	6% sodium nitrite + 2% calcium nitrite	0.45	-20° C	16%	A, Table 1
	3% sodium nitrite + 3% calcium nitrite	0.48	+20° C	115%	A, Table 1
	3% sodium nitrite + 3% calcium nitrite	0.48	-5° C	91%	A, Table 1
	3% sodium nitrite + 3% calcium nitrite	0.48	-10° C	39%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% sodium sodium nitrite + 0.06% potassium carbonate	0.39	+20° C	104%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% sodium sodium nitrite + 0.06% potassium carbonate	0.39	-5° C	96%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% sodium sodium nitrite + 0.06% potassium carbonate	0.39	-10° C	93%	A, Table 1
	6% sodium sodium nitrite + 0.06% potassium carbonate	0.45	+20° C	80%	A, Table 1
	6% sodium sodium nitrite + 0.06% potassium carbonate	0.45	-5° C	103%	A, Table 1
	6% sodium sodium nitrite + 0.06% potassium carbonate	0.45	-10° C	91%	A, Table 1
	6% sodium sodium nitrite + 0.06% potassium carbonate	0.45	-20° C	15%	A, Table 1

Table C.2, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information (see key at end of table)
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% potassium carbonate + 1% lignosulfonate retarder	0.39	+20° C	81%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% potassium carbonate + 1% lignosulfonate retarder	0.39	-5° C	53%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% potassium carbonate + 1% lignosulfonate retarder	0.39	-10° C	64%	A, Table 1
	6% potassium carbonate + 1% lignosulfonate retarder	0.45	+20° C	58%	A, Table 1
	6% potassium carbonate + 1% lignosulfonate retarder	0.45	-5° C	70%	A, Table 1
	6% potassium carbonate + 1% lignosulfonate retarder	0.45	-10° C	79%	A, Table 1
	6% potassium carbonate + 1% lignosulfonate retarder	0.45	-20° C	26%	A, Table 1
	10% urea	0.45	+20° C	91%	A, Table 1
	10% urea	0.45	-5° C	88%	A, Table 1
	10% urea	0.45	-10° C	42%	A, Table 1
	10% urea	0.45	-20° C	0%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% propylene glycol	0.39	+20° C	75%	A, Table 1

Table C.2, con'd

Components	Anti-freeze Admixtures	W/C Ratio	Curing Temperature	28 Day Compressive Strength	Source of Information (see key at end of table)
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% propylene glycol	0.39	-5° C	43%	A, Table 1
Cement:Aggregate = 1:5.3; max aggregate size = 3/4"; Type I Portland cement	6% propylene glycol	0.39	-10° C	19%	A, Table 1
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	7.2% calcium chloride (% of cement weight)	.53	-5° C	2668 psi (83% of control cured at +21° C)	B, Table VII
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	5.9% sodium chloride	.53	-5° C	2604 psi (81%)	B, Table VII
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	3.7% calcium chloride + 3.7% sodium chloride	.53	-5° C	3244 psi (101%)	B, Table VII
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	12.8% calcium chloride	.47	-10° C	3680 psi (115%)	B, Table VII
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	9.5% sodium chloride	.50	-10° C	1918 psi (60%)	B, Table VII
Cement:Aggregate (all sand) = 1:3; Type 1 Portland cement	5.7% calcium chloride + 5.7% sodium chloride	.48	-10° C	2490 psi (78%)	B, Table VII

Information sources: A: Korhonen et al (1994); B: Stormer (1970)

Table C.3 Freeze-thaw Durability of Cold Concrete, based on research by Goncharova and Ivanov (1975)

Admixture	Compressive Strength*, kg/cm²		
	Prior to Cycling	After 400 cycles; frozen in air; thawed in fresh water	After 400 cycles; frozen in air; thawed in water containing 5% sodium chloride
Control -- no admixture	330	0 after 260 cycles	0 after 130 cycles
8.5% calcium chloride + sodium chloride	350	390	160
10% sodium nitrite	300	200	270
10% potash	230	0 after 240 cycles	0 after 70 cycles
9% calcium nitrate + urea	270	290	340
9% calcium nitrate/nitrite +calcium chloride + urea	330	380	360
9% calcium chloride + sodium nitrite	330	350	230

