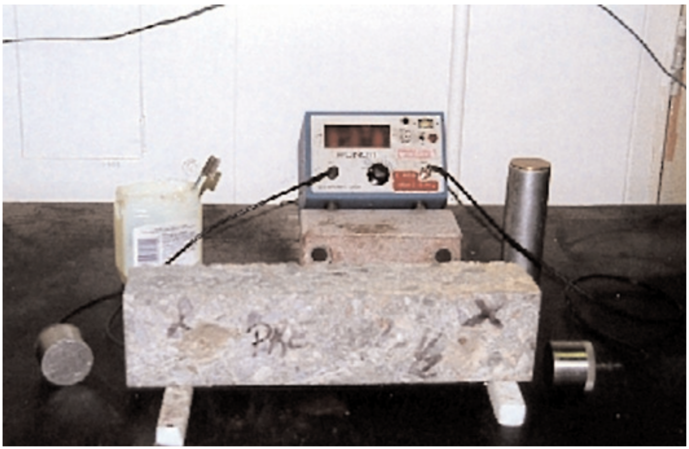
Frost Durability of Roller-Compacted Concrete Pavements

by Service d'Expertise en Matériaux Inc.



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Concrete Thinking for a sustainable world
PCA Portland Cement Association

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Research and Development Bulletin RD135

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Abstract: The growth of roller-compacted concrete pavement use in cold climate regions often is impeded by concerns regarding its ability to resist frost attack. Most published laboratory test results have indicated that the frost resistance and particularly the deicer salt-scale resistance of RCC are not always satisfactory. However, long-term field performance indicates that non-air entrainment RCC can be quite resistant to frost action. The report provides a comprehensive review on the current practices and recent developments in material selection and aggregate gradation, mixture design methods, production process and placement techniques. Improved construction techniques and recent developments in mixture design methods have resulted in stronger more durable RCC. Data shows that as little as 1.5% of spherical air bubbles can have a beneficial influence on the frost resistance durability of RCC. Test results indicate that ASTM C 1262 appears to be a reliable method of assessing the frost durability of RCC.

Keywords: Air entrainment, durability, free-thaw durability, frost durability, mix design, pavements, RCC, roller-compacted concrete, salt-scaling resistance

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TABLE OF CONTENTS

Preface vii

Chapter 1 – Literature Review of the Frost Durability of Roller-Compacted Concrete Pavements 1
- 1.1 Current Practices 1
  - 1.1.1 Material Selection 1
  - 1.1.2 Conventional Mixture Design Methods 6
  - 1.1.3 Production of RCC 10
  - 1.1.4 Construction 11
  - 1.1.5 Typical Applications 16
- 1.2 Recent Developments 17
  - 1.2.1 New Mixture Design Methods 17
  - 1.2.2 High-Performance RCC 19
  - 1.2.3 Low-Binder-Content RCC 20
- 1.3 Frost Durability of RCC Pavements 21
  - 1.3.1 Resistance to Internal Microcracking 21
  - 1.3.2 Resistance to Deicer Salt-Scaling 23
  - 1.3.3 Field Performance 27
  - 1.3.4 Concluding Remarks 28
- 1.4 Air Entrainment 28
  - 1.4.1 Air Entrainment in the Laboratory 28
  - 1.4.2 Field Experience 32
  - 1.4.3 Measuring the Air-Void Characteristics of RCC Mixtures 33
  - 1.4.4 Concluding Remarks 33
- 1.5 References 34

Chapter 2 – Test Program, Materials, and Experimental Procedures 41
- 2.1 Test Program 41
- 2.2 Materials 41
  - 2.2.1 Cement and Cementitious Materials 41
  - 2.2.2 Coarse and Fine and Aggregates 44
  - 2.2.3 Water 44

2.2.4 Admixtures 45
2.3 Experimental Procedures 46
2.4 Properties of Fresh RCC 48
2.5 Properties of Hardened Concrete 49
2.5.1 Compressive Strength and Flexural Strength 49
2.5.2 Characteristics of the Air-Void System 50
2.5.3 Microscopic Observations by Scanning Electron Microscopy 51
2.5.4 Frost Durability 51
2.5.5 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A) 51
2.5.6 Deicer Salt-Scaling Resistance (ASTM C 672) 52
2.5.7 Freezing and Thawing Durability (ASTM C 1262) 53
2.5.8 Pulse Velocity Measurements 54
2.5.9 Chloride Penetration Profiles 54
2.5.10 Surface and Internal Microcrack Measurements 55

Chapter 3 – Assessing the Frost Durability of RCC Pavements 57
3.1 Test Section Sampling and Visual Inspection 57
3.1.1 Sampling Procedure 57
3.1.2 Visual Inspection 57
3.2 Test Program and Results 59
3.2.1 Compressive Strength 59
3.2.2 Flexural Strength 60
3.2.3 Pulse Velocity Measurements 61
3.2.4 Chloride Penetration Profiles 62
3.2.5 Internal Microcrack Measurements 63
3.2.6 Characteristics of the Air-Void System 64
3.2.7 Micro Air-Void Analysis by Scanning Electron Microscopy 65
3.2.8 ASTM C 1262 Test Results 66
3.3 Discussion 68
3.4 References 69

Chapter 4 – Influence of Air-Entrainment on the Frost Durability of RCC 71
4.1 Mixtures Characteristics 71

4.2 Fresh Concrete Properties 73
4.3 Properties of Hardened Concrete 74
    4.3.1 Mechanical Properties 74
    4.3.2 Characteristics of the Air-Void System 75
    4.3.3 Microscopic Observations by Scanning Electron Microscopy 76
    4.3.4 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A) 77
    4.3.5 Deicer Salt-Scaling Resistance (ASTM C 672) 78
    4.3.6 ASTM C 1262 Test Results 80
4.4 Discussion 81
4.5 Concluding Remarks 82
4.6 References 82

Chapter 5 – Influence of Silica Fume and Fly Ash on the Frost Durability of RCC 83
5.1 Mixture Characteristics 84
5.2 Test Results and Discussion 84
    5.2.1 Fresh Concrete Properties 84
    5.2.2 Compressive and Flexural Strengths 85
    5.2.3 Characteristics of the Air-Void System 86
    5.2.4 Microscopic Observations by Scanning Electron Microscopy 87
    5.2.5 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A) 87
    5.2.6 ASTM C 672 Test Results 88
    5.2.7 ASTM C 1262 Test Results 90
5.3 Concluding Remarks 91
5.4 References 91

Chapter 6 – Influence of Mixer Type on the Production of Frost-Durable RCC Mixtures 93
6.1 Test Program 93
6.2 Materials 95
6.3 Mixture Characteristics 95
6.4 Fresh RCC Properties 96
6.5 Hardened RCC Properties 97
    6.5.1 Compressive Strength 97

        - 6.5.2 Characteristic of the Air-Void System . . . 98
        - 6.5.3 Microscopic Observations Using Scanning Electron Microscopy . . . 99
        - 6.5.4 ASTM C 666 (Procedure A) Test Results . . . 99
        - 6.5.5 ASTM C 672 Test Results . . . 100
        - 6.5.6 ASTM C 1262 Test Results . . . 101
    - 6.6 Concluding Remarks . . . 102
    - 6.7 References . . . 102

Chapter 7 – Summary and Conclusions . . . 103
    - 7.1 Air Entrainment . . . 103
    - 7.2 Frost Resistance-ASTM C 666 . . . 104
    - 7.3 Deicer Salt-Scaling – ASTM C 672 . . . 106
    - 7.4 Deicer Salt-Scaling – ASTM C 1262 . . . 107
    - 7.5 Concluding Remarks and Recommendations . . . 108
    - 7.6 References . . . 109

Acknowledgements . . . 109

APPENDIX A – ASTM C 666 Plotted Test Results . . . 111

APPENDIX B – ASTM C 672 Plotted Test Results After 50 Cycles . . . 117

APPENDIX C – ASTM C 1262 Plotted Test Results . . . 128

PREFACE

Over the years, roller-compacted concrete (RCC) has been used successfully for the construction of industrial pavements such as log sort yards, military hard stands, or container yards. In the area of industrial applications, RCC has proven to be extremely competitive compared to high-performance asphalt pavements. Even if its share of the global road-construction market remains relatively marginal in North America, RCC now increasingly is used for the construction of pavements exposed to very severe loading and environmental conditions. This growing interest in RCC has prompted contractors and engineers to come up with technical innovations. Placement and consolidation operations have been improved significantly over the years, and new mixture design methods that allow the production of RCC mixtures with optimum packing densities (and minimal binder contents) have been developed recently. Particularly in eastern Canada, high-performance RCC mixtures with a 7-day compressive strength of 55 MPa and a 7-day flexural strength of 7 MPa now are used regularly for the construction of full-scale jobs.

Despite the various advantages offered by the RCC technique, the growth of its use in cold climate regions often is impeded by concerns, expressed by several potential users, regarding its ability to resist frost attack. Most laboratory test results that have been published during the last two decades have indicated that the frost and particularly the deicer salt-scaling resistance of RCC are not always satisfactory. According to most laboratory data, RCC appears to be more susceptible to deicer salt-scaling than conventional portland cement concrete mixtures of the same compressive strength. One of the main reasons for this behavior appears to be the difficulty in obtaining a proper air-void system in such dry mixtures when they are produced under field conditions.

But how does RCC perform under natural exposure conditions? Is frost resistance really such a problem? There is relatively little systematic information available on this topic. Contrary to the laboratory test results, many field surveys tend to indicate that non-air-entrained RCC can be quite resistant to frost action under severe exposure conditions when placed and cured properly. Some field surveys also indicate that non-air-entrained high-performance RCC even can be resistant to deicer salt-scaling, particularly when certain supplementary cementitious materials are used.

Chapter 1

LITERATURE REVIEW OF THE FROST DURABILITY OF ROLLER-COMPACTED CONCRETE PAVEMENTS

In North America, the use of roller-compacted concrete (RCC) for pavement applications has expanded significantly over the past decades. Generally viewed as more economical and relatively easier to produce, RCC gradually has been considered an attractive alternative to conventional road construction. Presently, a significant number of off-highway pavement projects in the United States and Canada have been completed using the RCC technology.

The growing interest in RCC pavement applications has resulted in several studies on topics such as mixture design, production processes, construction techniques, air entrainment, and frost durability. This chapter is devoted to a review of the technical literature published over the past decades on these topics.

Current practices and recent developments in materials selection, mixture design methods, production process, and construction techniques are reviewed in the first two sections of this chapter. A survey of the available information on the frost and salt-scaling resistance of RCC pavements is presented in the third section. Finally, air-entrainment mechanisms in RCC are reviewed in the last section of this chapter.

1.1 CURRENT PRACTICES

1.1.1 Material Selection

Since its first application, RCC mixture design procedures have progressed a long way. Only a few years ago, RCC mixture characteristics were still quite conventional, and it seemed that producers were more tempted to keep production costs as low as possible than to improve the performance of their products.

Thus, to obtain a concrete with a given consistency, the required amount of water was simply added to a dry mixture of cement and aggregates. The quantity of water and the aggregate grading were fixed empirically to reach a maximum density, and the binder (cement) content was adjusted to meet the specified mechanical resistance. Most of the time, no chemical admixtures were used.

Gradually, producers refined their mixture designs and materials selection. In order to allow greater transportation times and prevent problems due to placement delays at the construction site, water-reducing agents and set retarders began to be used commonly. For economical reasons, mineral admixtures, such as fly ash and slag also were considered as partial cement replacement. In order to obtain greater densities, gap-graded aggregates recently were introduced.

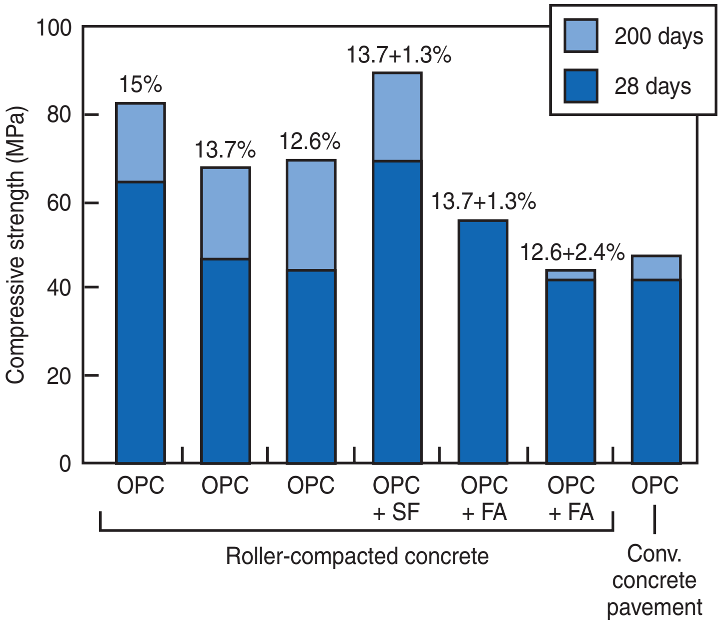
1.1.1.1 Binder

In North America, most RCC pavements presently are made with ordinary portland cement and fly ash. In addition to the economies made by reducing the cement content, the use of fly ash is considered to improve the consolidation of the concrete by increasing the percentage of fines in the mixture. In some cases, the addition of fly ash also contributes to facilitating, during the finishing operations, the formation of a wearing surface with a closed texture. The amount of fly ash usually is limited to a maximum of 20% (by mass) of the total binder content. Some investigations have indicated that the addition of fly ash does not adversely affect the compressive strength of RCC.[1,2] According to these studies, the "filler effect" of some fly ashes can compensate for their lower hydraulic reactivity. However, these conclusions should be considered with caution. The term fly ash covers a large range of different by-products with various chemical reactivity, particle size distributions, and chemical composition (class C and class F fly ashes have different chemical compositions). It is therefore possible that some fly ashes are more suitable than others for the production of RCC.

The addition of other mineral admixtures, such as slag and silica fume, are used in Canada and in the United States. Recently, a few RCC pavement projects have been completed in eastern Canada using new ternary blended cements containing slag and/or fly ash, and silica fume. The addition of slag and silica fume in RCC pavement also is used widely in Europe. For instance, producers in Scandinavian countries tend to use silica fume as partial cement replacement to obtain high mechanical strength after only a short curing period.[3] The amount of silica fume usually is limited to 10% (by mass) of the total binder content. Similarly, ternary blended cements containing high proportions of slag and fly ash with a very low clinker content (or even without any clinker) were introduced on the French market years ago.[4,5] Ternary blended cements were also introduced in eastern Canada in 2000. Originally designed for RCC gravity dams, these binders have been gradually modified to fit the particular requirements of road construction. In addition, these blended cements offer the advantage of an increased setting time.

