An Evaluation of
Concrete Flatwork Durability Problems in Minnesota

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April 21, 1998

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ACKNOWLEDGMENTS

The author gratefully acknowledges the contributions of fellow ARM panel members Doug Schwartz of the Minnesota Department of Transportation, Kevin MacDonald of Braun Intertec Corporation and Richard Stehly of American Engineering Testing, Inc. These gentlemen provided a great deal of professional insight and historical perspective into the concrete flatwork quality issues described in this report. In addition, Mr. Stehly and Mr. MacDonald provided summaries of the results of similar in-house studies that were useful in validating the results of the ARM study that is described in detail in this report, and Mr. Stehly provided the photographs that are included in the report.

Mr. Kevin MacDonald also provided the data and accompanying discussion concerning the effects of cement type on the efficiency of air-entraining admixtures, which are presented in Appendix E of this report. In addition, Mr. Stehly provided data concerning a study of the effects of w/c, finishing tool selection and curing method on the scaling of concrete exposed to salt solutions and freezing and thawing; a summary of this project is presented in Appendix F of this report. These contributions were very helpful in the preparation of this report.

The author would also like to express his appreciation to Mr. Gerard Moulzolf of American Petrographic Services, Inc. Mr. Moulzolf's expertise in performing the tests and examinations of the ARM concrete test specimens was invaluable, as was his assistance in helping the author to independently verify the test and examination results for many of the specimens.

Finally, special thanks are given to Mr. Eugene Wright and the ARM Board of Directors for their support of this study and their proactive role in helping the concrete industry to minimize the occurrence of future concrete flatwork durability problems.

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1. INTRODUCTION

An unusually high number of exterior concrete problems were reported to concrete contractors, ready-mix concrete suppliers, concrete associations (e.g., the Aggregate and Ready-Mix Association of Minnesota) and other interested parties following the winter of 1996-97. Complaints generally concerned the scaling and spalling of concrete flatwork (e.g., driveways, patios and floors) placed during the summer of 1996. Some of the concrete projects were older (up to 3 years old) and popouts and other problems were also noted on some projects.

The reported problems were so widespread and unusually frequent that the Aggregate and Ready-Mix Association of Minnesota (ARM) initiated a study of the situation. The intent of this study was to determine the source(s) of the sudden increase in complaints and to recommend procedures for minimizing the possibility that these sorts of problems might occur again on such a widespread basis.

To accomplish these goals, ARM solicited samples of "problem" concrete from its members. These samples were to be examined and tested to identify the factors that probably contributed to the performance problems observed in the field. In addition, a panel of concrete durability and quality experts (representing the consulting industry, government agencies and academe) was assembled to perform the examinations and tests of the hardened concrete samples, to analyze the resulting data, and to develop recommendations for improving the quality of future concrete construction in Minnesota. Some panel members also contributed data from their own in-house studies of similar problems; these data were useful in confirming trends observed using only the ARM sample data.

This report describes the collection and evaluation of the ARM data, the evaluation of other data (provided by the consulting industry panel members), and provides recommendations for improving the quality of future concrete flatwork construction in Minnesota.

2. ARM PROJECT DATA COLLECTION, SAMPLING AND TESTING

On June 30, 1997, Mr. Eugene Wright of the Aggregate and Ready-Mix Association of Minnesota (ARM) sent a memo to Minnesota ready-mixed concrete producers informing them of ARM's intent to study the reported concrete flatwork durability problems and soliciting their assistance in providing study samples and case histories. Project case histories were to include information concerning the following factors that might affect project performance:

- construction project type and location,
- nature of the complaint,
- concrete mix design,
- sources of raw materials,
- whether water was added to the mix at the job site (i.e., tempering),
- time from mixing to placement,

- weather at the time of placement, and
- concrete finishing techniques.

In addition, driver and contractor comments were solicited, including the contractor's theory concerning the probable cause(s) of any problems that were observed. A copy of the project data solicitation form is included in Appendix A of this report. A summary of the data collected from these forms is included in Appendix B.

This solicitation resulted in the submittal of 33 concrete samples (one core or chunk of concrete per study project) and project data forms to the ARM offices by mid-November of 1997. It should be noted that each sample was retrieved by the contractor responsible for the specific project and is assumed to be representative of the overall condition of the concrete at the specific project.

The concrete samples were delivered to American Petrographic Services, Inc., where they were prepared for and subjected to a microscopic examination in accordance with ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete." This examination was performed for the following purposes:

- determine the general condition of the concrete;
- determine the causes of any distress or deterioration noted;
- provide a description of the cementitious matrix, including a determination of the types of cementitious material present and the presence of mineral admixtures;
- determine whether alkali-aggregate reactions have taken place;
- determine whether the concrete has been subjected to early freezing or freeze-thaw damage;
- identify evidence of inappropriate mix designs or retempering (i.e., high water-cement ratios);
- document the presence of nondurable aggregate particles; and
- document evidence of placement, finishing or curing problems (i.e., indications of the degree of hydration and the adequacy of curing, as indicated by the degree of carbonation present, if any).

A case-by-case summary of the results of the petrographic examinations of the 33 ARM project samples is included in Appendix B.