*Values estimated from curves in Figure 3 of Korhonen (1990)

Table C.4 Freeze-thaw Durability of Cold Concrete, based on research by Grapp, Grapp and Kaplan (1975)

	Ultra-sound Velocity*, meters per second	
Admixture	Prior to Cycling	After 400 Cycles
Control – no admixture	3950	3950
15% sodium nitrite	4250	4200
15% calcium nitrate + urea	3950	4250
15% calcium nitrate/nitrite + calcium chloride + urea	4200	4450
15% sodium nitrite + calcium chloride	4050	4200
15% potash	3900	Below 3200
25% potash	4200	Below 3200

*Values estimated from curves in Figure 4 of Korhonen (1990)

Table C.5 Freeze-thaw Durability of Cold Concrete, based on research by Stormer (1970)

Admixture	Curing Temperature	Number of Cycles	Average Weight Loss
7.2% calcium chloride (% of cement weight)	-10° C	39	1.52%
5.9% sodium chloride	-10° C	39	2.99%
3.7% calcium chloride + 3.7% sodium chloride	-10° C	39	1.48%
Control – no admixture	+21° C	34	1.66%
12.8% calcium chloride	-5° C	38	3.22%
9.5% sodium chloride	-5° C	38	2.60%
5.7% calcium chloride + 5.7% sodium chloride	-5° C	38	2.34%
7.2% calcium chloride	-10° C	58	1.78%
5.9% sodium chloride	-10° C	58	3.33%
3.7% calcium chloride + 3.7% sodium chloride	-10° C	58	1.73%
Control – no admixture	+21° C	58	1.90%

Table C.6 Corrosive Effects of Cold Concrete Admixtures

Admixture	Corrosive Effects from Korhonen Literature Review (1990)	Degree of Rust from One Year Water and Admixture Immersion Corrosion Test (Korhonen et al 1994)
Sodium nitrate	No corrosion	
Ammonia	No corrosion	
Calcium nitrate	No corrosion	
Potash	No corrosion	
Sodium sulfate	No corrosion	
Calcium nitrate + urea	No corrosion	
Calcium nitrite	Inhibitor	None
Sodium nitrite	Inhibitor	None
Sodium hydroxide	Inhibitor	
Sodium chloride	Causes corrosion	
Calcium chloride	Causes corrosion	
Potassium carbonate		Very low
Portland cement		Low
Urea		Medium
Propylene glycol		Medium

Appendix D

Design Guideline Development

ECONOMIC EVALUATION OF COLD CONCRETE
A Report on Design Guideline Development for Project SPR-UAF-92-13