Regardless of the mixture design method used, keeping the binder content in the 10% to 15% (of the total mass of dry constituents) range for the top portion of the pavement (i.e., for the first 150 mm) and in the 6% to 8% range for the lower layers generally is recommended. As can be seen in Figure 1.1, where the main conclusions of an investigation conducted by the Swedish Cement and Concrete Institute are illustrated,[3] the compressive strength of RCC varies with the amount and the type of binder. Nowadays, many producers tend to keep the binder content around 12%, approximately 300 kg/m^3, in order to ensure a sufficient paste volume to totally fill all the voids between aggregate particles and therefore reduce the compaction air-void content.

However, contractors and designers should be careful not to overdose the cement in their mixtures. A higher cement content does not necessarily result in a longer service life, and usually increases production costs and construction requirements. As pointed out by Schrader and McKinnon,[6] RCC pavements with a high cement content tend to exhibit more shrinkage and more brittleness. They have a greater demand for joints and require



Note: Ordinary portland cement (OPC), silica fume (SF), and fly ash (FA)

Figure 1.1. Influence of type of binder and binder content on the compressive strength of RCC.[3]

more stringent construction controls. It is thus often cheaper and more adequate to limit the cement content and to increase the thickness of the pavement. Furthermore, recent experience clearly indicates that it is possible to obtain superior mechanical properties with low binder contents.[7]

1.1.1.2 Aggregates

The aggregates represent approximately 75% to 85% of the volume of a typical RCC pavement mixture. They markedly influence both the fresh and hardened concrete properties.[8] Proper selection of suitable aggregates will result in greater economy in construction and longer serviceability of RCC pavements.

1.1.1.2.1 Conventional Aggregates

In order to reduce segregation during transportation and placement operations, using crushed aggregates is recommended. Although natural aggregates are often cheaper and usually reduce the water demand, they may increase significantly the risks of segregation.[3] Those risks can be reduced further by limiting the maximum size of the aggregate to 19 mm.

It is also commonly recognized that the type and the grading of the aggregate particles can influence significantly the in-situ density of RCC and the texture of the wearing surface. Over the years, many grading curves have been proposed to maximize the density of RCC mixtures. Some, like that recommended by the Portland Cement Association[9] (see Figure 1.2), or that specified by the U.S. Army Corps of Engineers,[10] are continuous and mostly resulting from previous experiences with granular materials such as asphalt. Others, obtained from the theoretical analysis of the optimum arrangement of grains of various sizes, are often discontinuous and seem to yield more uniform and improved performances.[11]

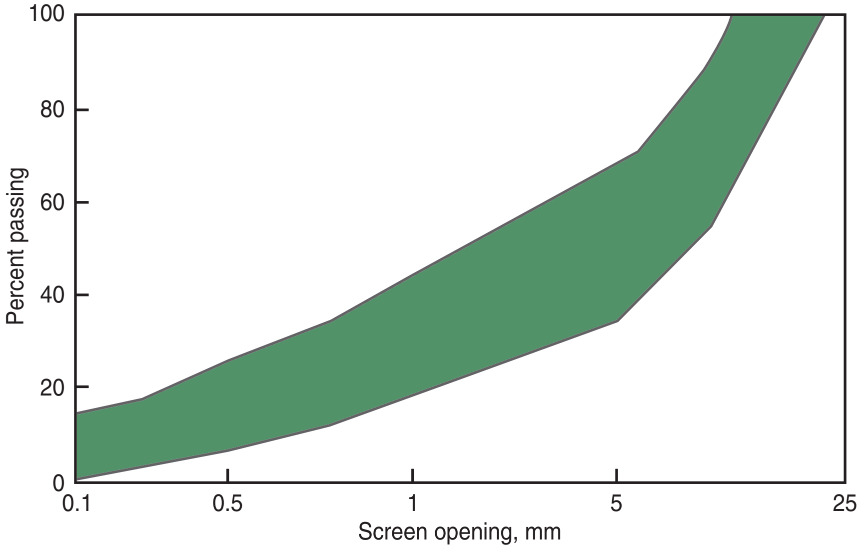


Figure 1.2. Aggregate gradation curves for roller-compacted concrete.[9]

Most authors agree that it is mostly the fine particles (i.e., < 75 µm or passing the #200 sieve) that affect the properties of RCC mixtures. It seems that the amount of these particles can influence significantly the workability of RCC and, subsequently, the consolidation process. Many authors argue that a high content in fine particles (higher than 11%) increases the mechanical strength and improves the surface texture.[3,9,12,13] Some authors recommend keeping the sand proportion around 50% of the total mass of dry aggregates and the fine particles content in the 5% to 10% range.[14,15] In order to increase the amount of fine particles, mineral admixtures such as fly ash and calcareous fillers sometimes are used as partial sand replacement.

1.1.1.2.2 Marginal Aggregates

Having noticed the beneficial effect of the addition of fine particles on the overall performance of RCC, many researchers have investigated the use of marginal materials as partial replacement of conventional aggregates. For instance, Nanni[16] studied the possibility of using low-quality aggregates, such as limestone crusher-run and tailings resulting from quarry screening operations, in RCC mixtures. In the laboratory, he prepared several RCC mixtures with various cement contents and coarse-to-fine aggregate ratios. The optimum water-cement ratio (or in that case, the optimum moisture content) of each mixture was selected according to the ASTM D 1157 – *Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort*.

This procedure routinely is used in soils testing and was recommended by the American Concrete Institute (ACI) for the mixture design of RCC pavements.[17] In all cases, the dry density of the samples was calculated and compressive strength measurements were carried out after 28 days of curing in water.

The most significant data obtained by Nanni are summarized in Figures 1.3 and 1.4. As can be seen in Figure 1.3, it appears that, regardless of the cement content, the mechanical strength of RCC increases with the amount of fine aggregates in the mixtures. In addition, the results in Figure 1.4 clearly indicate that the mixtures with crusher-run are superior to the ones prepared with continuously graded aggregates, and that the addition of tailings improves the strength (for the range of cement contents tested). Nanni concludes that RCC performance can significantly benefit from the use of some less expensive marginal aggregates.

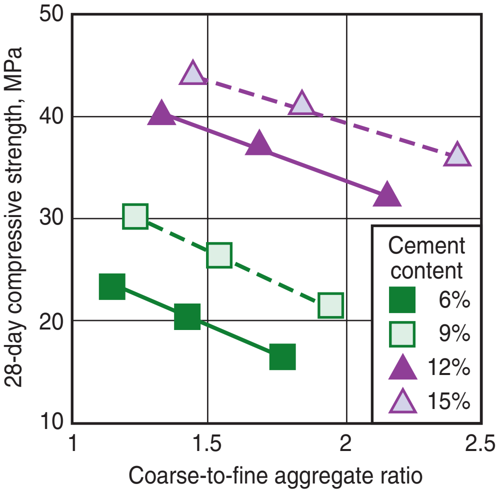


Figure 1.3. Influence of the fine content on the compressive strength.[16]

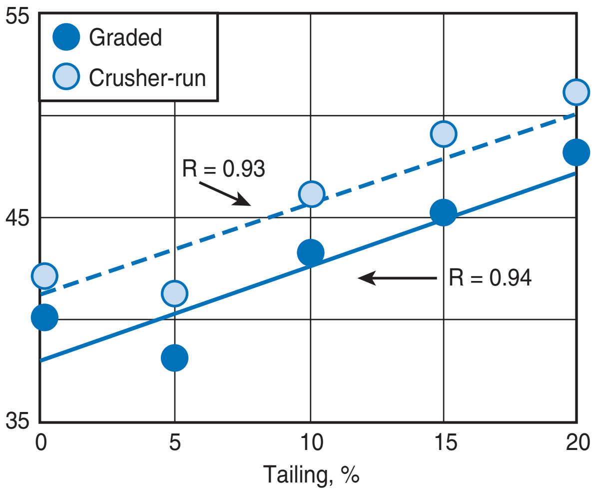


Figure 1.4. Influence of the type of aggregate and the tailing content on the compressive strength.[16]

The significant savings that can be made by using marginal aggregates and industrial by-products have prompted many authors to investigate the use of various materials in RCC pavements. The density and the mechanical strength of RCC made with marginal aggregates, such as all-in aggregate, shale, greywacke, dune sand, silt, and clay were studied in the laboratory by Haque,[18] and Haque and Ward.[19] Their test results indicate that most marginal aggregates, when compared to standard quality aggregates, require higher cement contents to achieve similar strengths.

The addition of various waste materials was studied in the late 1980's by many investigators. Numerous materials were found to be detrimental to RCC properties. Among the few successful experiences, the use of phosphogypsum powder, an industrial by-product composed mainly of dehydrate calcium sulfate, was found to be one of the most promising.[20]

The addition of these fine particles was found to improve the mixture compaction ability and the surface finish without being detrimental to the strength development. Phosphogypsum also was found to increase the setting time, thus allowing a greater period for construction and compensating for drying shrinkage.

Although most studies tend to indicate that substantial economies can be made by using marginal aggregates and industrial wastes, RCC pavement designers and producers should be careful when choosing the aggregates for their mixtures. Most of these investigations were carried out exclusively in the laboratory where only small quantities of aggregate are required. Since it is well known that the variability of aggregates during construction significantly can affect the performance of the final product, the supply consistency of such aggregates should be verified.

Although several methods have been suggested,[21,22,23] it has never been clearly demonstrated that any of them faithfully can reproduce field conditions. Moreover, it should always be kept in mind that it is often much easier to achieve high strength RCC in the controlled conditions of the laboratory than in the field where several unexpected factors can affect production and placement operations. Finally, it should be noted that the influence of marginal aggregates on the durability of RCC pavements in general, and on their frost and salt-scaling resistances in particular, never has been seriously investigated.

1.1.1.3 Chemical Admixtures

Although very few experiments have been reported on the influence of chemical admixtures, it seems that many of them can be useful to improve the properties of RCC.[17] Water-reducing admixtures and small dosages of superplasticizers have been used successfully to improve the homogeneity of the cement paste and to enhance the “plasticity” of the concrete mixture. However, the effect of water-reducers tends to decrease dramatically with the reduction of the water content. Furthermore, the ability of a water-reducing admixture to lower the water requirements appears to be somewhat dependent on the amount and type of aggregate finer than the No. 200, 75 µm, sieve.[8] The addition of a set-retarding admixture also can be effective for allowing a delay of the rolling process without the formation of cold joints. The use of air-entraining admixtures in RCC mixtures will be reviewed in detail later in this chapter.

1.1.2 Conventional Mixture Design Methods

There is actually no commonly accepted procedure to proportion RCC mixtures for pavement applications. Over the years, several methods using different approaches have been used successfully throughout the world.

Some were adapted from techniques specifically developed to design RCC mixtures for dam construction while others are more general and can be used to proportion RCC mixtures for paving applications. Most conventional RCC mixture-proportioning methods are essentially empirical procedures that require making a certain number of trial batches to obtain the optimum mixture proportions.

Regardless of the method, the design of a RCC mixture generally should meet the following requirements: 1) The type of cementitious materials and the total binder content should be such that the specified mechanical strengths are achieved at minimal cost. 2) The water-cement ratio (or the water content) should be adjusted in order to make the mixture suitable for compaction with a roller as well as to obtain the optimum density. Ideally, the water content should be kept just below a certain level at which rutting of the fresh concrete under vibratory rollers occurs and just above which the dryness of the mixture can cause an increase in segregation. The optimum water content is dependent on the aggregate used, the type of cementitious materials, and the binder content. 3) Finally, the coarse to fine aggregate proportion should be fixed to achieve the required density and to ensure a closed surface texture.

1.1.2.1 The ACI Mixture Proportioning Methods

In a survey of existing empirical methods specifically developed to proportion RCC mixtures, the ACI Committee 207 has divided the various procedures into three categories:[17]

- method for proportioning RCC to meet specified limits of workability;
- method for selecting mixture proportions to achieve the most economical aggregate-binder combination;
- method for designing RCC using soil compaction concepts.

In the methods falling in the first category, where RCC mixtures are proportioned to meet a specified consistency, the mixture characteristics generally are determined according to the following three-step procedure. To determine the minimum paste volume, a first series of trial mortar mixtures of various water-binder and sand-cement ratios is prepared and cast. In each case, the density of the mixture is measured. For a fixed water-binder ratio, there is a certain sand-binder ratio that gives an optimum mixture density.[24] The water-binder ratio is selected to meet the required mechanical strength. Once the water-binder and sand-cement ratios are determined, the coarse and fine aggregate proportions are adjusted to achieve a certain workability (Vebe time). This method is very similar to the one developed by Talbot and Richards in the early 1920's to design conventional concrete mixtures.[24]

The main difference is based on the fact that this ACI method relies on the combined use of vibration and compaction to consolidate the concrete mixture. Although the ACI procedure was developed mainly for proportioning mixtures for dam construction, it can be used to design mixtures for pavement applications.[25,26]

RCC mixtures also can be proportioned on the basis of cost.[17] In this second approach, the design is based mainly on suggested gradation curves to determine the fine to coarse aggregate proportion. Then, several trial mixtures with various binder contents are prepared and cast. In each case, the water content is adjusted to meet the workability requirements. Compressive strength measurements are made, and the most economical combination of cementitious materials and aggregates that provide the specified strength is selected. This procedure, mostly established for the design of dams, rarely is used to proportion RCC pavements.

Finally, RCC mixtures often are proportioned using traditional soil compaction procedures. This method is believed to be more appropriate for RCC pavement mixtures where smaller aggregates and higher binder contents are used.[17] Usually, the fine to coarse aggregate proportions are fixed according to suggested gradation curves.[9] Then, a series of concrete mixtures with various binder contents is prepared. The cementitious materials content may vary from 12% to 17% of the total mass of dry materials. For each series (i.e., for a fixed binder content), mixtures are prepared with different water contents. The optimum water content for each series is established by following the method described in ASTM D 1557. It involves determining the moisture content corresponding to the maximum "dry density" of the mixture using a Modified Proctor compaction procedure. Each mixture is compacted in a cylindrical mold with a specified energy. The mass of the compacted volume is measured, and the corresponding dry density is calculated. The peak of the density curve, as shown in Figure 1.5, indicates the maximum calculated dry density and the optimum moisture content. Usually the wet density changes very little in the range of this peak even though the calculated dry density is affected more significantly.[17] Compressive strength measurements are made on mixtures at optimum water content. The mixture with the minimum binder content that meets the specified strength is selected.