3. EVALUATION OF ARM STUDY DATA

Copies of the project data forms and the results of the petrographic examinations were submitted to the author for evaluation in November of 1997. A case-by-case summary of the project data, containing both contractor- and petrographer-supplied data, was prepared and is presented in Appendix B. A summary of the types of problems reported by the ARM contractors and/or their clients is presented in table 1. Each type of problem is discussed briefly below.

Scaling

The most frequently reported problem was *scaling*, which refers to a loss of the finished pavement surface, usually to a depth of ¼ inch or less and resulting in rough-surfaced areas of exposed aggregate and mortar. Scaling can result when a weak surface layer is subjected to heavy loads or shearing forces (e.g., turning or stopping of vehicles), or when nondurable paste is subjected to repeated cycles of freezing and thawing. There are other causes of scaling as well (e.g., corrosion of reinforcing steel near the concrete surface, alkali-aggregate reactions, etc.), but these were not observed or considered likely on the subject projects.

Table 1. Performance Problems Cited in ARM Study

Problem Cited (Number of Projects)	**Percent of Projects/Samples**
Scaling (28 cases)	85 %
Popouts (10 cases)	30 %
Mortar Flaking (4 cases)	12 %
Random Cracking (1 case)	3 %
Spalling (1 case)	3 %

Popouts

Popouts are localized pits in the concrete surface that are the result of the excessive expansion of individual coarse aggregate particles, usually as a result of freezing and thawing in a critically saturated condition. The excessive expansion of a coarse aggregate particle near the concrete surface (where it may be more easily saturated than particles located more deeply within the concrete structure) causes the mortar above the particle to spall away; the aggregate particle itself may disintegrate as well, leaving behind a small socket surrounded by spalled concrete. Examples of aggregate types that are generally associated with popouts include chert, shale, opal and clay ironstone, although other types of aggregate may cause popouts as well. These types of aggregate are present in many aggregate sources, but are generally limited by specification to relatively small quantities (e.g., Mn/DOT specifications for general concrete applications allow up to 1.5 percent by weight in coarse aggregate and 2.5 percent by weight in fine aggregate). Thus, the presence of *some* popouts is not unexpected in most exterior concrete; however, popout densities exceeding 1 or 2 per square yard *may* be considered unacceptable, depending upon their size and the use of the pavement.

Mortar Flaking

Mortar flaking refers to the localized loss of thin layers of cement paste or mortar, usually over flat, coarse aggregate particles near the concrete surface. Unlike popouts, mortar flaking usually does not result in the appearance of freshly fractured aggregate particles or conical surface voids. While mortar flaking sometimes precedes more widespread surface scaling, it is not necessarily an indicator of future extensive scaling.

Mortar flaking is caused by many of the same mechanisms that produce scaling, and often develops as a result of excessive and early surface drying of PCC after placement on hot, windy days. This drying of surface mortar can be aggravated when bleed water is trapped beneath flat aggregate particles and cannot migrate to the surface to replace evaporated water, resulting in a dry mortar layer with low strength, poor durability, high shrinkage and poor bond with the aggregate particle. This thin, weakened layer can break away from the aggregate when it is frozen in a saturated condition. Poor finishing practices can also exacerbate the problem.

Random Cracking

Random cracking is the formation of any crack at a location other than beneath a contraction or control joint. The stresses responsible for the formation of these cracks are generally assumed to be due to shrinkage (loss of moisture) or contraction (temperature-related) movements that are resisted by friction with foundation layers or connections with adjacent structures. In these cases, the cracks develop soon after placement of the concrete (generally within 24 hours) unless joints are sawed or formed at appropriate locations to create weakened planes, forcing any cracks to form at these locations. When sawed or formed in a timely fashion (usually within 10 hours of concrete placement), these joints prevent uncontrolled cracking and provide a straight discontinuity at the concrete surface which is easily sealed, if desired. Uncontrolled cracks may also develop as a result of repeated heavy load applications (i.e., fatigue cracking), although this type of cracking is rarely observed in driveways or other concrete pavements with proper thickness designs. Cracking in pavement slabs can also be caused by loss of foundation support due to frost heave or swelling soils, particularly in combination with heavy load applications.

Spalling

Spalling refers to the localized loss of concrete at joints and cracks, usually proceeding along a plane oriented at approximately 45 degrees with respect to the pavement surface and the pavement joint or crack. The spalled area may range in length and width from a few inches to several feet. Spalling may be caused by the entrapment of incompressible materials in unsealed joints or cracks, which produce locally high stresses when the joints or cracks try to close in hot weather. Spalling may also result when differential vertical movements across undoweled joints or cracks produce excessive shearing forces due to frictional contact or aggregate interlock across the joint or crack.

The data presented in Appendix B were examined and considered in the context of generally accepted practices and standards to develop lists of possible causative factors for each project. These factors are listed in the last column of the table presented in Appendix B and a summary of most of these factors is presented in Table 2. Brief descriptions of the identification of each of these factors and their influence on the observed distresses follow. It should be noted that the factors listed are only those for which there was direct evidence of their presence; other factors for which there was no direct evidence may have been involved in some cases (e.g., long transit time or low cement content may have been factors in some cases where transit time and mix proportions were not reported by the contractor). In addition, it is apparent from Appendix B and Table 2 that more than one factor may have been involved in the development of distresses on many projects. In other words, it was often impossible to point to a single factor as the source of distress on any given project. Furthermore, it cannot be said that any one factor was primarily responsible for all of the problems observed on the projects that were considered in this study. However, several factors (i.e., air entrainment, finishing, curing and low cementitious content problems) may have contributed to the problems observed on many projects.