F. Lawrence Bennett, P.E.
UAF School of Engineering

June 1994

Introduction

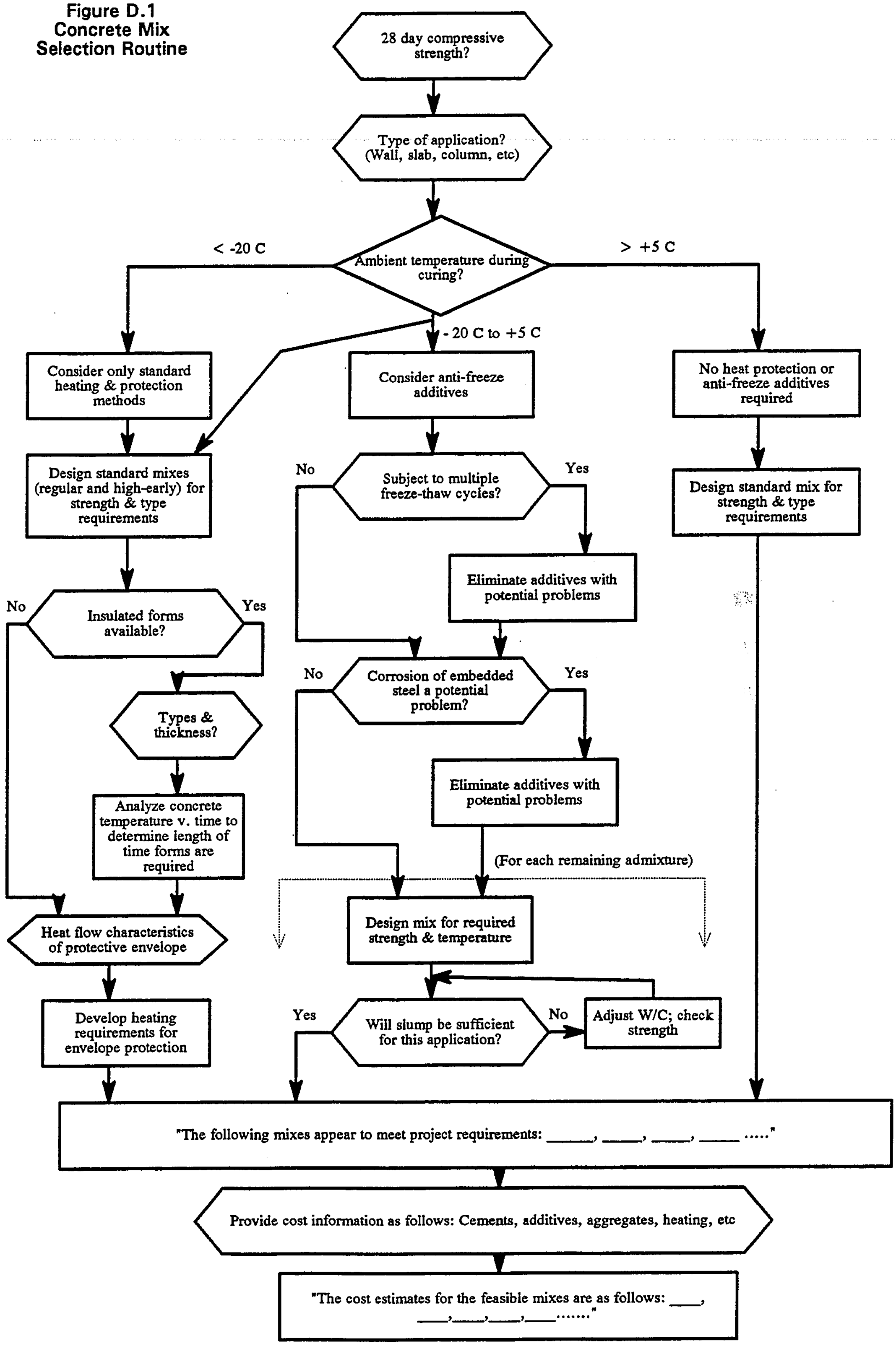
This section presents the basic framework for a system that can provide guidance in the selection of an appropriate concrete mix for a given set of use requirements and environmental conditions. This approach is cast in the form of a preliminary expert system in which the user responds to an ordered set of computer-generated questions whose answers lead to successive questions until the suggested mixes are indicated. Costs of each can then be estimated to provide the user with economic decision-making guidance.

We present a general description of the approach, including a flow chart, followed by a sketch of a hypothetical example. Additional enhancements required to render the approach realistic yet practical are then described, followed by a final brief section suggesting additional data that will be required before this method can be utilized completely.

General Description

Figure D.1, "Concrete Mix Selection Routine," presents a flow chart of the general procedure. Initial queries relate to the required 28 day compressive strength and the type of application (important for the slump required during placement). The routine then asks for the ambient temperature during curing. If

Figure D.1
Concrete Mix
Selection Routine



that temperature is above +5° C, no heat protection or anti-freeze additives are required, and the design provided is for a standard mix for the required strength and type of application.