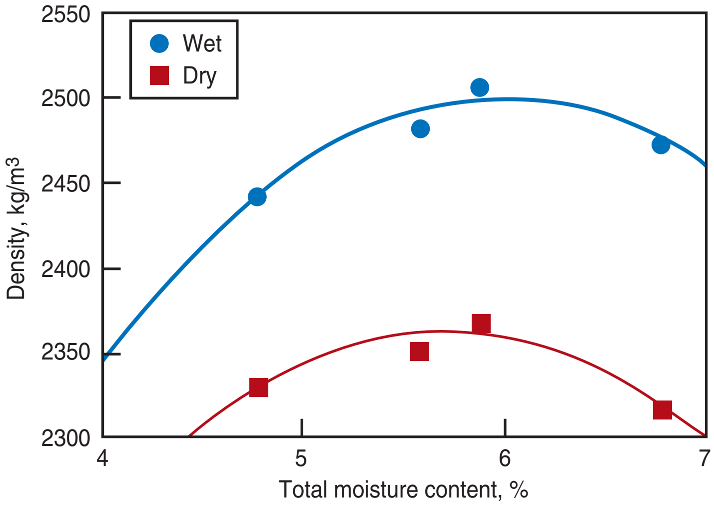


Figure 1.5. Typical moisture/density curves obtained for RCC mixtures.

The most popular of these three methods is the first one, which has proven to give good results in practice.[17,25] This method generally is considered to yield mixtures with optimum proportions (i.e., with the minimum binder content with respect to the given requirements). The mixture characteristics derived from the two other methods can be, in certain cases, far from the optimum proportions. The last two methods rely on tabulated grading curves to adjust the aggregate proportions of the mixture. These curves are average values obtained from a large number of experiments made using various types of aggregates. Recent studies clearly have shown that fine-coarse aggregate ratios determined on the basis of these tabulated grading curves do not yield the optimum packing density.[26,27] An inappropriate fine-coarse aggregate ratio can, in certain cases, contribute to artificially increasing the binder content of the mixture. This is particularly the case for RCC mixtures designed for pavement applications for which the mechanical strength requirements often prompt the concrete producer to use larger binder contents to achieve the specified values.

The main drawback of these empirical methods is that they are time consuming. All three procedures solely rely on the preparation of laboratory trial batches to determine the optimum mixture proportions. In some cases, as many as 25 trial batches are required to obtain one mixture design in the laboratory. In many cases, additional trial batches are required on site to adjust the workability of the mixture.[3,28] The mixing energy provided by a plant concrete mixer and pugmill mixer is generally much different from that of a laboratory pan-mixer, which tends to affect the initial workability of the mixture. Furthermore, the entire mixture design process may have to be repeated if, for some reason, the source of aggregates (fine or coarse) or the type of binder is changed during the course of the project.

1.1.2.2 The U.S. Army Corps of Engineers Proportioning Method

The U.S. Army Corps of Engineers method can be used to proportion RCC for dams or other types of massive structures.[29,30] The method is basically a step-by-step process that helps determine some mixture design parameters (water-cementitious material ratio, binder content, aggregate grading, volumetric fractions of coarse and fine aggregates) in order to achieve any strength, workability, or durability requirements. Suggested values for these design parameters are based essentially on past experience and empirical relations.

The U.S. Army Corps of Engineers method may be summarized as follows. The first step involves the selection of the aggregate proportions. Ideal grading curves for both coarse and fine aggregates are proposed. The fine to total aggregate ratio can be selected from tabulated values that are functions of the nominal maximum size and type of coarse aggregate. The second step consists in selecting the water-binder ratio on the durability and strength criteria. The selection of the water-binder ratio, that should match the short- and long-term strength requirements, is based on empirical relationships. The next step consists of selecting the water content from suggested values that depend on the required modified VEBE time and on the maximum nominal size of the coarse aggregate. Finally, the total binder content is computed from the water content and the water-cement ratio.

According to the U.S. Army Corps of Engineers guidelines, the mortar content must be within specified limits that depend on the nominal maximum size and type of the coarse aggregate. If necessary, the fine aggregate content can be adjusted to approach the recommended average value for mortar content. A minimum volumetric paste-mortar ratio of

0.42 is recommended for all types of RCC mixtures. If necessary, the volume of cementitious material, the volume of filler material (less than 75 µm), or the volume of water should be increased to achieve this minimum ratio.

Some trial batches generally are required to adjust the final mixture design to satisfy workability (VEBE time) and strength requirements. Adjustments of the paste volume are generally required to obtain the specified workability (VEBE time). Additional batches with lower and higher water-binder ratios also may be needed to select the final mixture proportions to satisfy the strength requirement.

The method can be considered as semiempirical since it does not rely solely on the preparation of trial batches to proportion the RCC mixture. The main drawback of the method is that it relies on tabulated grading curves to determine the fine-coarse aggregate ratio of the mixture. For the reasons mentioned above, the use of these empirical curves might give inappropriate ratios.

Furthermore, the method can, in certain cases, be as time-consuming as the fully empirical procedures since trial batches always are needed to adjust the workability. Workability is a key parameter controlling many important properties of RCC (compaction, strength, permeability, segregation, bonding between layers). Depending on the source of aggregates, the number of laboratory batches required to obtain the right workability can be quite important. Recent studies clearly have demonstrated that for a given paste volume, the workability (VEBE time) is very sensitive to grading, shape, and surface texture of the aggregates, particularly to the physical characteristics of the fine aggregate.[31,32] Depending on the shape and the surface texture of the aggregates, the VEBE time of a RCC mixture can increase, and even double.

1.1.3 Production of RCC

RCC production requires a vigorous mixing action to disperse the relatively small amount of water evenly mixed throughout the matrix. The concrete production can be accomplished successfully using either a continuous flow pugmill mixer or a central mix concrete batch plant.[8] These two methods are presented in the next paragraphs. RCC also can be produced in transit mixers. However, the homogeneity of the mixture has to be controlled carefully when using such mixers.

1.1.3.1 Production Using Continuous-Flow Pugmill Mixer

In Canada and in the United States, RCC typically is mixed in continuous-flow pugmill mixers such as those used for asphalt concrete construction. A schematic illustration of a pugmill is given in Figure 1.6. Mixers of this type are known to provide a vigorous mixing action that facilitates the homogeneous dispersion of the water throughout the mixture.[30] The main advantage of pugmill mixers is the fast production rate, since they can produce 200 to 250 tons of RCC per hour. They are usually relatively easy to transport to construction sites, which contributes to reducing RCC transportation delays. The only drawback of such units is that the continuous process prevents any modification of the mixing sequence. It is, for instance, impossible to premix the mortar fraction of the

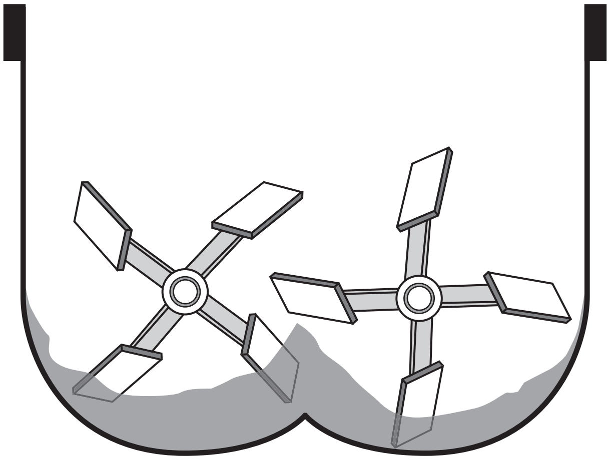


Figure 1.6. Pugmill mixer.[26]

mixture with the chemical admixtures to fluidify the paste or entrain air. Pugmills are more adapted for large jobs where important RCC volumes require high production rates.

1.1.3.2 Production Using Central Mix Concrete Batch Plant

For smaller jobs, where high production rates are less important, RCC can be produced in central mix concrete batch plants. Before selecting this type of mixer, producers should consider that the production rate of RCC in these plants is significantly slower than that of regular concrete.[3] Given the reduced water content of RCC and its low workability, the mixer only can be filled with about half to three-quarters of the normal quantity to ensure homogeneous mixing. For similar reasons, mixing time often has to be extended. Since the quality of most dry concrete mixtures is particularly sensitive to any modification of the water content, alternating the RCC production with other types of concrete should be avoided as much as possible. The main advantage of central mix concrete batch plants is that the mixing sequence usually can be modified to allow the premixing of the mortar fraction of the mixture with the chemical admixtures. Although this procedure tends to further increase the mixing time, it facilitates the production of a homogeneous mixture. Furthermore central mix concrete batch plants are used by most producers and are therefore more readily available for the production of RCC.

1.1.4 Construction

In the past few years, the growing demand for RCC has pushed contractors to significantly improve construction techniques and quality control procedures. These recent developments have been extensively discussed in the specialized literature. The purpose of this section is to describe briefly the different steps involved in the construction of RCC pavements. Emphasis will be put on the operations of RCC placement that are likely to affect the performance and durability of the pavements.

1.1.4.1 Transportation

After mixing, RCC is hauled from the batching plant to the construction site in ordinary dump trucks (Figure 1.7). Special care should be taken to avoid segregation during unloading operations from the mixer to the truck. In order to avoid any risk of premature setting, transportation time should not exceed 60 minutes even if a retarding admixture has been added to the mixture. Transportation also should be planned so that any unnecessary delays are avoided on the site. Trucks should be equipped with a tarp to limit evaporation of water during transportation.

Figure 1.7. Dump trucks for transportation. (IMG15514)

1.1.4.2 Placement

On site, placement of RCC can be performed with a conventional asphalt paver (Figure 1.8) or a high-density paver (Figure 1.9). Graders are used in certain cases. However, it is usually harder to achieve a high quality surface when placement is carried out with graders since lamination of the upper part of the pavement sometimes occurs, and more surface waving problems are generally encountered. The use of a grader should be limited to the placement of bottom layers or in areas with restricted access.

Quality RCC placement usually is carried out with asphalt pavers. These tend to provide a more uniform thickness and an improved surface smoothness. When available, pavers equipped with a tamping screed are preferred to those equipped with a vibrating screed since they tend to achieve a higher degree of consolidation and reduce surface waving problems during compaction operations. However, the increased compaction capacity of the pavers equipped with one or more tamping bars (in addition to vibrating screeds) has been suggested as the cause of a network of interconnected superficial cracks sometimes observed in the pavement surface directly behind the heavy-duty screeds.[8] The formation of these cracks seems to be related to the moisture content of the RCC mixture and the amount of pressure applied by the screed to the surface. However, these cracks may be removed partially or totally during the rolling process. During placement, the thickness of the layer should be increased by 15% to 25% so that the right pavement thickness will be obtained after compaction. For high capacity pavers equipped with dual tamping bars, the thickness of the layer may be increased up to 10%.

Figure 1.8. Conventional paver. (IMG15515)

More recently introduced, high-density asphalt pavers have high capacities (about 150 m^3 per hour) and usually can place 300-mm thick layers. However, as pointed out by Nanni et al.,[33] the placement of RCC should be done in two or more lifts for pavements thicker than 250 mm. The introduction of high-density asphalt paving machines to place and compact the RCC mixture has been the single most significant factor to influence RCC pavement construction according to Piggott.[34] RCC pavements with riding qualities equal to conventional concrete and asphalt pavements have been built.

In the past decade, improved paving equipment has been introduced on the market.[35] These new pavers, mainly manufactured by European makers, primarily have been developed for asphalt placement and compaction. They usually are equipped with a high compaction screed, several pressure bars, and two vibrating plates. Small modifications are needed to fully adapt the paver to the placement of dry concrete mixtures.

The major improvement of these pavers is that they are so efficient that it is possible to pave and fully compact the concrete with the paver alone; hence the name suggested by Bager:[36] “Paver Compacted Concrete – PCC.” Thereby a large obstacle toward using RCC for road pavements without a regulating asphalt overlay seems to be overcome.

Although the cost of these new paving machines is significantly higher than that of ordinary pavers, substantial savings can be made during placement operations since no roller is required to achieve the final consolidation of the concrete. In addition, the introduction of these pavers significantly expands the market for compacted concrete pavements. It previously was limited to heavy-duty applications, due to the unevenness of the concrete surface.

Figure 1.9. High-capacity ABG paver. (IMG15516)

1.1.4.3 Consolidation

Compaction should begin immediately after the placement of the fresh RCC. Primary consolidation operations are carried out by heavy dual-drum rollers having a static line load of 15 to 30 kN/m^3. Rollers (Figure 1.10) can be used either in the vibratory or the static mode but their speed should be limited to 3 km/h to preserve the evenness of the surface. Customarily, 4 to 10 passes of the roller are needed to achieve the required density. For a higher quality texture, the dual-drum roller may be followed by a heavy rubber-tired roller that will tighten the surface. Roller marks left on the surface can be removed by a light static dual-drum roller.[15]

At the end of the consolidation operations, the concrete layer must have a degree of compaction of at least 98% of the optimum Modified Proctor density, as previously determined in the laboratory. However, the number of passes of the different rollers should be limited as much as possible to avoid any overworking of the surface.

The degree of compaction in the field usually is verified using a nuclear density meter. The great advantage of this radioactive isotope meter is that it quickly can monitor the moisture content and the density, wet and dry, of the fresh concrete at different depths.

When well calibrated, these meters tend to give reliable and consistent wet density measurements. Dry density measurements should however be considered very carefully, since nuclear density meters are not very accurate when measuring the concrete moisture content. More accurate water contents can be obtained from the conventional oven drying method.

Figure 1.10. Dual-drum roller. (IMG15517)

1.1.4.4 Curing Procedures

Given the low water content of RCC, proper curing is particularly necessary to prevent the loss of surface moisture. To be effective, curing treatments should begin right after the consolidation operations. Any delays generally result in dusting of the surface with subsequent loss of cement particles and fine aggregates. Both water curing and curing compounds successfully have been used. If water curing is selected, a minimum period of 7 days of continuous treatment is recommended. In the first 24 hours, special care should be taken to prevent washing out of the cement particles. A water truck equipped with a spray bar commonly is used to keep the surface moist on the first day, after which an irrigation sprinkler system, wetted burlap, or continued use of the water truck is applied to keep the surface moist for the rest of the curing period.[8] Most of the time, it is more practical and often less expensive to cover the surface with a curing compound. To prevent any loss of moisture, the curing compound should be applied in two directions (i.e., two coverages), and the doubled quantity recommended by the manufacturer should be used, which is often not the case for conventional concrete. Failure to spray a sufficient amount of curing compound inevitably will result in a premature drying of the top part of the pavement and in subsequent reduced resistance to abrasion and salt-scaling.