Air Entrainment Problems

Air entrainment problems were noted in 70 percent of the projects considered (although the greatest portion of these were observations of low air content near the pavement surface only, which is probably indicative of a loss of entrained air during the finishing process).

The need for entrained air in concrete that will be subjected to freezing and thawing conditions is well-documented. Water expands about 9 percent volumetrically upon freezing. Any pores in the concrete paste that are more than about 91.7% saturated will be subjected to hydraulic pressures when ice forms and unfrozen water is forced out of the pores ahead of the freezing front. The hydraulic pressure generated increases as the distance to an unsaturated boundary increases. Microscopic air bubbles (generally less than 0.01 inches in diameter) are entrained in cement paste to provide a good distribution of unsaturated locations into which unfrozen water can flow.

Table 2. Controllable Factors Affecting Performance in ARM Study

Contributing Factor	**Percent of Projects/Samples**
Air Entrainment Problems	(70 % total)
Low Air at Surface Only	48 %
Low Air Content Throughout	15 %
No Air Entrainment	6 %
Finishing Problems	61 %
Inadequate Curing	61 %
Low Cementitious Content [< 564 lbs/yd^3]	55 %
Long Transit Time [> 45 minutes]	42 %
High w/(c+p) [> 0.45]	39 %
Nondurable Aggregate	30 %
Deicing Chemicals	6 %
Improper Joint Spacing or Sawing Time	3 %
Cement or ASR Problem	3 %

While the total air content of fresh concrete (typically measured in the field using a pressure-based air meter) can provide an indication of the volume of entrained air present, microscopic examinations of polished hardened concrete samples provide the best indication of the actual sizes and spacing of entrained air voids. Figures 1 and 2 are photographs of properly air-entrained and non-air-entrained concrete specimens, respectively. A trained petrographer can reasonably assess the adequacy of concrete air void systems by informal observation, as was done in the ARM study; however, more quantitative (and time-consuming) measures of the air void system are also available (and were used in independent studies of different specimens performed by AET and Braun Intertec, as described in section 4 of this report). One parameter commonly used to characterize the distribution of the entrained air void system is the "spacing factor," which is represented by the symbol L-bar. The spacing factor represents the average maximum distance that unfrozen water will have to travel from any given point in the concrete matrix to reach an entrained air bubble. It is generally accepted that a spacing factor of less than 0.008 inches (0.2 mm) will provide good resistance to freeze-thaw damage in the cement paste.

The cases where no entrained air was observed are assumed to be due delivery of the wrong load of concrete to the job site, accidental oversights or faulty equipment at the batch plant. Low air

Figure 1. Polished concrete specimen with good air void system (1/16-in scale divisions)

Figure 2. Polished concrete specimen with no entrained air (1/16-in scale divisions)

contents may also be due to the same factors or overmixing in transit, but there is another possible factor as well.

A recent study by Braun Intertec Corporation (summarized in Appendix E) shows that variations in cement source (and even minor variations between different lots within the same cement source) can result in widely varying air contents, even when all other factors are controlled as closely as possible. This indicates the need for more frequent monitoring of concrete air content at the batch plant and possibly for more frequent adjustment of air-entrainment admixture dosage.

Observances of low air content at the pavement surface when the lower portions of the slab have adequate air void systems are an indication that the pavement has been overfinished, as discussed in the next section.

Finishing Problems

Finishing problems were noted wherever the entrained air void system appeared to be adequate throughout the slab except near the surface. Repeated passes of hand floats and trowels provide the mechanical energy necessary to help move entrained air bubbles toward the pavement surface (especially with the use of small tools that allow the application of higher surface pressures). This phenomena is easily seen by observing bubbles bursting immediately behind the trowel or float during hand finishing. This problem is particularly associated with premature finishing (before the concrete has set). Figure 3 is a photograph of a concrete specimen that exhibited a loss of entrained air near the finished surface.

Figure 3. Polished concrete specimen exhibiting loss of entrained air at surface (1/16-in scale)

Another problem associated with premature finishing is the presence of a high water-to-cementitious material ratio at the pavement surface. This is easily seen in petrographic examinations as a more lightly colored, softer layer of mortar at the pavement surface. The source of this problem is premature finishing, often before the bleed water has completely evaporated, resulting in the combination of bleed water with the surface mortar. This layer will be less dense and more porous than the rest of the concrete. As a result, it will be more susceptible to freeze-thaw damage and it will permit more rapid penetration of water and chemicals, which may allow more rapid development of popouts, freeze-thaw damage and corrosion of steel below the concrete surface.

Finally, premature troweling can also produce a dense layer of surface mortar by sealing the surface so air and water can't escape. This can result in the entrapment of water just below the finished surface, a condition that makes the concrete susceptible to delaminations along this weakened plane. This condition was observed in several of the ARM study samples.