If the temperature during curing is expected to be below -20° C, anti-freeze admixtures will not be practical, and the routine assumes that standard heating and protection methods with standard concrete mixes will be used. In this case, insulated forms, if they are available, are considered, and an analysis is performed to correlate concrete temperature, and therefore strength, with time after placement. This analysis permits a decision on when the forms can be removed. This part of the routine also considers the construction and heating of an envelope in which the fresh concrete is cured. Its heat flow characteristics, and thus the required heat input, are calculated.

The third primary option considers the case in which the ambient temperature during curing is expected to be between -20° C and +5° C. For this temperature range, anti-freeze admixtures may be the most economical solution. The routine first determines whether long-term freeze-thaw durability and/or corrosion of embedded steel must be taken into account. If so, those admixtures that have been found to be inappropriate in such conditions are eliminated from further consideration. Then, for each remaining anti-freeze admixture that has proven to be effective at the stated ambient temperature, a mix is designed, based on the required compressive strength (taking into account the expected decrease in strength due to the admixture) and temperature. The expected slump is determined and, if it is not sufficient for the type of application, the water content, and thus the cement content, are adjusted until the slump is appropriate.

Another important aspect of this third branch of the analysis is that it may be more economical, under these temperature conditions, to utilize a standard mix with no anti-freeze admixtures, with temporary protection and heating supplied during some of the curing period. The routine provides for considering such an option, as described in the paragraph above for the case of an ambient temperature below -20° C.

After all mix options have been generated for the specified temperature range, they are reported, and unit cost estimates for the various elements of cost are requested. With this information, the routine develops an overall cost estimate for each of the feasible options.

Hypothetical Example

To date, only the framework for such a system has been developed. No such expert system exists, nor has any computer code been written or data base developed. To show how such a system could operate, we present a hypothetical example, with the caveat that the mixes have not really been designed nor the costs estimated accurately. The word suppose is an important part of the description found in the balance of this section.

Initial information --

28 day compressive strength required? 3000 psi

Type of application? Wall

Ambient temperature during curing? -10° C

Therefore 1) consider anti-freeze additives and 2) also design standard mixes using regular and high early strength cement and temporary heating.

For admixture design --

Multiple freeze-thaw? Yes

Therefore eliminate potassium carbonate.

Corrosion a potential problem? Yes

Therefore eliminate sodium chloride, calcium chloride, urea and propylene glycol.

Eliminate calcium nitrite alone as ineffective below -5° C.

Thus, design with the following admixtures:

Option A. 6% sodium nitrite; W/C = 0.45. Base design on 28 day compressive strength of 3000/0.82 = 3660 psi (based on research results on effect of this additive on compressive strength).

Option B. 9% sodium nitrite; W/C = 0.45. Base design on 28 day compressive strength of 3000/0.93 = 3225 psi.

Option C. 6% sodium nitrite + 2% calcium nitrite; W/C = 0.39. Base design on 28 day compressive strength = 3000/0.96 = 3125 psi.

Option D. 6% sodium nitrite + 2% calcium nitrite; W/C = 0.45. Base design on 28 day compressive strength = 3000/1.00 = 3000 psi.

[Note that a "real" data base may provide many more options.]

Suppose the initial proportions, in pounds per cubic yard, from the design are as follows: (NOTE -- This is only a hypothetical example; no mix design has been performed!)

Option	Cement	Water	Aggregate	Anti-freeze Additives	Total Weight
A	660#	297#	3100#	40#	4097#
B	640	288	3120	58	4106
C	620	242	3190	50	4102
D	605	272	3175	48	4100

(Other additives are neglected in this analysis.)

Suppose further that the slump for Option B is insufficient for placement in a wall. We increase the W/C to 0.48 and the cement to 665 pounds and arrive at a revised recipe for Option B as follows:

Cement	665#
Water	319
Aggregate	3060
Additive	60
Total	4104#

Finally, suppose the analysis determines that the forms must be left in place for 10 days with each of these four options.