1.1.5 Typical Applications

RCC first was used to build dams. Besides the reduced construction costs resulting mainly from labor and equipment savings,[37-39] its principal advantage for mass construction is the low cement content of the mixture which greatly reduces problems due to the heat of hydration of cement.[40,44] Since the completion in 1982 of the first two major RCC projects, i.e., the Shimajigawa Dam in Japan and the Willow Creek Dam in United States, the technique has gained wide acceptance throughout the world. At the beginning of the last decade, more than 40 major projects had been completed worldwide and more than 40 other RCC dams were constructed.[42]

Also attracted by the significant construction cost savings, road contractors rapidly adapted the technique to their needs. As with dam construction, the method offers the advantage of rapid production rates with readily available equipment and the need for a limited technical crew. Considered as a high-strength concrete pavement well adapted for heavy-duty applications, RCC gradually has been viewed by many road designers as an interesting alternative to conventional portland cement concrete and asphalt pavements.

Even if its share of the global road-construction market is still extremely low in North America, RCC is now commonly accepted as an unsurfaced pavement for the construction of truck and aircraft parking areas, container ports, haul roads and hard-stands for tracked vehicles.[9,43] Overtopped with an asphaltic hot mixture, RCC also can serve as a rigid foundation for secondary city streets.[44]

In 1998, it was estimated that more than 140 RCC pavements projects had been constructed in North America.[34] In a recent survey by the Cement Association of Canada,[45] well over 125 RCC pavements were completed in the province of Quebec from June 1995 to November 2002, with surface areas ranging from 1000 to 87,000 m^2. An overview of some major RCC pavement projects completed in North America between 1986 and 1996 is given in Table 1.1.[9,12,34,34]

Table 1.1. Some Major North American RCC Paving Projects

Project	Year	Thickness, mm	Total surface area, m^2
Burlington. Northern Santa Fe (Denver,CO, USA)	1986	375–500	105,350
Fort Drum (New York, NY, USA)	1988	250	360,000
Saturn Corporation (Spring Hill, TN, USA)	1989	180	543,000
Andrews Air Force Base (Washington, DC, USA)	1989	360	84,000
Safeway Store Inc. (Tracy, CA, USA)	1992	200	226,000
Alberta Pacific Forest Ind. (Arthabaska, AB, Canada)	1992/93	200–350	47,000
Domtar Papers Inc. (Windsor, QC, Canada)	1996	300	87,000

1.2. RECENT DEVELOPMENTS

This section briefly presents the recent developments in the mixture proportioning methods, the use of high-performance RCC and the design of low-binder-content RCC.

1.2.1 New Mixture Design Methods

As noted under Conventional Mixture Design Methods earlier, most RCC mixture proportioning methods are essentially empirical procedures that often require the production of numerous trial batches to obtain the optimum mixture proportion. In order to overcome this problem, more theoretical methods recently have been introduced. These methods are based on a better understanding of the parameters that affect the fresh and hardened properties of RCC. For these methods, the number of trial batches required to achieve the optimum mixture proportions generally is limited. Two of these new mixture design methods are presented briefly in the next paragraphs.

1.2.1.1 The Optimal Paste Volume Method

The optimal paste volume method was developed to design RCC mixtures for the construction of massive structures.[47] The method is based on the concept that an optimal RCC should have just enough paste to completely fill the interparticle spaces remaining when the granular skeleton has reached its maximum density under compaction. If less paste is used, the voids remaining after compaction may reduce the mechanical properties and increase the permeability.

The method includes three major steps. The first step is to select an aggregate grading that contains a minimal volume of voids under a given compaction energy. The volume of remaining voids per cubic meter of compacted aggregate then is used to determine the paste volume. The final step consists of selecting the water-cement ratio and the proportions of cement and pozzolanic materials to produce a paste with enough binding capacity to satisfy the strength requirements.

1.2.1.2 The Solid Suspension Model

In recent years, the field of concrete mixture design has undergone rapid developments. One of the major breakthroughs in this field is the introduction of theoretical methods that permit the design of concrete with optimum packing densities.[47]

One of the most promising methods is the one developed by de Larrard and his co-workers.[48,49] This model is an improved version of a previous method, which originally had been developed to design high-performance concrete mixtures.[50] The solid suspension model has been adapted and tested with success, in the laboratory, to design RCC mixtures for both dam and pavement applications.[26,27] It also has been used to proportion high-performance mixtures for the construction of full-scale RCC projects in eastern Canada.

Basically, the model can be used to predict the packing density of an arrangement of grains of various diameters d_i ($d_1 > d_2 > d_n$) on the basis of:

1. the intrinsic packing density ($\propto_i$) of each class of grains (i.e., the packing density of an arrangement of grains of similar diameter d_i);
2. the mass proportion y_i of each class of grains (expressed as a ratio of the total solid volume).

The solid suspension model is derived from the work of Monney on the viscosity of concentrated suspension of solid particles.[48,49] The solid suspension model rests on the assumption that the reference relative viscosity (η_r*) of an arrangement of grains, consolidated by any type of technique, has a finite value. For a unimodal arrangement of grains of diameter d_i, the reference relative viscosity can be calculated using the following equation:

$$\eta^{*}_{r,i} = \exp\left(\frac{2.5}{\frac{1}{\alpha_i} - \frac{1}{\beta_i}}\right) \qquad \text{[Equation 1]}$$

where β_i stands for the intrinsic virtual packing density of the class of grains (i). It can be demonstrated theoretically that, if someone were to place one by one a certain number of spherical grains, the packing density of this ideal arrangement would reach 0.74 (β_i = 0.74). However, such an arrangement is unachievable in practice. This is why β_i is termed the virtual packing density. It also can be shown that, in practice, the optimum packing density of spherical particles hardly can be higher than 0.64 ($\propto_i$ = 0.64). If the values of β_i and $\propto_i$ are placed in Equation 1, it can be seen that the maximum relative viscosity ($\eta_{r,i}$*) of the class of spherical particles is 136,000.

In practice, the actual values of $\propto_i$ for each class of grains easily can be determined experimentally.[49,50] For aggregate particles, this can be done simply by measuring the packing density of each size fraction using the VEBE apparatus. For powders such as cement, fly ash, and mineral fillers, an experimental method has been prepared to measure the value of $\propto_i$. This method consists of placing a certain amount of water in a mortar mixer. The value of $\propto_i$ is obtained when the amount of water is sufficient to pass from a dry cement to a plastic paste. Assuming that the maximum relative viscosity ($\eta_{r,i}$*) is similar to that of an arrangement of spherical particles and is equal to 136,000 (8000 for powders), the value of β_i can be computed from Equation 1 for each class of grains.

Once the values of β_i have been determined for each class of grains, the virtual packing density (γ) of the arrangement of grains can be obtained from the following relationship:

γ = the lowest value of all

$\gamma_i \neq 0$

and the value of each γ_i can be computed using the following equation:

$$\gamma_i = \frac{\beta_i}{1 - \sum_{j-1}^{i-1}\left(1 - \beta_i + b_{ij}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right)y_i - \sum_{j=i+1}^{n}\left(1 - a_{ij}\left(\frac{\beta_i}{\beta_j}\right)\right)y_j} \qquad \text{[Equation 2]}$$

In the previous equation, γ_i corresponds to the mass proportion of each class of grains. The value of y_i can be obtained on the basis of the grading curve of each material. For aggregates, these curves can be obtained by the usual method. For powders, it requires the use of a laser apparatus.

Equation 2 takes into account the various interactions that can take place between grains of various sizes. For instance, small grains can contribute to decreasing the packing density of larger grains. The parameter a_{ij} in of Equation 2 takes into account this effect. Similarly, large grains also can reduce the packing density of smaller grains. The latter is known as the wall effect. The latter is taken into account by the variable b_{ij}.

Once the virtual packing density (γ) of the mixture is known, one can calculate the "real" packing density (c) of the mixture on the basis Equation 3.

$$\eta_r^* = \exp\left(\sum_{i=1}^{n} \frac{2.5\, y_i}{\frac{1}{C} - \frac{1}{\gamma_i}} \right) \qquad \text{[Equation 3]}$$

In order to use this equation, one has to assume a certain value for the reference relative viscosity (η_r*) for the mixture. For conventional concrete, the notion of viscosity can be more or less directly linked to that of the mixture workability. For no-slump concretes, such as RCC, the application of the notion of viscosity is more ambiguous. Experience has shown that the value η_r* can be quite variable from one RCC application to another. RCC mixtures for dam construction (that have to be designed with a VEBE time of approximately 15 seconds) should be proportioned with a value of η_r* that is much different than that of RCC mixtures used for pavement applications. The value of η_r* has to be set on the basis of previous experience.

The optimum proportion of a given RCC mixture can be obtained by trial and error or by using a numerical algorithm. All this procedure is arduous but with the use of a computer and a simple worksheet the whole calculation is simple.

Systematic use of the solid suspension model has shown that it yields very similar results to that obtained with the ACI empirical method.[26,27] The model can be used to design RCC mixtures for any type of application and does not require making a large number of laboratory trial batches. The main advantage of the model is that it can be used to recalculate very quickly the optimum proportions of an RCC mixture. As previously mentioned, this can be of great help on the construction site where the source of aggregates or the type of binder may change on short notice.

1.2.2 High-Performance RCC

As previously emphasized, RCC is used increasingly for the construction of industrial pavements exposed to very severe loading and environmental conditions. Under such conditions, RCC mixtures often must be designed to develop compressive and flexural strengths as high as 40 MPa and 5 MPa, respectively, after only 7 days.[46] The development of such high compressive and flexural strengths requires the design of high-performance RCC mixtures. By optimizing the packing density of RCC mixtures (using the suspension model presented in the previous subsection) and by using a silica fume blended cement, it is possible to produce high-performance RCC.[46] The use of silica fume improves the mechanical properties of RCC and favors its early strength development. Furthermore, according to Pigeon and Marchand,[51] the use of silica fume increases freeze-thaw durability and deicer salt-scaling resistance of RCC.

A typical high-performance RCC[†] mixture composition is given in Table 1.2. This RCC mixture, optimized using the solid suspension model, was used to produce an 87,000 m^2 high-performance roller compacted concrete log yard at the Windsor Mill complex of Domtar Papers (located 150 km southeast of Montreal). The compressive strength developed by this RCC mixture after 28 days was more than 50 MPa. The flexural strength developed was 8.1 MPa after 28 days.

Table 1.2. Typical High-Performance RCC Mixture Composition[46]

Type 10 SF cement, kg/m^3	Water, kg/m^3	Fine aggregates 0.5 mm, kg/m^3	Coarse aggregates 5-20 mm, kg/m^3	Water reducer admixture, ml/kg of binder
295	103	774	1347	4

1.2.3 Low-Binder-Content RCC

Roller-compacted concrete mixtures often are designed using relatively high binder contents (approximately 300 kg/m^3). For the construction of RCC pavements in urban areas and low traffic roads, these binder contents seem to be high and are not always justified.[7] The mechanical strengths needed for these types of pavements are lower than those required for industrial pavements. Furthermore, RCC production and placing operations in these areas have to be an economical alternative since RCC is in direct competition with asphalt concrete and often other low-cost materials.

The development of RCC mixtures specifically adapted to the construction of low-traffic pavements has been investigated recently by Reid et al.[7] The main objective of the project was to confirm the possibility of using the high-performance RCC mixture design methods for the production of low-binder content RCC with good mechanical properties and an excellent resistance to freezing and thawing cycles. RCC mixtures with binder content ranging from 175 kg/m^3 to 225 kg/m^3 were prepared and tested under laboratory conditions. The results of this investigation indicated that the design of low-binder content RCC mixtures, according to the optimized packing density method, allows the production of concrete with very interesting mechanical properties: Compressive strength

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[†] *Typically, high-performance RCC is defined by a compressive strength higher than or equal to 40 MPa after 7 days and a flexural strength higher than or equal to 5 MPa after 7 days.*

and flexural strength as high as 50 MPa and 5.7 MPa respectively were obtained after 7 days of curing. However, it is important to underline that the production of RCC mixtures with low-binder content can decrease significantly the strength of the materials if the packing density of the mixture is not correctly optimized.[7]

From a durability point of view, all RCC mixtures, including those produced without any air-entraining agent, had low drying shrinkage and were found to still have an excellent frost durability after 300 freeze-thaw cycles.

1.3. FROST DURABILITY OF RCC PAVEMENTS

The necessity of air entrainment for an adequate frost protection of RCC pavement has been a subject of primary concern for engineers. Much of this situation originates from the fact that only a few investigations have been carried out up to now to evaluate the frost durability of RCC pavements. Although a great deal of effort has been made lately toward designing new test procedures to evaluate the frost resistance of these materials, few laboratory data are presently available, and reports on field performance remain unfortunately limited.

RCC pavements, like all other types of concrete elements, can be subjected to two types of deterioration due to frost: internal cracking and surface scaling. In service, each type of damage can occur separately, but, in some cases, certain concrete elements can be exposed to the combined action of the two aggressions. It is then difficult to distinguish the two effects. However, since most authors agree to make a clear distinction between the two types of aggression, and considering that most laboratory test procedures are designed to study each mechanism independently, information concerning these two phenomena will be presented separately.

1.3.1 Resistance to Internal Microcracking

Internal microcracking generally is associated with the bulk destruction of a water-saturated concrete element subjected to repeated cycles of freezing and thawing. The ability of concrete to resist frost-induced microcracking usually is determined in the laboratory using the procedure described in the ASTM Standard C 666 – *Resistance of Concrete to Rapid Freezing and Thawing*.

There is very little published data on the freezing and thawing durability of RCC pavements. This lack of interest probably can be explained by the fact that pure freezing and thawing cases are rare in the field where most structures are more likely to be subjected to freezing in the presence of deicer salts.