<u>Inadequate Curing</u>

Proper curing requires that adequate moisture and temperature conditions are maintained for a period of time sufficient to gain adequate strength and durability. The time over which curing conditions must be maintained varies with the mix design (especially with varying water-cement ratio and pozzolan content), ambient temperature and moisture conditions, and the required strength and durability. High water-cement ratios, the presence of fly ash in the mix, cool temperatures and dry conditions all increase the period of time necessary to achieve a given level of concrete strength and durability at early ages.

Inadequate curing is indicated by: 1) the presence of unhydrated cement grains near the concrete surface; 2) a soft, porous surface layer without indications of overfinishing; or 3) evidence of carbonation. Carbonation refers to the loss of natural alkalinity associated with portland cement concrete pore water solutions due to neutralization of calcium hydroxide by acids formed by atmospheric carbon dioxide (or sulfur dioxide) and water. This loss of alkalinity is often accompanied by the dissolution of some hydration products, resulting in increased paste porosity and permeability. Some carbonation (up to 0.1 inch) is generally considered normal; carbonation to greater depths indicates a permeable, improperly cured surface.

In this study, carbonation was indicated by the use of phenolphthalein, an acid-base indicator that turns pink in the presence of alkaline solutions. Freshly cut concrete specimens were treated with phenolphthalein; carbonated regions failed to turn pink. Figure 4 is a photograph of a phenolphthalein-treated concrete specimen showing surface carbonation to a depth of ¼ inch.

<u>Low Cementitious Content</u>

The American Concrete Institute has a long-standing recommendation that a minimum cement content of 564 lbs per cubic yard of concrete be used in concrete intended to be exposed to severe freeze-thaw conditions. It is generally accepted that good freeze-thaw durability can be achieved with lesser amounts of cement when pozzolans (i.e., fly ash, silica fume, granulated ground blast furnace slag, etc.) are used and the amount of cement and pozzolan totals at least 564 lbs per cubic yard. Longer curing times are often required to achieve good durability and strength when pozzolans (especially fly ashes) are used, however.

Figure 4. Polished concrete specimen exhibiting carbonation to ¼ inch depth (1/16-in scale)

In this study, any project with a mix design reported to contain less than 564 lbs of cementitious material per cubic yard of concrete was identified as having a low cementitious content. Mix proportions were unavailable for some projects, so low cementitious content may have been a factor in a higher percentage of the projects than indicated in Table 2.

<u>Long Transit Time</u>

Any reported transit time exceeding 45 minutes was considered as a possible contributing factor in the observed concrete durability problems. Long transit times may contribute to reductions in total air content (resulting in the presence of a marginal or inadequate entrained air system) as extended mixing or agitating results in a loss of air bubble stability that allows small bubbles to combine and form larger bubbles that leave the mix more readily. Long transit times also reduce the amount of time available to finishers before the concrete stiffens and sets, forcing finishers to temper the mix (add water) and/or overwork the surface in an effort to achieve an acceptable finish. Either approach may result in the production of a nondurable concrete surface.

<u>High Water-to-Cementitious Material Ratio (w/(c+p))</u>

The American Concrete Institute recommends that the water-cement ratio should not exceed 0.45 when concrete will be exposed to a freezing and thawing environment in a moist condition. A low water-cement ratio (combined with proper curing) helps to ensure the development of a dense, impermeable paste that is resistant to freeze-thaw damage. In this study, high water-cementitious material ratio was considered a possible contributing factor in the development of scaling, popouts and other distresses if: 1) the reported ratio was greater than 0.45, 2) reported rates of tempering were sufficient to produce a w/(c+p) greater than 0.45, and/or 3) in the absence of a reported w/(c+p), the estimated w/(c+p) based on petrographic examination was greater than 0.45.

Use of Nondurable Aggregate

Nondurable aggregates are those that disintegrate or expand unacceptably when critically saturated and subjected to freezing and thawing (e.g., chert, shale, clay ironstone, etc.) or those that react with chemicals in the cement or pozzolans to produce expansive gels (e.g., alkali-silica reactions) or have other deleterious reactions. In this study, contractor- or petrographer-reported evidence of popouts and petrographer-reported evidence of alkali-silica reactivity was considered an indication that the use of nondurable aggregate was a possible contributing factor in the observed distresses.

Use of Deicing Chemicals

Deicing chemicals are commonly used to remove ice and snow by lowering the freezing point of water. They may also be responsible for additional deterioration in concrete pavements because they often increase the sorption and level of saturation in concrete and aggregates, making the paste and aggregates more susceptible to freeze-thaw damage when freezing finally does occur. The use of deicing chemicals also results in the development of osmotic pressures as the salt solutions move through the concrete pores in an attempt to achieve an equilibrium concentration. These pressures, if developed before the concrete gains sufficient strength, can cause fracture and delamination of the concrete surface.

In this study, the use of deicing chemicals was not cited as a possible contributing factor unless the contractor noted the early application of such materials. It is quite possible that early application of deicing chemicals did play a role in the deterioration of additional projects, particularly those that were paved late in the year and had not been cured adequately before deicers were applied.

Improper Joint Spacing or Delayed Joint Formation

As noted previously, uncontrolled cracking of concrete pavements is generally a direct result of the use of an inappropriate joint layout or from waiting too long to saw or form the joints. Based on contractor comments, this was observed on only one project; the joint spacing and time of sawing was not reported for this project.