For the standard heating and protection option --

Suppose a 3000 psi mix for use in a wall, when cured in an envelope at +20° C, or inside insulated forms at +25° C, requires the following, in pounds per cubic yard:

Cement (regular or high early strength)	612#
Water	275
Aggregate	3210
Total	4097#

Insulated forms available? Yes

Type and size? Plywood/Styrofoam/plywood panels, with heating elements that maintain +25° C temperature

Suppose the analysis indicates that 3 days of this form use will be necessary to attain sufficient strength before heat removal for regular cement (Option E), and 2 days for high early strength cement (Option F).

Suppose further that the analysis determines that 7 days at +20° C (inside the envelope) are required to attain sufficient strength before heat removal for regular cement (Option G), and 4 days are required for high early strength cement (Option H). Suppose it is determined that the protective envelope, at an outside temperature of -20° C, requires 20,000 BTU/hour per cubic yard of concrete, to maintain a concrete temperature of +20° C.

Summary of analysis and cost estimate --

The following mixes appear to meet project requirements:

Option	Cement	Water	Aggregate	Additives	Total Weight	Protection
A	660#	297#	3100#	40# sodium nitrite	4097#	None
B	665	319	3060	60 sodium nitrite	4104	None
C	620	242	3190	37.5 sodium nitrite + 12.5 calcium nitrite	4102	None
D	605	272	3175	48 sodium nitrite + 12 calcium nitrite	4100	None
E	612 (regular)	275	3210	None	4097	Insulated forms at +25° C for 3 days
F	612 (high early)	275	3210	None	4097	Insulated forms at +25° C for 2 days
G	612 (regular)	275	3210	None	4097	Temporary +20° C heat in temporary enclosure for 7 days
H	612 (high early)	275	3210	None	4097	Temporary +20° C heat in temporary enclosure for 4 days

Provide cost information as follows: [Again, in this hypothetical analysis, these costs may not be representative of actual practice.]

Cement

Regular — $0.05 per pound

High early strength — $0.07 per pound

Aggregate — $0.003 per pound

Sodium nitrite — $0.50 per pound

Calcium nitrite	$0.60 per pound
Batching labor, equipment, overhead & profit	$30 per cubic yard
Concrete transportation	$15 per cubic yard
Concrete placement	$40 per cubic yard
Forms	
Uninsulated	$3 per cubic yard per day
Insulated	$20 per cubic yard per day
Protective envelope labor and materials	$25 per cubic yard
Heating cost for protective envelope	$0.15 per 10,000 BTU
Energy cost for insulated forms	$3 per cubic yard per day

The cost estimates for the feasible mixes are as follows:

Option	Cost per cubic yard
A	$177.30
B	$186.43
C	$181.82
D	$179.98
E	$194.23
F	$183.47
G	$221.63
H	$203.27

The results of this very hypothetical example show that three of the anti-freeze admixture options have the lowest cost per cubic foot, followed closely by the insulated form option that utilizes high early strength cement.

The spreadsheet in Table D.1 was used to calculate these sample costs for this hypothetical example.

Suggested Enhancements

The reader will quickly realize two things about the routine described in this report. First, much programming will be required in order provide a useful computer-based tool that performs even the rudimentary functions that are the basis for the present version of the model. Second, even if that model were completely translated into a computer-based expert system, it would not mimic all of the factors or options that the decision-maker usually considers when selecting a concrete mix and construction method. To provide for a thorough analysis of options, the following enhancements might be included:

- An option for using "warm" (25° to 30° C) or "hot" (above 30° C) concrete, in which some of the components are heated prior to mixing, or the entire mix heated subsequent to mixing.

- The possibility of using combinations of heating and protection devices. For example, a valid option in many cases is to use insulated forms plus additional heat. The hypothetical example used forms with resistance heating elements embedded; other options are possible.