As part of a laboratory study of the engineering properties of RCC pavements, Gomez-Dominguez[25] analyzed the influence of air entrainment on frost durability. Several concrete mixtures were prepared with various water-cement ratios (w/c = 0.30, 0.40 and 0.50), and with and without an air-entraining admixture. The efficiency of three air-entraining agents was studied. The mixing sequence was altered in order to entrain spherical air bubbles. The frost durability of all concrete mixtures was determined after

28 days of water curing in accordance with ASTM C 666. Some mixtures were tested according to Procedure A (freezing in water) while others were tested according to Procedure B (freezing in air). The deterioration of the specimens was evaluated by monitoring the pulse velocity changes during the test. Although all mixtures showed significant signs of deterioration (none had a durability factor over 70% after 300 freezing and thawing cycles), the author concludes that the addition of an air-entraining agent had a positive effect since the air-entrained mixtures withstood without damage more cycles of freezing and thawing than their companion plain mixtures. Test results indicate no significant influence of the type of air-entraining admixture.

In a survey conducted for the U.S. Army Corps of Engineers, Ragan[52] studied the frost durability of nine RCC pavements made between 1976 and 1985. Specimens were sawed from the various pavements and submitted to freezing and thawing cycles in accordance with ASTM C 666 – Procedure A. The frost durability of two series of laboratory-fabricated specimens also was investigated according to the same test method. In all cases, the air-void characteristics of the different concrete mixtures were determined in accordance with ASTM C 457 – *Microscopic Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete*. The main conclusion of this study was that the frost durability of RCC is related directly to the air-void spacing factor. As shown in Figure 1.11, the value required for good concrete durability was evaluated to be apagesroximately 250 µm. Since an air-entraining agent had been added to only two of these mixtures and because no significant amount of air bubbles was found during the microscopic examinations, the results of these tests tend to indicate that the compaction air-void system in RCC pavements can offer the same protection against frost action as entrained air-voids. Furthermore, in a laboratory investigation of the influence of two

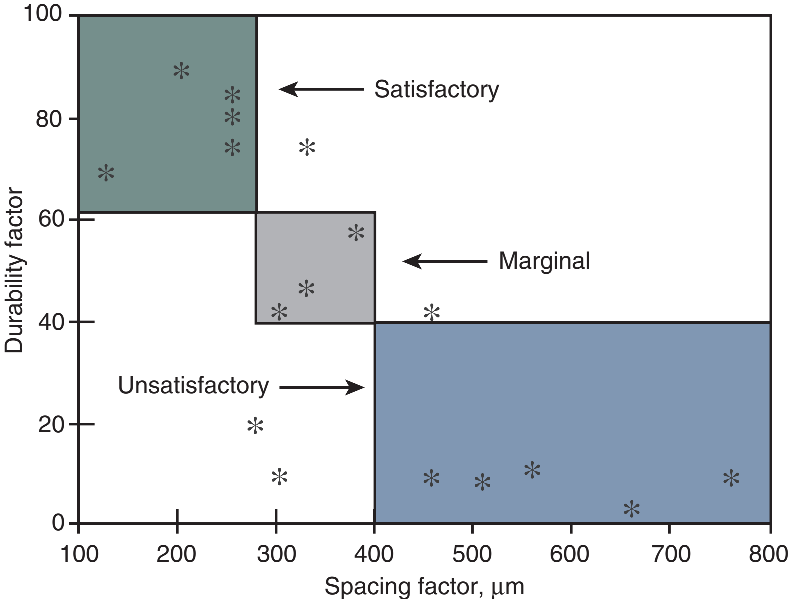

Figure 1.11. Durability factor versus the spacing factor.[52]

Canadian fly ashes on the engineering properties of lean RCC mixtures, Joshi and Natt reached similar conclusions.[53] Their test results showed that non-air-entrained RCC can be, to a certain degree, resistant to frost-induced microcracking. Another investigation conducted by Ghafoori and Cai[54] also has shown that non-air-entrained RCC can perform well in an environment with repeated freezing and thawing cycles. Their investigation was conducted on laboratory-made RCC containing pulverized coal combustion high-calcium dry bottom ash as fine aggregate.

However, some other investigations have shown that an air-entraining agent should be used to produce durable RCC mixtures (see, for instance, Guiraud and Pigeon[55]). In their research project, Guiraud and Pigeon observed that laboratory-fabricated RCC mixtures (prepared with normal portland cement at water-cement ratios ranging from 0.35 to 0.80) were generally more frost durable when an air-entraining agent was used. The results of two studies reported by ACI Committee 325[8] also have shown that generally laboratory-made RCC mixtures which do not contain an air-entraining agent were susceptible to damage due to freezing and thawing cycles, and those containing an air-entraining agent were not susceptible to frost damage. There were, however, some exceptions to both cases.

Frost durability of RCC pavements also was recently investigated at Laval University in Canada. During a four-year research project, more than a thousand cubic meters of RCC were produced and cast under field conditions by Pigeon and Marchand.[51] Each year, after the casting and curing operation, hardened concrete cores were transported to Laval University to be sawed and subsequently tested. Many freezing and thawing tests were performed in the first three years of the project. Many parameters, such as the type of binder, the water-cement ratio, air-entrainment, and aggregate grading were investigated.

The experimental results obtained by Pigeon and Marchand have shown that most mixtures of the first and third years withstood 300 cycles of freezing and thawing (according to ASTM C 666) without any important deterioration. According to the authors, the poor frost resistance of the second year RCC pavements has emphasized the importance of achieving a sufficient degree of compaction to produce frost-resistant RCC pavements (most mixtures of the second year had a degree of compaction below 98% of the optimum Proctor density). Test results also have shown that several non-air-entrained mixtures withstand 300 cycles of freezing and thawing without any deterioration. This tends to suggest that some compaction air-voids probably can act as air bubbles. As pointed out by Pigeon and Marchand, the positive influence of compaction voids on frost resistance should not be emphasized too much. In many cases, the length change after 300 cycles was not very important though higher than 200 µm/m and therefore probably indicating that some microcracking had occurred. In addition, several mixtures were quite severely damaged after 450 cycles.

1.3.2 Resistance to Deicer Salt-Scaling

In most Nordic countries, the chloride-induced deterioration of many concrete structures is a matter of growing concern. The widespread use of deicing salts during winter roadway maintenance operations is known to increase significantly the damage caused by repeated freezing and thawing cycles. Since many RCC pavements are susceptible to exposure to deicer salts, their scaling resistance is of primary importance and often is considered by many potential users as an acceptability criterion.

Investigations into the salt-scaling resistance of RCC pavements are very limited in the technical literature. This can be explained partly by the fact that the introduction of this technology is relatively recent (for instance, the first RCC pavement was built in 1976 in Canada). Moreover, very few RCC pavements have been constructed in cold climate regions. The need for information on the salt-scaling behavior of such pavements was therefore less urgent.

In a study on the performance of various mixtures, Andersson[56] reported that air-entrained RCC could have a good salt-scaling resistance. He noted that a good compaction (i.e., over 97% of the optimum Proctor density) was needed to ensure the durability of RCC, and that the addition of silica fume was highly beneficial. However, mixtures with fly ash were not found to be durable. Good compaction also has been pointed out by Todres[57] to have a marked effect on resistance of RCC pavements to salt-scaling. Horrigmoe and Brox Rindal came to the same conclusion as Andersson concerning the addition of silica fume on salt-scaling resistance of RCC.[58] In their investigation, they noted that the addition of silica fume and the use of an air-entraining agent had led to a significant improvement of the frost durability of their mixtures (see Figure 1.12). It is important to underline that, with the exception of the investigation conducted by Todres, testing was performed only on sawed surfaces. The structure of the top layers in RCC is influenced by the rolling operations, and deicer salt-scaling tests on the rolled surface could yield different results.

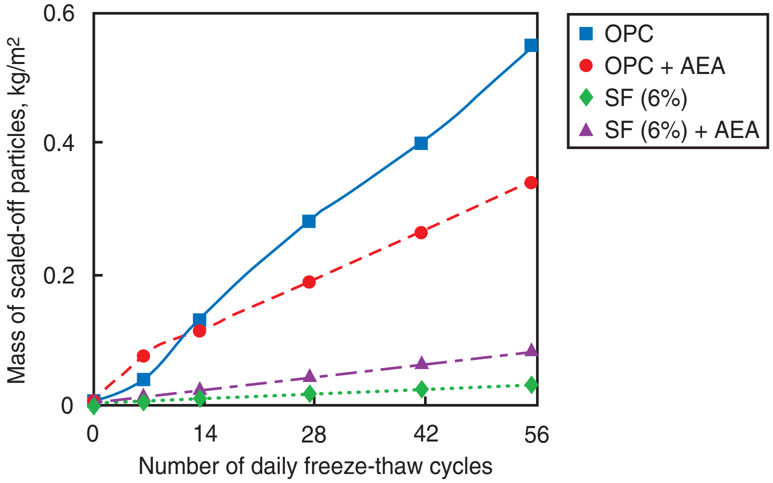

Figure 1.12. Influence of the addition of silica fume and an air-entraining agent on the deicer salt-scaling resistance of concrete.[58]

It has been shown very clearly that surface scaling is related not only to the global quality and properties of the concrete but also to the internal structure of the layers just below the concrete surface.[34,59] In certain cases, for reasons that are not yet quite clear, the top layers of normal good quality air-entrained mixtures are more porous and thus very susceptible to scaling.[60] For conventional concrete, scaling resistance appears to be related directly to the permeability of the surface, probably since more permeable surfaces get critically saturated more easily.[61] The data recently published on the scaling resistance of RCC also tend to confirm the influence of the permeability of the surface layers on scaling. Numerous recommendations such as, low water-cement ratio, good compaction, and addition of mineral additives improve the concrete permeability and potentially the salt-scaling resistance. In addition to those recommendations, an RCC mixture containing a sufficiently large volume fraction of mortar must be used to obtain a salt-scaling resistant surface. The large volume fraction of mortar is necessary to obtain a so-called closed surface (i.e., a surface with no apparent large compaction voids). However, it is not obvious that all the previous guidelines are sufficient to produce durable RCC pavements. Given the limited number of investigations carried out on the subject, many questions remain unanswered.

In order to better understand the mechanisms of salt-scaling in RCC pavements, Delagrave et al.[62] have published the results of an investigation carried out to study the deicer salt-scaling durability of RCC produced and placed under field conditions. For this project, a 1-km road section with four different mixtures was constructed near Montreal (Québec, Canada) in July 1990. This road section was divided into four 250-m-long, 6-m-wide, test sections. Each section was built with a different mixture (see Table 1.3). Two different binders (a blended silica fume cement and an ordinary portland cement with 20% fly ash), and two binder contents (250 kg/m^3 and 300 kg/m^3) were used. An air-entraining agent was added to three of the four mixtures. All concretes were prepared with the same coarse and fine aggregates. Two different membrane forming curing compounds were used.

Table 1.3. Mixture Compositions

Mixture	Binder, kg/m^3	Water, kg/m^3	Fine aggregate, kg/m^3	Coarse aggregate, kg/m^3	AEA, ml/m^3	WRA, ml/m^3
OPC + Class F fly ash						
1-FA-1A	300+60	105	1015	1000	1000	960
Blended silica fume cement						
2-SF2A	250	90	1130	1070	1000	960
3-SF1A	300	105	1075	1000	1000	960
4-SF1N	300	105	1075	1000	n/a	960

The results of the deicer salt-scaling tests, which were performed on the rolled surfaces (in accordance with ASTM C 672 standard) are presented in Figure 1.12. This figure gives the mass of scaled-off particles after 50 cycles for each set of two specimens tested. For each mixture, the average test result was calculated for each curing compound (see Table 1.4). In most cases, the mass of scaled-off particles after 50 cycles exceeded the usual limit of 1 kg/m^2 (see Figure 1.12). As underlined by Delagrave et al.,[62] the results obtained in this investigation were quite variable, the lowest value being 0.11 kg/m^2 and the highest 3.02 kg/m^2. According to the authors, such a scatter of the test results can be explained by the consolidation operations which tend to unevenly affect the quality of the surface. Considering the variability of the test results, none of the parameters analyzed (mixture composition, curing compound, and position of the specimen in the test section) have been found to have a significant influence. However, the test results obtained by Delagrave et al.[62] have indicated clearly the importance of good concreting practices. Indeed, during the course of this project, the application of the curing membrane often was delayed and the amount of curing compound sprayed was not always sufficient. This situation clearly has contributed to significantly reducing the average deicer salt-scaling resistance of RCC.

Delagrave et al.[62] have emphasized that ASTM C 672 (with the 1 kg/m^2 limit) is a severe test that probably tends to underestimate the true durability of concrete. In fact, despite the low scaling resistance of some RCC mixtures (according to ASTM C 672 test), the surface of the test pavement still showed very little sign of deterioration after four years of service. According to Pigeon and Marchand,[51] the 1 kg/m^2 limit should be considered cautiously for RCC mixtures prepared and cast under field conditions. Indeed, this limit was established for concretes made and tested in the laboratory. All these concretes had been cured in ideal conditions and subsequently dried in mild conditions. In the project discussed in the previous paragraphs, RCC mixtures were cast in July during two hot and sunny days. The mixtures were then

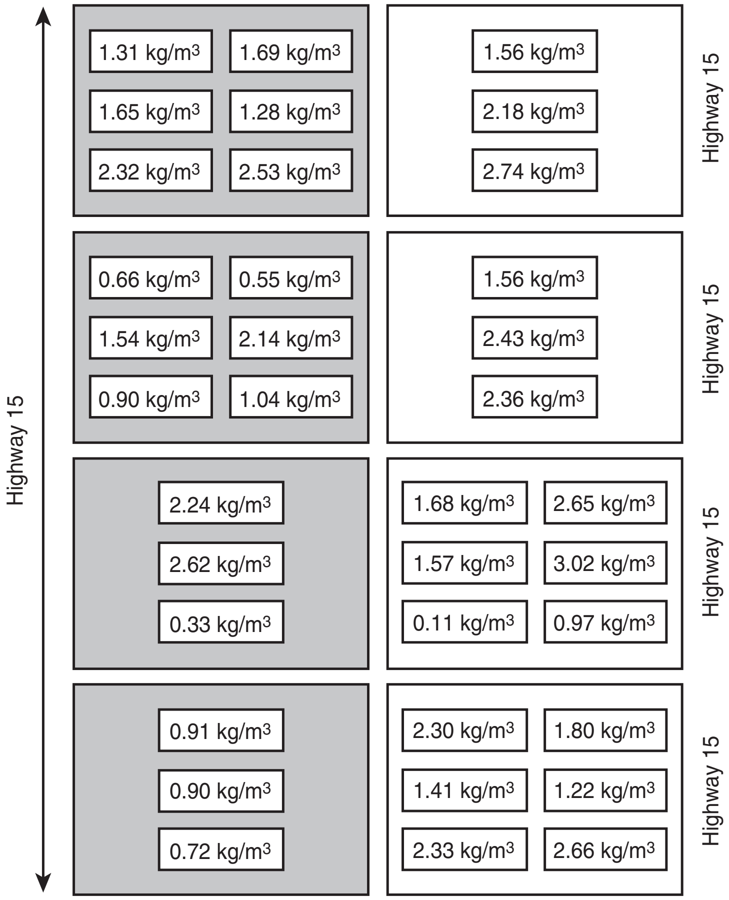

Figure 1.13. Salt-scaling test results.[62]

Table 1.4. Salt-Scaling Test Results[62]

Mixture	Mass of scaled-off particles		
	Membrane 1, kg/m^2	Membrane 2, kg/m^2	Mean value, kg/m^2
1-FA1A	0.84 [3]	1.95 [6]	1.58
2-SF2A	2.43 [2]	2.23 [4]	2.30
3-SF1A	1.14 [6]	2.12 [3]	1.46
4-SF1N	1.80 [6]	2.16 [3]	1.92

Number in brackets indicates number of sets of two specimens included in the average.

submitted to a harsh drying treatment. Studies have indicated that the salt-scaling resistance of concrete is very much dependent of the moisture history of the tested specimen, and that severe pre drying treatments can reduce their durability significantly.