Cement or Alkali-Aggregate Reaction Problems

Alkali-aggregate reactions generally manifest themselves as a form of map cracking or sand-sized popouts. Even before such problems are apparent in the field, petrographic evidence can be observed in the form of reaction rims and gel deposits around reactive aggregates in the concrete structure.

There were no contractor reports of alkali-aggregate problems in this study, although evidence of possible minor alkali-silica reactivity was observed in one concrete sample.

Late Season Paving

Although not listed as a separate causative factor, it is suspected that late season paving was a contributing factor in many cases. Five of the ARM study projects were paved in mid-to-late October, three of the American Engineering study projects were paved in late October or early November (see Appendix C), and six of the Braun study projects were paved in October, November, December or during "winter" conditions (see Appendix D). Late season (or winter) paving projects cannot be expected to develop adequate strength and durability prior to freezing unless appropriate measures are taken to ensure that proper temperature and moisture conditions are maintained for a sufficient duration. This is especially true for mixtures containing fly ash, which have an even slower rate of initial strength gain than conventional mixtures.

Other aspects of late season paving have been the subject of recent articles in Concrete Construction magazine (Suprenant and Malisch, 1998) and Concrete International magazine (Bimel, 1998). These articles cite the following additional factors as being possible causes of delamination (scaling) of concrete slabs:

- placing concrete on a cold subgrade;
- using a sheet plastic vapor barrier or vapor retarder; and
- addition of a water-reducing admixture that also retards set time.

These conditions all contribute to increased potential for bleeding, which can result in entrapped layers of water and the formation of weakened planes below the finished concrete surface.

Severe Winter Weather

In addition to the factors listed in Table 2, all of which can be controlled during the proportioning, mixing, placement, finishing and curing segments of production, the weather experienced in Minnesota during the winter of 1996-97 was unusually hard on the concrete. A summary of some key weather statistics for that period is presented in Table 3.

This table shows that the winter of 1996-97 was unusually hard on exposed concrete in the state of Minnesota. An unusually warm and dry late summer and fall was followed by a very wet November (which allowed thorough saturation of concrete surfaces prior to freezing) followed by a cold winter that included an unusually high number of freeze-thaw cycles. The water in weak, porous concrete surfaces would expand with each freezing cycle, causing high internal stresses (especially where air entrainment was deficient) and dilation of the pores, which allowed additional water to enter during the thaw cycles. After a sufficient number of freeze-thaw cycles, the weak, porous, nonair-entrained concrete would fail, causing scaling. Popouts would result from similar repeated expansions of nondurable aggregate particles. These mechanisms certainly acted in combination with the factors listed in Table 2 to accelerate the onset of the observed distresses, which might otherwise have taken years of additional exposure to develop.

Winters characterized by frequent freeze-thaw cycling are generally considered to be more detrimental to concrete durability than winters of extreme, extended cold weather where little freeze-thaw cycling takes place.

Table 3. Weather Facts for Winter 1996-97 (after American Engineering Testing)

Precipitation:

Month	Normal	Actual	Assessment
August 1996:	4 inch	1 inches	Very Dry
November 1996:	1.5 inches	5 inches	Very Wet

Average Temperature and Temperature Cycling:

November 1996:	Average temperature = 7 ^{o}F below normal – very cold
Winter 1996-97:	77 freeze-thaw cycles through 32 ^{o}F
	81 freeze-thaw cycles through 25 ^{o}F

4. EVALUATION OF DATA FROM OTHER MINNESOTA CONCRETE DURABILITY STUDIES

4.1 American Engineering Testing Concrete Durability Study

Earlier in 1997, American Engineering Testing, Inc. (AET) performed a similar study of pavement scaling problems for a private client. A summary of the field data and the results of petrographic examinations of samples taken from these projects is included in Appendix C.

The process used by AET in identifying probable causative factors for the field distresses was similar to that use by this author for the ARM data. The results of that evaluation are presented in table 4.

Table 4. Controllable Factors Affecting Scaling in AET Field Study

Contributing Factor	Percent of Projects/Samples
Low Air Content At Surface	44 %
Poor Curing	40 %
Concrete More Than 1 ½ Hrs Old	36 %
High w/c	32 %
Low Air Content	25 %
Not Air-Entrained	4 %

The relative frequencies of the probable factors involved in the development of spalling are strikingly similar to the relative frequencies of the same factors in the ARM study. This provides strong evidence of the validity of the ARM study, given that both studies yielded similar results even though performed using different sets of data and evaluated independently by different agencies.

4.2 Braun Intertec Concrete Durability Study

Earlier in 1997, Braun Intertec Corporation also performed a study of concrete flatwork durability problems. A summary of the field data and the results of petrographic examinations of samples taken from these projects is included in Appendix D.

The process used by Braun in identifying probable causative factors for the field distresses was also similar to that used by this author for the ARM data. The results of that evaluation are presented in table 5.

Again, the relative frequencies of the probable factors involved in the development of field distresses in this study are similar to those observed in the ARM study, providing validation of those results.