Table D.1 Cost estimates for eight hypothetical concrete mixes

				Option A			Option B			Option C			Option D	
Element of cost	Unit cost	Unit	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y
Cement:Regular	$0.05	pound	660	pounds	$33.00	665	pounds	$33.25	620	pounds	$31.00	605	pounds	$30.25
Cement:High early	$0.07	pound												
Aggregate	$0.00	pound	3100	pounds	$9.30	3060	pounds	$9.18	3190	pounds	$9.57	3175	pounds	$9.53
Sodium nitrite	$0.50	pound	40	pounds	$20.00	58	pounds	$29.00	37.5	pounds	$18.75	36	pounds	$18.00
Calcium nitrite	$0.60	pound							12.5	pounds	$7.50	12	pounds	$7.20
Batching labor,equip, O.H., profit	$30.00	c.y	1	c.y.	$30.00	1	c.y.	$30.00	1	c.y.	$30.00	1	c.y.	$30.00
Concrete transportation	$15.00	c.y.	1	c.y.	$15.00	1	c.y.	$15.00	1	c.y.	$15.00	1	c.y.	$15.00
Concrete placement	$40.00	c.y.	1	c.y.	$40.00	1	c.y.	$40.00	1	c.y.	$40.00	1	c.y.	$40.00
Forms:Uninsulated	$3.00	c.y./day	10	days	$30.00	10	days	$30.00	10	days	$30.00	10	days	$30.00
Forms:Insulated	$20.00	c.y./day												
Protective envelope labor & matls	$25.00	c.y.												
Heating for protective envelope	$0.15	10,000 btu												
Energy for insulated forms	$3.00	c.y./day												
Total Cost per Cubic Yard					$177.30			$186.43			$181.82			$179.98

				Option E			Option F			Option G			Option H	
Element of cost	Unit cost	Unit	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y	Quantity	Unit	Cost/c.y
Cement:Regular	$0.05	pound	612	pounds	$30.60				612	pounds	$30.60			
Cement:High early	$0.07	pound				612	pounds	$42.84				612	pounds	$42.84
Aggregate	$0.00	pound	3210	pounds	$9.63	3210	pounds	$9.63	3210	pounds	$9.63	3210	pounds	$9.63
Sodium nitrite	$0.50	pound												
Calcium nitrite	$0.60	pound												
Batching labor,equip, O.H., profit	$30.00	c.y	1	c.y.	$30.00	1	c.y.	$30.00	1	c.y.	$30.00	1	c.y.	$30.00
Concrete transportation	$15.00	c.y.	1	c.y.	$15.00	1	c.y.	$15.00	1	c.y.	$15.00	1	c.y.	$15.00
Concrete placement	$40.00	c.y.	1	c.y.	$40.00	1	c.y.	$40.00	1	c.y.	$40.00	1	c.y.	$40.00
Forms:Uninsulated	$3.00	c.y./day							7	days	$21.00	4	days	$12.00
Forms:Insulated	$20.00	c.y./day	3	days	$60.00	2	days	$40.00						
Protective envelope labor & matls	$25.00	c.y.							1	c.y.	$25.00	1	c.y.	$25.00
Heating for protective envelope	$0.15	10,000 btu							336	10,000 btu	$50.40	192	10,000 btu	$28.80
Energy for insulated forms	$3.00	c.y./day	3	days	$9.00	2	days	$6.00						
Total Cost per Cubic Yard					$194.23			$183.47			$221.63			$203.27

- More sophisticated means for handling costs. For simplicity, the routine as described uses a cost per cubic yard as the basis for determining the total cost of many of the elements. In many cases, such costs are not linearly proportional to concrete volume.

Necessary Additional Data

The general method suggested herein is highly dependent on the availability of sufficient data, some of which are not available in an organized form at this time. Indeed, a comparison of the database schema developed in another section of this project with the data found to be actually available makes it clear that such a data base would have a large number of missing elements if developed at the present time.

The following data must be added, either from experimentation, literature review, manufacturer data or contractor records:

- Temperature v. time performance data for all mixes in the data base. Such information is necessary in order to use the maturity method to determine strength as a function of time.

- Additional performance results for the several prospective anti-freeze admixtures.

- Data on the heat flow characteristics of the various potential temporary protection envelopes.

- Cost data of all types. Especially needed are cost data for various temporary protection and heating methods. The routine as described expects the user to provide cost data only for those options identified as feasible, rather than have the program extract the data from the concrete performance database.