1.3.3 Field Performance

Field performance observations of existing pavements built in British Columbia and in New Hampshire, respectively reported by Piggott,[9] and by Hutchinson et al.,[13] have indicated that non-air-entrained RCC can be resistant to frost-induced internal cracking. This conclusion should, however, be considered cautiously since most of these pavements were exposed to a mild frost attack for only a limited period. Moreover, the validity of some of these observations has been questioned by the test results reported by Ragan,[52] since the samples taken from one of the British Columbia pavements showed poor durability in the ASTM C 666 test. The samples used in Ragan's laboratory investigation were approximately eight years old at the time of testing and, according to Piggott, had shown no sign of deterioration in service. Further discrepancies between laboratory test results and field performance of RCC structures have been reported by Liu[12] of the U.S. Army Corps of Engineers.

More recently, a study carried out by Piggott[34] in 1998 addressed the long-term performance of numerous RCC pavement loading applications under various climatic conditions. A total of 34 RCC pavements were inspected visually throughout this study carried out in the United States and Canada. Representing a variety of applications (roads, military facilities, storage areas, etc.), the age of the reported RCC pavements varied from 3 to 20 years. The observations made in the field during this study indicated that it is possible to construct durable RCC pavements exposed to winter climates.

Piggott[34] concluded that RCC pavement with adequate portland cement content that is well mixed, placed to the specified density, and properly cured appears to be resistant to the effects of freezing and thawing, and deicing salt.

1.3.4 Concluding Remarks

On the basis of numerous published test results, it can be stated that the construction of a frost-and deicer salt-scaling-resistant RCC pavement is possible, but only under certain conditions, some of which are not yet clearly defined. Good construction practices (including sufficient compaction and proper curing) clearly are required. The use of supplementary cementitious materials also appears to be mandatory for RCC pavements, and there may be a requirement for a minimum cement content to ensure a certain degree of homogeneity of the microstructure. It is not clear, however, if air entrainment is required, and the conditions under which air entrainment in dry concretes can be successful are not yet clearly determined.

The discrepancies between laboratory and field behaviors as well as the unresolved question of the necessity of air entrainment suggest the need for further research on the frost durability and scaling resistance of RCC mixtures. The lack of information on the frost durability of RCC also emphasizes the need for research in the field. The effect of the consolidation operations on the frost protection and salt-scaling resistance also needs to be elucidated. In addition, it would be interesting to see if there is any correlation between the resistance to freezing and thawing of RCC and some of their physical properties.

1.4 AIR ENTRAINMENT

Over the past decades, the use of air entrainment has been shown to be extremely beneficial for conventional concretes. In addition to improving the workability of the fresh mixture, there exists an overwhelming body of laboratory and field data indicating that the entrainment of a sufficient number of spherical air bubbles has a beneficial influence on the frost durability of the hardened concrete.

The necessity of entraining air bubbles in RCC mixtures for adequate protection against frost-induced microcracking and deicer salt-scaling actually appears to be a controversial subject. Although these mixtures generally are proportioned to achieve an optimum density at the end of the consolidation operations, RCC mixtures are characterized by the numerous irregularly shaped voids formed during the compaction process. As will be seen in the next paragraphs, the role played by these "compaction voids" in the protection against frost remains nowadays an open question. While some field observations and laboratory investigations tend to indicate that some compaction voids can act as air bubbles and are sufficient to offer adequate protection against frost-induced internal cracking,[9,52,59-63] other reports have demonstrated that non-air-entrained RCC mixtures can be frost susceptible.[64,69]

1.4.1 Air Entrainment in the Laboratory

When a conventional concrete mixture has to be air-entrained, usually just enough air-entraining agent is frequently used to obtain an adequate spacing factor. Air-entraining agents are generally surface-active agents (surfactants) that concentrate at the air-water interface in the paste.[70] They are made of long organic molecules and usually facilitate air entrainment by reducing surface tension, but they mostly act to stabilize the air bubbles that are entrained by the mixing process.

Most air-entraining molecules (which have a hydrophobic and a hydrophilic end) are electrically charged and this explains in good part their stabilizing influence, because the air bubbles become attached to the clinker grains (see Figure 1.14).[71] Vinsol resin, which is used commonly as an air-entraining agent in North America, reacts with the lime liberated by the hydration of cement to form a water-repellent membrane around the air-voids.[72] The stabilization process allows the smaller voids (which are necessary to obtain a low spacing factor) to stay in the mixture, because the natural tendency of air bubbles is to coalesce since this reduces the free energy.[73]

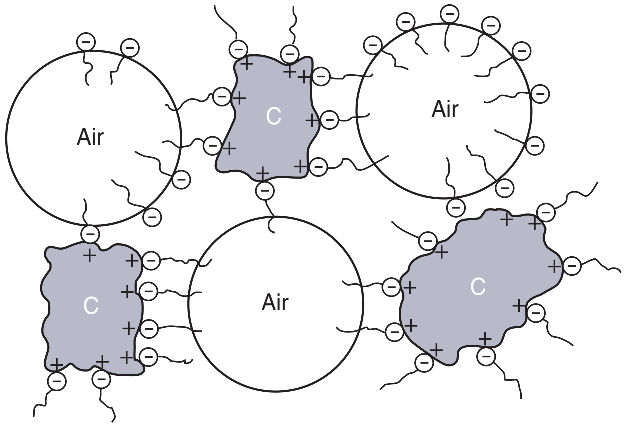

Figure 1.14. Illustration of the action of air-entraining agents in the formation of spherical air bubbles.[66]

Of course, many parameters affect the process of air-void production in concrete. Generally speaking, all parameters that affect the viscosity of the paste (such as aggregate grading, water content, water-cement ratio, water-reducing admixtures, etc.) also affect air entrainment. For usual concrete mixtures, as the viscosity increases, the dosage of the air-entraining agent must be increased because air entrainment in a stiffer paste requires more energy. However, over a certain viscosity (or below a certain water-cement ratio), the concrete mixture becomes too stiff. As can be seen in Figure 1.15, the energy requirement for air-void production is then too high for the stirring capacity of most concrete mixers.[74]

As explained by Powers,[73] the formation of an air bubble is only possible if a sufficient amount of water is available. For an efficient air-entraining agent, there must be enough water to form a film around each bubble. When the quantity of water added to the mix is decreased significantly, water tends, first of all, to cover solid surfaces. There is thus a fight for water between the bubbles and the solid particles. Below a certain water content, the efficiency of the air-entraining agent is thus minimized, even at fairly large dosages.

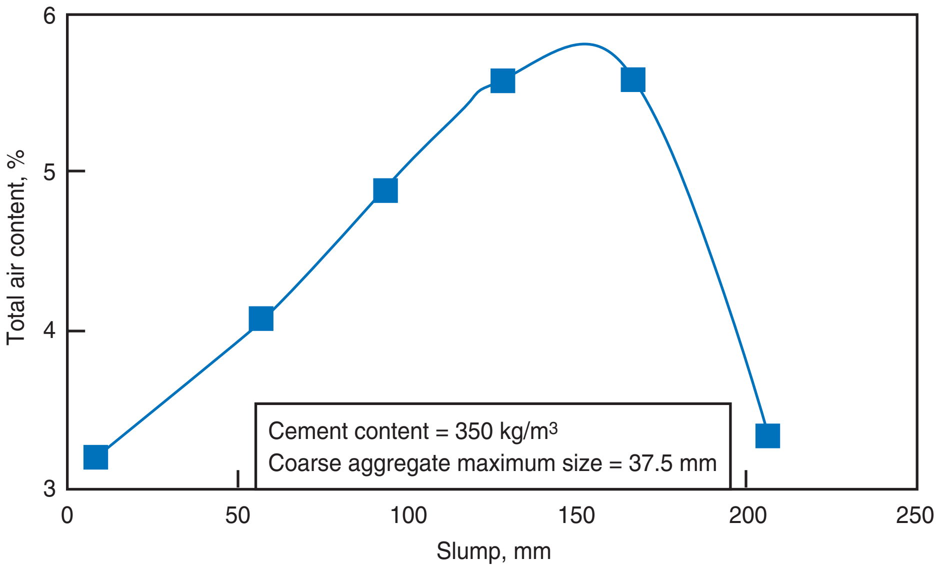

Figure 1.15. Influence of the workability of the mixture on the total air content.[74]

The water content of most RCC mixtures is usually of a minimum quantity required to entrain spherical air bubbles. This is why most researchers agree that the addition of an air-entraining agent in such concretes is useless if the batching sequences commonly used in the industry are not modified significantly. A survey of existing RCC pavements carried out by the U.S. Army Corps of Engineers has indicated that the use of an air-entraining agent was not very efficient, even at large dosages.[52] As part of the same investigation, additional tests carried out in two different laboratories showed that the effect of the air-entraining admixture on the concrete air-void system was ambiguous.

According to the available information, it seems that the only possible way to entrain spherical air bubbles in RCC mixtures is to alter the batching sequence. Andersson,[3] for instance, states that attempts to entrain air in RCC mixtures can be successful if the air-entraining agent is premixed with the cement paste, a small portion of the coarse aggregate, and a superplasticizer before adding sand. Similar results were obtained, in the laboratory, by Gomez-Dominguez,[25] and by Horrigmoe and Brox Rindal.[58] The authors of both investigations reported that a significant number of spherical air bubbles can be entrained in RCC mixtures when the paste fraction is premixed with the admixture in a counter-current pan mixer.

Such an application procedure unfortunately is restricted in practice for RCC production. Premixing operations require concrete to be mixed in a central concrete batch plant while most RCC producers use continuous flow pugmill mixers. It appears that this procedure is not necessarily bound to succeed and could be the source of another kind of problem. A laboratory investigation, conducted by the Portland Cement Association,[75] indicates that the type of air-entraining agent and the dosages added to the mixture have a strong influence on the final result. While studying the possibility of air entrainment in no-slump concrete (i.e., with a consistency just a little less stiff then that of usual dry concrete mixtures), Whiting found that the amount of admixture required to entrain spherical air bubbles could be 10 times more than to that used in conventional concretes. His results also demonstrate that it was outright impossible to entrain any air bubble with some air-entraining agents even when large dosages were used. Furthermore, Whiting underlined that the required dosages of air-entraining agents can affect the consistency of the concrete mixture although significantly increasing the slump.

Marchand et al.[76] also have clearly shown that air entrainment in RCC mixtures is an extremely difficult task. In their investigation, 21 different RCC mixtures were produced under laboratory conditions (using a counter-pan or rotary drum-type mixer). Four different air-entraining agents, selected for their different chemical composition, were tested at three different dosages (from 1 to 4 ml/kg of cement). A non-air-entrained mixture also was prepared to serve as reference concrete. The air-void characteristics of each mixture were measured in accordance with the ASTM C 457. In the majority of cases, the use of an air-entraining admixture did not result in entraining any significant amount of spherical air-voids, and it is clear that most of the air-voids observed resulted from the consolidation operations. Indeed, the experimental measurements have shown that spherical air-bubble content was lower than 1.5% in most cases. Despite this low spherical air-void content, Marchand et al.[76] have measured a total air content relatively high for many mixtures. The total air content was also extremely variable from one mixture to another (ranging from 6% to 12%). In that respect, mixtures prepared with the rotary drum-type mixer have shown a higher total air content.

Air entrainment in RCC mixtures also has been studied by Cannon.[77] According to this researcher, the entrainment of air in RCC appears to be possible only in workable mixtures that will consolidate under vibration within 30 seconds without the application of a surcharge weight. For these RCC mixtures, the required dosage of air-entraining agent may range from 2 to 4 times over what is normally required to achieve a given air content in conventional concrete.

Even if most of the published data indicate that air entrainment in RCC mixtures is extremely difficult under the usual conditions met in the industrial production, the introduction of more powerful air-entraining admixtures especially designed for this type of concrete has raised new hopes. Deeper research certainly is needed to determine if these admixtures can consistently produce an adequate air-bubble network without adversely affecting the required workability of the mixture. Encouraging results of successful air entrainment in RCC mixtures have been reported by Dolen[28] and Ragan.[30]

According to the latter, a significant amount of spherical air bubbles can be entrained under laboratory conditions with apparently no alteration of the batching sequence. These results subsequently were reproduced in field trials using a pugmill mixer.

1.4.2 Field Experience

The air entrainment has been extensively studied under field conditions by Pigeon and Marchand.[51] During a four-year project (conducted between 1987 and 1990 near Montreal), many attempts have been made to entrain air bubbles in RCC pavements. In the course of this project, many different air-entraining agents were used. The mixing sequence also has been studied to facilitate air entrainment.

Overall, the test results obtained by Pigeon and Marchand[51] have indicated that air entrainment in RCC pavements is an extremely difficult, if not impossible, task when concrete is mixed in a standard pre mix unit. This project has shown clearly that, in the vast majority of cases, the use of an air-entraining admixture did not result in the entrainment of any significant amount of spherical air-voids, and it was clear that most, if not all, of the air-voids observed resulted from consolidation operations. Despite the various attempts made throughout the project to entrain air bubbles, Pigeon and Marchand have concluded that the consistency of the mixtures was almost always too high for an air-entraining agent to act. Neither the fairly large dosages of a mixture that were used nor the different modifications to the batching procedures had any beneficial effect on air entrainment. Similarly, Pigeon and Marchand had observed that the use of various types of air-entraining agents did not have any significant effect on the production of air bubbles.