Table 5. Controllable Factors Affecting Performance in Braun Field Study

Contributing Factor	**Percent of Projects/Samples**
Air Entrainment Problems	38 %
Low Air Content	21 %
Low Air Content At Surface	13 %
Not Air-Entrained	4 %
Overfinishing	33 %
Nondurable Aggregate	29 %
Poor Curing	17 %
ASR	17 %
Deicing Chemicals at Early Age	13 %
High w/c	8 %

5. CONCLUSIONS

1. All of the projects that were submitted for consideration in the ARM study featured scaling/mortar flaking or popouts (or both). Other observed distresses (e.g., random cracking and spalling) can be considered to be of lesser importance in this study because they were observed only infrequently.

2. The last column in the table in Appendix B contains lists of the factors that may have contributed to the distresses observed on each study project. Consideration of this table shows that it was often impossible to point to a single factor as the source of distress on any given project. Furthermore, it cannot be said that any one factor was primarily responsible for all of the problems observed on the projects that were considered in this study.

3. Further consideration of Appendix B suggests that several factors may have contributed to the problems observed on many projects. A list of the controllable factors that may have

contributed to the premature deterioration of the greatest number of study projects would probably include:

- the use of aggregate containing nondurable particles;
- inappropriate mix designs (e.g., high w/(c+p) and/or low cementitious content) for exterior exposure in Minnesota;
- long transit times (which may decrease air entrainment and reduce mix workability at placement);
- mix retempering (which produces a higher w/(c+p));
- finishing problems (including the use of techniques and tools that remove entrained air from the surface layer or entrap water below the surface, or adding "finishing" water to the concrete surface); and
- inadequate curing (resulting in a weak, permeable surface, or insufficient strength and durability before freezing).

4. It is suspected that late season paving was a contributing factor in many cases. Late season (or winter) paving projects cannot be expected to develop adequate strength and durability prior to freezing unless appropriate measures are taken to ensure that proper temperature and moisture conditions are maintained for a sufficient duration. This is especially true for mixtures containing fly ash, which have an even slower rate of initial strength gain than conventional mixtures.

5. In addition to the factors listed above, all of which can be controlled during the proportioning, mixing, placement, finishing and curing segments of production, the weather experienced in Minnesota during the winter of 1996-97 was unusually hard on the concrete. It is highly likely that the large number of freeze-thaw cycles experienced during this period acted to accelerate the onset of the observed distresses, which might otherwise have taken years of additional exposure to develop.

6. It is worth noting that there was not an increase in the incidence of scaling, popouts or other durability-related distresses on Minnesota highway paving projects following the winter of 1996-97. The most relevant prinicipal differences between Minnesota highway paving projects and the concrete flatwork projects considered in this study are with respect to:
   - mix design (current Mn/DOT highway paving specifications allow a maximum w/(c+p) of 0.40),
   - finishing (very little hand work is performed on highway paving projects), and
   - curing (a spray-on curing compound is generally used and the application of deicing salts is generally delayed for many days or weeks until the pavement is opened to traffic).

7. The results of American Engineering Testing, Inc.'s scaling study suggest that limiting w/(c+p) to 0.45 or less is the most effective way to minimize scaling. Burlene curing was also found to be effective in reducing scaling severity.

8. Braun Intertec's study showed that cement brand (and lot) can significantly affect entrained air content when all other factors are held constant. This suggests that more frequent testing of air content (and adjustment of air-entraining admixture dosage) at the batch plant may be warranted, especially when cement sources are changed.

9. There was no evidence to suggest that any of the cement used in the study projects was inferior in any way, regardless of the source of that cement.

10. The types of aggregate that produce popouts are present in many aggregate sources, but are generally limited by specification to relatively small quantities (e.g., Mn/DOT specifications for general concrete applications allow up to 1.5 percent by weight in coarse aggregate and 2.5 percent by weight in fine aggregate). Thus, the presence of *some* popouts is not unexpected in most exterior concrete; however, popout densities exceeding 1 or 2 per square yard *may* be considered unacceptable, depending upon their size and the pavement application.

6. RECOMMENDATIONS

The following recommendations are offered to cement and admixture suppliers, ready-mix operators, concrete contractors and the concrete industry in general in response to the conclusions drawn from the evaluation of the project data that were provided for this study. It is recognized that some or all of these recommendations may already be standard practice for some suppliers, operators and contractors. It is also worth noting that many of the recommendations provided simply advocate the adoption of what has always been considered good practice.

<u>Materials Selection/Quality</u>

1. Cement and fly ash suppliers should advise concrete ready-mix plant operators when sources change so that plant operators can perform appropriate tests and adjust their mix proportions accordingly.

2. Ready-mix plant operators should perform workability and air content tests at least as often as aggregate stockpile tests are performed (generally at least twice daily) and whenever the source of any mix component changes. Mix proportions should be adjusted based on the results of these tests. It should never be assumed that materials from a new source or lot can be substituted without making adjustments to other batch quantities.

3. Aggregate sources should be selected or blended to produce well-graded materials that will improve mix workability, thereby reducing water demand and/or the need for mixture retempering at the job site.

4. Aggregate sources should be selected in general compliance with specifications for highway paving concrete to help reduce the number of nondurable aggregate particles present. However, contractors should inform clients of the potential for a few popouts whenever it is appropriate to do so. Clients could also be offered the option of purchasing concrete containing "premium" aggregate (e.g., Mn/DOT Class "A" aggregate), which would minimize the inclusion of nondurable particles.

Mix Designs

5. The mix proportions used for non-highway-related concrete flat work should be reviewed to ensure that the selected w/(c+p) and cementitious material contents are appropriate (i.e., in compliance with ACI recommendations) for the expected exposure conditions.

6. Mix designs should be evaluated to ensure that they provide an acceptable balance between strength, durability, workability and finishability. Appropriate mix design modifications should be made based on the results of periodic tests of concrete workability and air content.

7. Target air contents for air-entrained concrete should be indexed to aggregate top size, since mixtures that use smaller top sizes (e.g., "stamped" or "patterned" concrete, some exposed aggregate applications, etc.) generally have higher cement contents, greater paste contents and a need for a higher percentage of air-entrainment. Furthermore, consideration should be given to increasing currently accepted target air contents slightly to help guarantee that an adequate air void system remains after placement, consolidation and finishing are complete.

Transportation to Job Site

8. Haul times must be minimized wherever possible; alternates to batch plant mixing (e.g., shrink-mixing or on-site mixing) should be considered, if necessary. ASTM and ACI limits on mixing and agitation must be adhered to help ensure the development and preservation of a durable air-entrained paste.

Placement and Finishing

9. Retempering must be prohibited when the added water will cause the w/(c+p) to exceed 0.45 or the design water content, whichever is less. Any necessary improvements in workability that might be achieved through the addition of water beyond these limits should be achieved by using admixtures.

10. Minimize contact with the concrete during placement and finishing – strike or screed it off first, float using a bull float or darby, and finally allow any bleed water to *completely* evaporate before continuing. Minimize hand work (especially troweling) of air-entrained concrete.

Curing

11. Improve curing practices and materials to more fully develop the strength and durability potential of all concrete mixtures, especially for late season paving and when fly ash or other pozzolanic admixtures are used. Curing covers or membranes must maintain or provide surface moisture for a period of time sufficient for the development of strength and durability. "Natural" curing should not be used if exposure to freezing and thawing is expected.

12. Develop guidelines for late-season finishing and curing to provide contractors with additional guidance in determining how long to maintain appropriate temperature and moisture conditions for different paving mixtures (e.g., as a function of cement content, w/(c+p), pozzolan type and content, and curing temperature) to ensure the development of adequate strength and durability before exposure to freezing conditions. This would help to eliminate inappropriate mix designs and inadequate curing as the causes of scaling.

<u>Training</u>

13. A short course on “Total Quality Management” in concrete production and paving should be identified or developed and offered periodically as a refresher course for personnel involved in all aspects of concrete production (including suppliers of concrete components, ready-mix plant operators, contractors and finishers).

7. REFERENCES

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Bimel, C. “Is Delamination Really a Mystery?” Concrete International, Vol. 20, No. 1. American Concrete Institute, Detroit, MI. January, 1998.

Appendix A – ARM PCC Sample Request and Data Sheet

Appendix B – Complete Tabulation of ARM Study Data

Appendix C – Complete Tabulation of AET Durability Study Data

Appendix D – Complete Tabulation of Braun Intertec Durability Study Data

Appendix E – Effect of Cement Brand on Air Entrainment and Setting Times (Braun Intertec Study)

by

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Effect of Cement Brand on Air Entrainment and Setting Times

by

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The dosage of air-entraining agent required to produce concrete with a good air void system that will be protective of the concrete when subjected to freezing and thawing in the saturated condition is affected by a number of variables, including water-cement ratio, the total volumetric water content, and the chemistry and fineness of the cement. The use of other chemical or mineral admixtures can also impact the performance of the air-entraining agent.

In this study, the effectiveness of the air-entraining agent was measured by determining the plastic air content of mortar samples (w/c = 0.5, cement/aggregate = 1:3) prepared using 6 different brands of ASTM C 150 Type I cement (Brands A through F), Ottawa 20-30 silica sand and a fixed dosage of a neutralized vinsol resin air-entraining agent (60 ml/100 kg of cement, or 1 oz/cwt). Air contents were measured using a volumetric air meter; set times were measured using a Vicat apparatus. The lab temperature was 68 to 72 degrees Fahrenheit during the testing.

Samples of cement brand C were obtained from three different lots, designated C1, C2 and C3 in Table E1. Brand A was tested three times, with air contents ranging from 5.8 to 6.0 percent; these results indicate good precision and repeatability in the test procedures. All other cement brands were tested once.

The results of this test program, presented in Table E1, show air contents varying from 5.4 to 10.2 percent when the only apparent variable is cement brand. This illustrates the need for the requirement that the air content of the concrete be determined on a regular basis to monitor the quality of the material being produced. This is especially important when cement sources are subject to change, but is also important to monitor potential variability in air entrainment between different lots obtained from the same source. Ready-mix plants should determine the air content of concrete on a frequent basis. This determination should be made at least twice per day, or as often as the moisture of the aggregate stockpiles is checked, which is even more frequently.