Despite the low spherical air-void content of all mixtures, the test results obtained in this investigation have shown that the total air content was, for many mixtures, surprisingly high. The total air content was also extremely variable from one mixture to another. For instance, air contents higher than 15% were measured on several mixtures, while that of others was found to be lower than 5%.

Considering that the use of air-entraining agents was not successful, relatively low spacing factors were measured. In most cases, the values were smaller than 250 µm. This was due to the relatively high content of small compaction voids.

According to Pigeon and Marchand,[51] the absence of air bubbles in the mixtures containing an air-entraining agent is not so surprising considering previous experience reported in the literature.[57,61,74,75] The results obtained, despite all the efforts made to entrain spherical air bubbles, clearly indicate that air entrainment in these low slump concretes is a much more complex problem that in conventional concretes.

Regardless of the type of chemical admixture used, the quantity of water in RCC pavements is probably too low to wet all the aggregates and cement particles and, at the same time, allow the formation of air bubbles.

Pigeon and Marchand[76] also have explained their results by the fact that the energy of the plant mixer was insufficient to entrain air bubbles. Even when the mixing time was considerably increased or the batching sequence altered to pre entrain air in the mortar fraction of the mixture, the stirring energy of the premix was too low to allow the formation of air bubbles. This could explain why it was possible for Delagrave et al.[79] to entrain air in similar mixtures (as those used by Pigeon and Marchand) batched in a laboratory pan mixer (spherical air bubble content was around 1.5%). Pan mixers can exhibit a much higher stirring energy and certainly facilitate the action of the air-entraining admixture.

1.4.3 Measuring the Air-Void Characteristics of RCC Mixtures

The fact that the air-void system of numerous RCC pavements is found to be formed essentially by entrapped compaction air-voids underlines the somewhat ambiguous application of the ASTM C 457 standard to this type of concrete (Pigeon and Marchand,[51] Delagrave et al.[62] and Marchand et al.[75]). The irregular shape of these air-voids and their variable distribution throughout the paste seem to lead to large variations of the air-void characteristics even in a single concrete batch. It is also clear that the characterization of an air-void system made of large irregularly shaped compaction air-voids using a method designed for spherical air-voids of various sizes is not appropriate, especially no one has ever established clearly the role played by these voids in the protection against frost damage.

It is possible that the usual relationship between the spacing factor and the frost durability is not applicable to RCC mixtures, even if all air-voids were unsaturated and free to contribute to freezing and thawing resistance. As pointed out by Pigeon and Marchand,[51] the usual spacing factor limit of 250 mm has been determined for conventional concrete having a typical permeability and protected mostly by air bubbles ranging in size from about 10 mm to 1 mm. It is probable that RCC has a much higher permeability and that the gradation of the air-voids resulting from the compaction operations is quite different than that of air bubbles in conventional concrete.

1.4.4 Concluding Remarks

In conventional concretes, the use of air entrainment to ensure adequate frost resistance is nowadays standard procedure. An overwhelming body of laboratory and field data indicates that the entrainment of a sufficient number of spherical air bubbles has a beneficial influence on the frost durability of hardened concrete. The necessity of entraining air bubbles in RCC mixtures for adequate frost protection remains an open question. Although the stiff consistency of RCC mixtures generally makes air entrainment extremely difficult, results indicate that it is possible in certain cases to entrain air bubbles in RCC mixtures. However, it involves a more complicated procedure than simply adding an air-entraining admixture to the concrete in the mixer. The type of air-entraining admixture and the type of mixer seem to play an important role.

The introduction of more powerful air-entraining admixtures has raised new hopes. More research certainly is needed to determine if these admixtures consistently can produce an adequate air-bubble network without adversely affecting the properties of the fresh concrete.

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Chapter 2

TEST PROGRAM, MATERIALS, AND EXPERIMENTAL PROCEDURES

2.1 TEST PROGRAM

The test program mainly consists of a number of laboratory tests to assess the frost durability of existing RCC pavements (Chapter 3) and the production and testing of frost-durable RCC mixtures made in the laboratory and with large-scale production units (Chapters 4, 5, and 6). The test program for each part of the study is presented clearly in each chapter.

All mixtures made in Chapters 4, 5, and 6 were designed using a new procedure (the Solid Suspension Model) in order to optimize the packing density of the granular skeleton.[1] As discussed in Chapter 1, the model uses the intrinsic packing density, the specific gravity, and the grading curves of all dry constituents (including those of the cementitious materials) in order to optimize the packing density of the RCC mixture. The optimization of the packing density of all dry materials contributes to reducing the fine particles content of the mixture, reducing therefore the amount of paste necessary to bind together all aggregates.

2.2 MATERIALS

This section describes the materials used for the production of RCC mixtures in the laboratory. With the exception of the fine and coarse aggregates, the same materials also were used for the large-scale production of RCC mixtures with a continuous flow pugmill mixer and a central concrete batch plant.

2.2.1 Cement and Cementitious Materials

An ordinary Type 10 cement manufactured by Lafarge Canada Inc. was used in the RCC mixtures made in the laboratory (with the exception of mixtures containing silica fume).

For the part of the study investigating the influence of silica fume, a blended cement (Type 10 cement incorporating approximately 7% silica fume) provided by Lafarge Canada Inc. was used instead of a normal Type 10 cement. The chemical composition and the physical properties of both cements are given in Table 2.1. Their gradation curves are presented in Figure 2.1.

Two different fly ashes were used in the production of some RCC mixtures. Both fly ashes, a Class C and a Class F, were provided by Minerals Solutions Inc. from Eagan, Minnesota. As previously mentioned, a blended cement (incorporating approximately 7% silica fume in replacement of the cement) also was used.

Both fly ashes were used as a partial cement replacement and therefore considered in the total binder content. The Class C fly ash (a high-calcium-content fly ash) had a specific gravity of 2.73 and the Class F (a low-calcium-content fly ash) had a specific gravity of 2.43. The grading curves of the fly ashes are given in Figure 2.2.

Table 2.2 presents the physical properties of the fly ashes.

Table 2.1. Chemical Composition and Physical Properties of the Cementitious Materials

Constituent, %	CSA – Type 10 cement	CSA – Type 10 SF cement
Chemical composition		
SiO_2	20.30	26.60
Al_2O_3	4.42	4.10
Fe_2O_3	3.00	2.90
CaO	62.60	58.10
MgO	2.74	2.70
SO_3	3.08	2.90
K_2O	0.82	
Na_2O	0.29	0.79 (equivalent)
TiO_2	0.20	
SrO	0.29	
P_2O_5	0.22	
Mn_2O_3	0.05	
ZnO	0.02	
Cr_2O_3	0.02	
Loss on Ignition (LOI)	1.91	1.30
Mineral composition		
C_3A	7	N/A
C_3S	58	N/A
C_2S	15	N/A
C_4AF	9	N/A
Physical properties		
Specific gravity	3.15	3.00
Blaine, m^2/kg	393	555
% passing 45µm sieve	89.0	92.8

Table 2.2. Physical Properties of the Fly Ashes

	Class C fly ash	Class F fly ash
Specific gravity	2.73	2.43
% passing 45 µm sieve	78	68

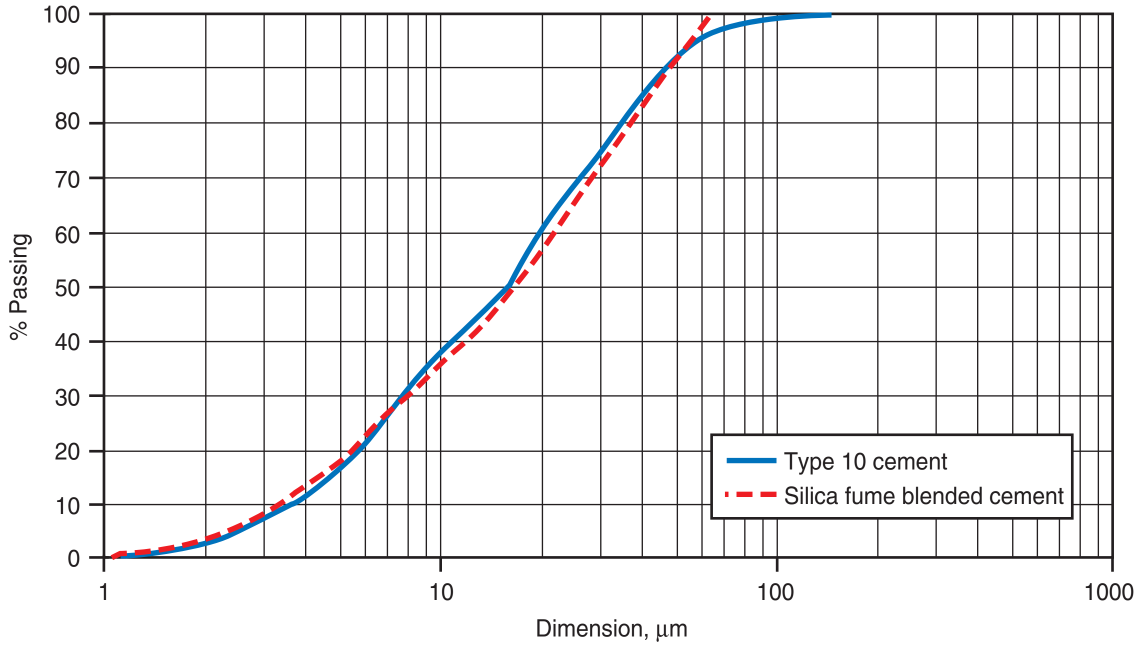

Figure 2.1. Grading curves of the cements.

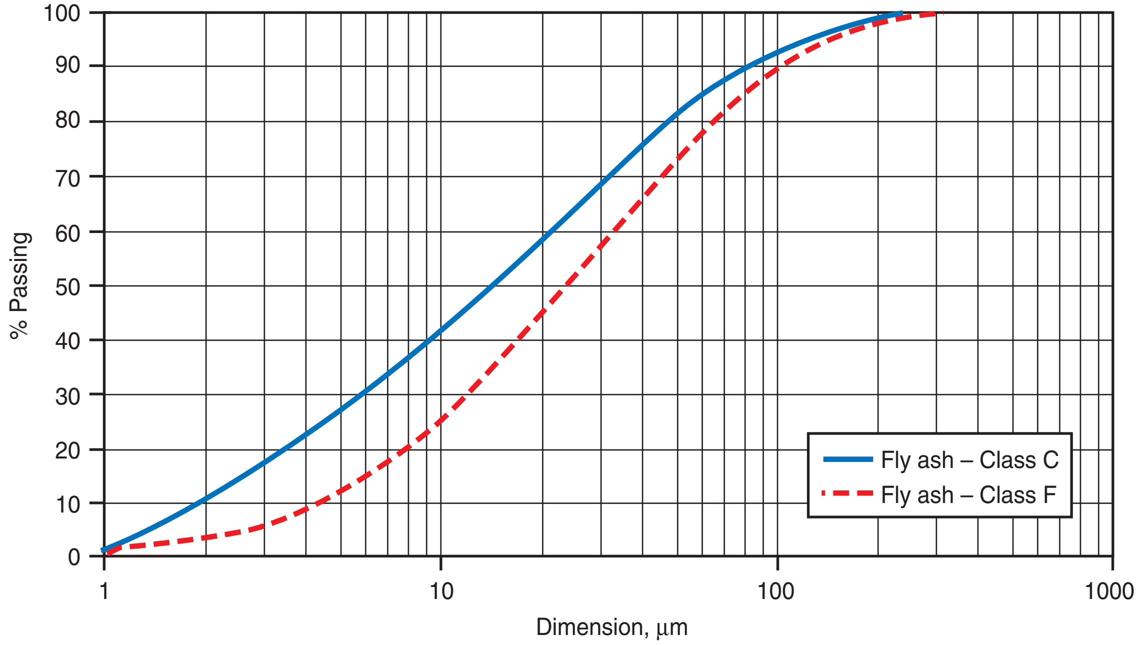

Figure 2.2. Grading curves of the fly ashes.

2.2.2 Coarse and Fine Aggregates

In all laboratory-made RCC mixtures, the same crushed granitic coarse aggregate, with a nominal maximum size of 20 mm, was used. The coarse aggregate had a specific gravity of 2.65 and a 24-hour absorption of 0.84 %. The fine aggregate used was a granitic sand with a specific gravity of 2.63, a 24-hour absorption of 0.81%, and a fineness modulus of 2.4. Figure 2.3 gives the grading curves of the coarse aggregate and the fine aggregate.

2.2.3 Water

The water used in the production of the RCC mixtures was a fresh and clean drinking water, free from any harmful substance such as oil, acid, salt, alkali, organic matter, and other substances deleterious to the hardening of RCC.

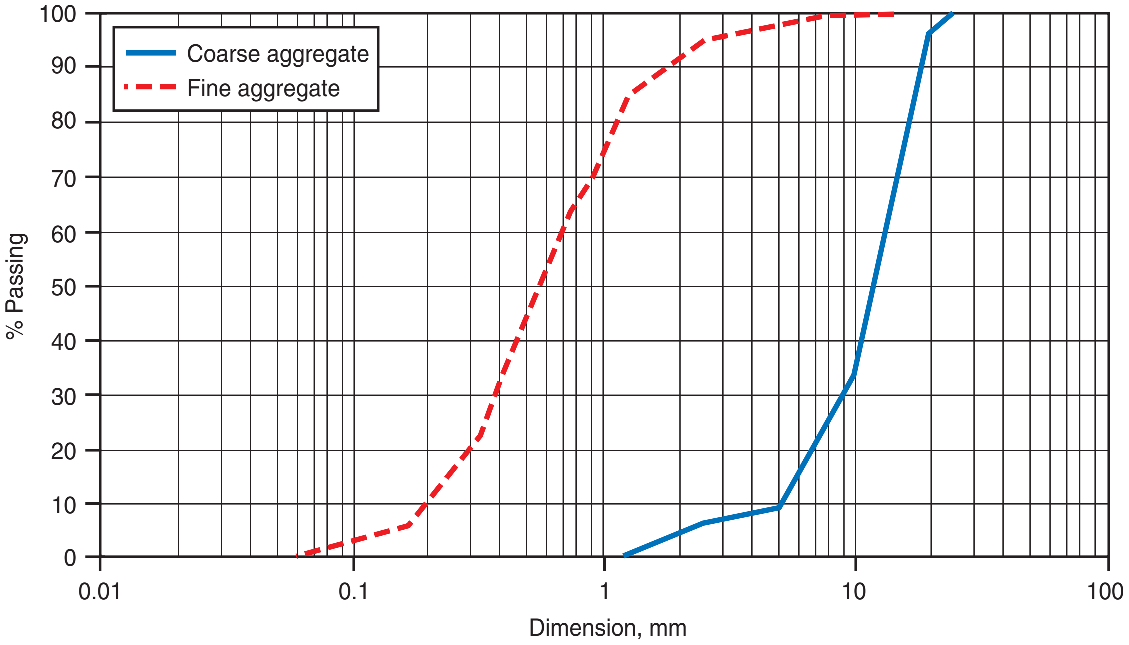

Figure 2.3. Coarse and fine aggregates grading curves.