The setting times of the mortar samples were tested at a constant temperature, but also varied significantly with cement type. The purchasers and producers of concrete for use in residential driveways should be aware that a change in cement brand can (and often does) have a significant impact on the characteristics of the plastic and hardened concrete; batching and finishing procedures should be adjusted accordingly as a routine step in the process of achieving durable concrete flatwork.

Table E1. Results of Air-Entrainment Tests for Different Cement Brands

Cement ID	Air Content, %	Initial Set, HR:MN	Final Set, HR:MN
A	6.0	3:30	5:18
B	9.0	3:50	5:40
C1	7.6	2:58	4:31
C2	8.4	3:15	5:05
C3	7.6	3:25	5:01
D	9.6	4:03	5:59
E	10.2	3:21	5:37
F	5.4	3:16	5:21
Range	5.4 to 10.2	2:58 to 4:03	4:31 to 5:59

Appendix F – Effects of Water-Cement Ratio, Finishing Tool and Curing Technique on Concrete Scaling (American Engineering Testing, Inc. Study Summary)

Effects of Water-Cement Ratio, Finishing Tool and Curing Technique on Concrete Scaling (American Engineering Testing, Inc. Study Summary)

In 1997, American Engineering Testing, Inc. performed an in-house study of the effects of water-cement ratio, type of finishing tool and curing technique on the scaling of concrete exposed to deicing chemicals and freeze-thaw conditions. Testing was performed in general accordance with the provisions of ASTM C 672 "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals."

The test variables and ranges incorporated in this study were:

- w/c (0.45, 0.67)
- finishing tool (wood float, fresno trowel, heifer float and steel trowel)
- curing method ("sunshine" [air cure], burlene, acrylic and MnDOT curing compound)

Concrete specimens were cast using a 6-sack mix (564 lbs of cement per cubic yard of concrete) comprising glacial gravel aggregate and 6 percent total air content (entrapped plus entrained). Each specimen was finished using one of several finishing tools before being broomed to provide the final surface texture. Acrylic and Mn/DOT curing compounds were applied at rates corresponding to manufacturer's recommendations.

After curing, a "dike" was constructed on one flat surface of each specimen to allow ponding to a depth of approximately ¼ inch with a solution of calcium chloride and water. Specimens were then placed in a freezing environment for 16-18 hours, then removed to laboratory air (~73^{o}F) for 6-8 hours. This cycle was repeated daily, with flushing and examination of the surface after every 5 cycles. Subjective surface ratings were assigned using the following codes:

0	no scaling
1	very slight scaling (1/8 inch depth, max; no coarse aggregate visible)
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	severe scaling (coarse aggregate visible over entire surface)

Testing was terminated after 50 cycles of freezing and thawing. It was noted that all of the specimens prepared using a w/c of 0.67 exhibited significant scaling after only 25 cycles. The conditions of the test specimens after 50 cycles of freezing and thawing in the presence of salt solution are summarized in Table F1.

Table F1. Results of AET Salt Scaling Tests (after 50 freeze-thaw cycles)

	W/C	
	0.45	**0.67**
Wood Float Finish		
Sunshine Cure	2	5
Burlene Cure	0	5
Acrylic Cure	2	3
Mn/DOT Curing Compound	0	3
Fresno Trowel Finish		
Sunshine Cure	0	5
Burlene Cure	0	2
Acrylic Cure	0 – Popout	4
Mn/DOT Curing Compound	1	3
Heifer Float Finish		
Sunshine Cure	1	5
Burlene Cure	0	2
Acrylic Cure	1	4
Mn/DOT Curing Compound	1	3
Steel Trowel Finish		
Sunshine Cure	1	5
Burlene Cure	0	2
Acrylic Cure	0	4
Mn/DOT Curing Compound	0	3

The most obvious conclusion that can be drawn from these data is that water-cement ratio plays an enormous role in concrete scaling. Reducing the w/c from 0.67 to 0.45 (the maximum recommended by ACI for concrete exposed to freezing and thawing in the presence of deicing chemicals) almost eliminated the incidence of scaling, regardless of finishing and curing techniques. The lower water-cement ratio provides a less porous, less permeable concrete that is more difficult to saturate and doesn't allow easy penetration of water or salt. It also results in a stronger, more dense paste that is better able to resist any pressures that develop as a result of repeated freezing and thawing.

It was observed that burlene curing generally provided the best scaling resistance, regardless of the finishing tool and water-cement ratio. This is probably because the burlene is more effective in maintaining surface moisture and allows more complete hydration of the cement near the concrete surface. This, in turn, in a less permeable surface which is more resistant to freezing and thawing effects. Conversely, the "sunshine" cure generally performed worst because the failure to prevent water from evaporating from the surface results in poor hydration of the surface cement and the development of a relatively weak, porous surface that is highly susceptible to scaling and freeze-thaw damage. The acrylic cure apparently provided better moisture retention than the "sunshine" cure, and the Mn/DOT curing compound provided further improvements (although neither performed as well as the burlene).

It is difficult to draw conclusions concerning the effects of different finishing techniques when other factors are held constant, although there appears that the wood float finish may produce a surface that is slightly more susceptible to scaling.

From the results of this study, American Engineering Testing concluded that scaling can be prevented by using a well-air-entrained concrete with a w/c < 0.45, providing effective curing and using good finishing techniques.