2.2.4 Admixtures

A water-reducing admixture was used in all RCC mixtures prepared in the laboratory. In eastern Canada, water reducers commonly are used in RCC mixtures to improve the homogeneity of the cement paste and enhance the plasticity of the fresh mixture. The water reducer Eucon WR-75, manufactured by Euclid Admixtures Canada Inc., was added to most RCC mixtures. This admixture, a modified polymer and lignosulfonate, meets the ASTM C 494 requirements for Type A water-reducing and Type D retarding and water-reducing admixtures. A dosage of 400 ml per 100 kg of cementitious materials (including mineral additions) was selected; the dosage recommended by the manufacturer ranges from 200 to 500 ml per 100 kg of cementitious materials.

For air-entrained RCC mixtures, a total of three different air-entraining agents were tested: a synthetic-detergent-based admixture (Micro Air), a powdered air-entraining admixture often used in shotcreting (Airmix), and a tensio-active agent (Air X-L). Each admixture was tested at two different dosages.

In conventional concretes, air-entraining admixtures commonly are used to provide the concrete with an extra protection against freezing and thawing cycles by creating air bubbles that are stable, small and closely spaced. As emphasized in Chapter 1, the usefulness and the efficiency of air-entraining admixtures in RCC is still ambiguous.

To account for the stiffness of the fresh RCC mixtures and to maximize the possibility of entraining air bubbles, the dosage of air-entraining agents was increased with respect to that recommended by the different manufacturers. Micro Air®, manufactured by Master Builders Technologies, is a synthetic detergent that meets the requirements of ASTM C 260. In conventional concretes, the suggested dosage ranges from 8 to 98 ml per 100 kg of cement. The dosage used for the production of the RCC mixtures ranged from 200 to 400 ml per 100 kg of cement. Manufactured by Euclid Admixtures Canada Inc., Airmix 200-P, derived from a modified resin, was used in a powder form. The recommended dosage of this air-entraining agent commonly used in dry process shotcrete is 0.4% of the weight of cement. The dosage used in the production of RCC mixtures was 0.2% to 0.4% of the weight of cement. AireX-L, derived from water-soluble hydrocarbons, also is manufactured by Euclid Admixtures Canada Inc. The dosage suggested by the manufacturer in conventional concretes is 100 ml per 100 kg of cement. The dosage used in this study ranged from 50 to 200 ml per 100 kg of cement.

Since different air-entraining agents provided by two different manufacturers were used in the production of air-entrained RCC, it was decided to rely on the water-reducing admixtures from the same manufacturers in order to eliminate any possibility of incompatibility between the different admixtures. For air-entrained RCC mixtures produced with Micro Air®, the water reducer Pozzolith® 200N, also manufactured by Master Builders Technologies, was used. This admixture is an hydroxylated polymer meeting the ASTM C 494 requirements for Type A water-reducing, Type B retarding, and Type D retarding and water-reducing admixtures. The suggested dosage ranges from 195 ml to 325 ml per 100 kg of cementitious materials (including mineral additions if any). In this study, the dosage used was 400 ml per 100 kg of cementitious materials.

2.3 EXPERIMENTAL PROCEDURES

All laboratory-made RCC mixtures were prepared in a 0.1 m^3 counter current pan mixer (see Figure 2.4) according to a mixing sequence similar to that found in practice. The mixing sequence of the RCC mixtures prepared in the laboratory is presented in Table 2.3. At the end of the mixing period, the properties of the fresh RCC were measured.

When a powdered air-entraining agent was used, this admixture was added to the dry materials that were in the mixer.

Figure 2.4. One-tenth cubic meter counter current pan mixer. (IMG15521)

Table 2.3. Laboratory Mixing Sequence

Time, minutes	Operation
1	Starting of the mixer
3	Dry mixing of the aggregates and the cement (and mineral additions if any) Addition of water and diluted water-reducing admixture (and diluted air-entraining admixture, for air-entrained RCC mixtures)
4	End of mixing

For each RCC mixture, a number of specimens were prepared: 150 x 300-mm cylinders for compressive strength tests, 100x100x400-mm beams for flexural strength test, ASTM C 1262 tests, ASTM C 666 tests and ASTM C 457 tests, and 225x350x75-mm slabs for ASTM C 672 tests. All specimens (cylinders, beams, and slabs) were consolidated with a percussion hammer manufactured by Kango (see Figure 2.5).

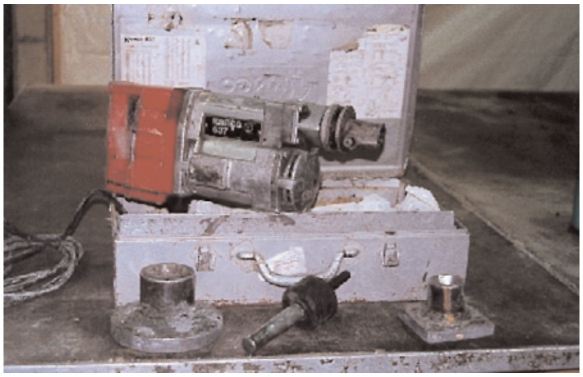

Figure 2.5. Percussion hammer used to consolidate RCC specimens. (IMG15522)

The molding of cylindrical specimens was carried out in accordance with a modified procedure of ASTM C 1435 *Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer*. The cylinders were compacted in four 75-mm successive layers (instead of three layers in accordance with the standard) while the beams and the slabs were prepared in two layers (50 mm for the beams and 38 mm for the slabs). The molding of the beams and slabs is not standardized, however. The molds used for the preparation of the cylinder, beam, and slab specimens are shown in Figures 2.6, 2.7, and 2.8. Once demolded, the test samples were sealed immediately in an adhesive aluminum paper and kept sealed until the day of testing, except for the slabs which were maintained for a period of 14 days in a 100% humidity chamber. Aluminum sealing was chosen because this method of curing is believed to be the most representative of the curing conditions of a field concrete specimen located in the middle of an RCC pavement.

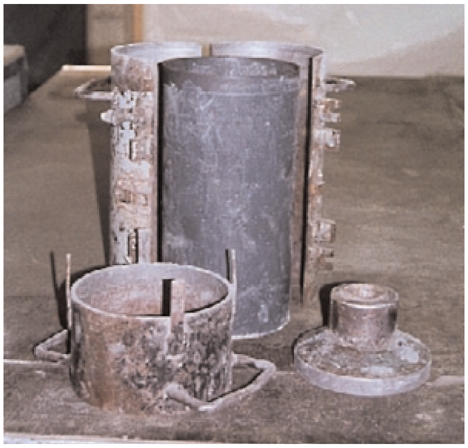

Figure 2.6. Cylindrical molds for compressive strength specimens. (IMG15523)

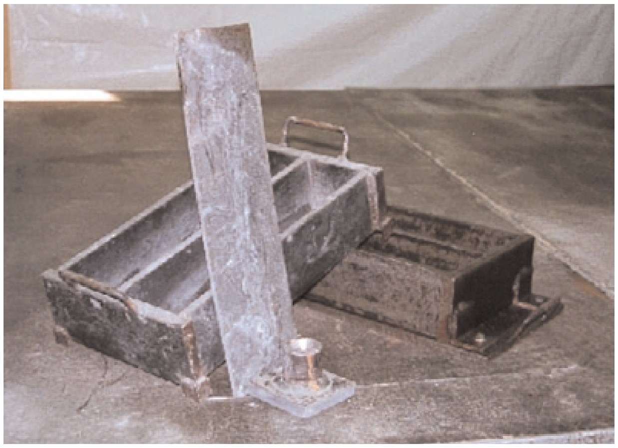

Figure 2.7. Molds used for consolidation of beams. (IMG15524)

Figure 2.8. Molds for deicer salt-scaling test specimens. (IMG15525)

2.4 PROPERTIES OF FRESH RCC

RCC can be defined as a concrete with an initial workability significantly lower than that of usual concrete mixtures. The final density and subsequently the overall performance of the material is affected directly by the consistency of the mixture.

For pavement applications, RCC must be stiff enough to facilitate effective consolidation operations by rollers as well as wet enough to allow an adequate distribution of the paste throughout the concrete mass during the mixing and placing operations.

For laboratory-made and for large-scale production RCC mixtures, VEBE and Modified Proctor tests were carried out on the fresh RCC once mixing was completed. The VEBE test was used to evaluate the “workability” of the fresh mixture. The Modified Proctor was performed to assess the unit weight of the fresh RCC.

The VEBE test method is used to determine the consistency of RCC mixtures, in accordance with ASTM C1170 – *Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table*. The procedure consists in placing a representative sample of RCC (approximately 13 kg) in a standardized cylindrical steel mould. The mould is fixed on a vibrating table, and a circular plastic plate is placed on top of the concrete sample. In order to consolidate the concrete, a removable mass (22.5 kg) is applied to the plate, and the vibrating table is turned on. The VEBE time (expressed in seconds) is essentially the period required to form a mortar rim around the plastic plate. The VEBE apparatus is shown in Figure 2.9.

The Modified Proctor test was carried out, in accordance with ASTM D#1557 *(Method D)*, in order to assess the unit weight of the freshly mixed RCC.

The procedure consists of compacting a fresh RCC mixture in a standardized cylindrical mold with a specified energy (a 10 lb., 4.54 kg, and 18-in.-, 460-mm-, long hammer). The RCC is compacted in five layers and each layer receives 56 hammer hits. The RCC surface then is leveled using a metal ruler. The mass of the compacted concrete is measured.

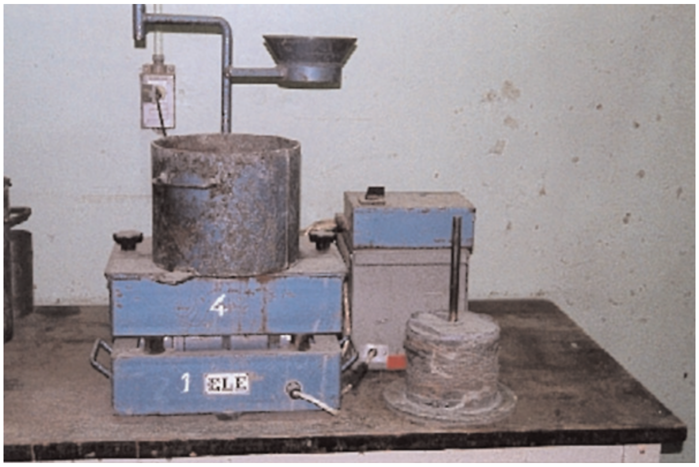

Figure 2.9. Vebe test apparatus. (IMG15526)

Knowing the volume of the mold (standard mold = 129.61 in.^{3}, 0.002124 m^3), the corresponding unit weight is calculated. The apparatus used for this test is shown in Figure 2.10. The unit weight is necessary to determine the mass of concrete to be consolidated in the molds.

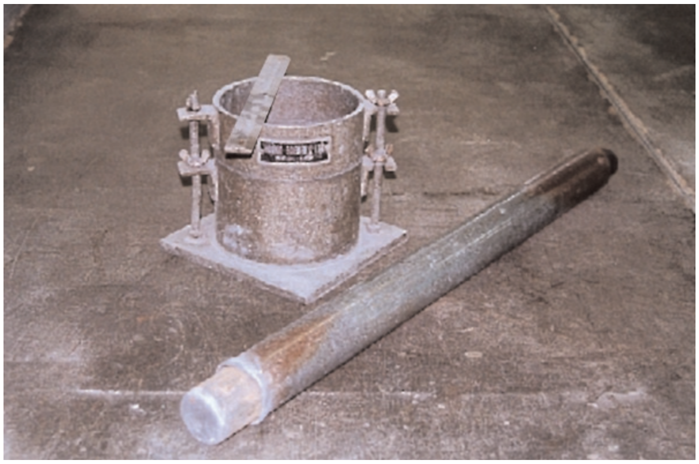

Figure 2.10. Modified proctor apparatus. (IMG15527)

2.5 PROPERTIES OF HARDENED CONCRETE

2.5.1 Compressive Strength and Flexural Strength

The compressive strength of RCC mixtures was determined in accordance with ASTM C 39 – *Compressive Strength of Cylindrical Concrete Specimens*. For each laboratory-made mixture, two cylindrical specimens (150x300 mm) were subjected to the test after 28 days of curing. Both ends of the cylindrical specimens were sawed and ground before testing.

The flexural strength tests were carried out in accordance with ASTM C 78 – *Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. For each mixture made in the laboratory, two 100x100x400-mm specimens were tested.

The compressive strength and the flexural strength test equipment are shown in Figure 2.11 and Figure 2.12, respectively.

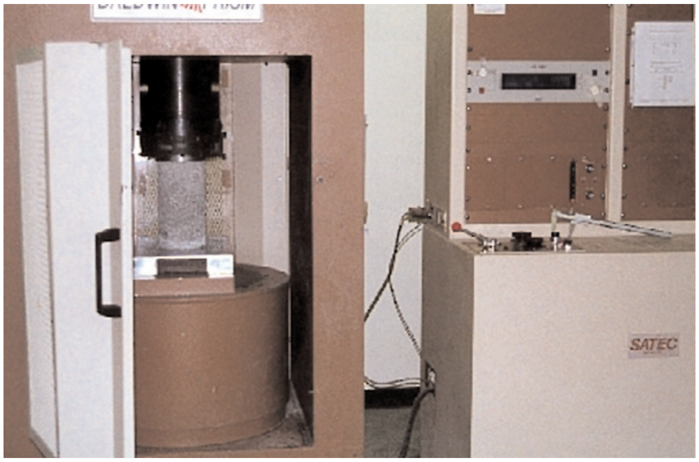

Figure 2.11. Compressive strength testing equipment. (IMG15528)

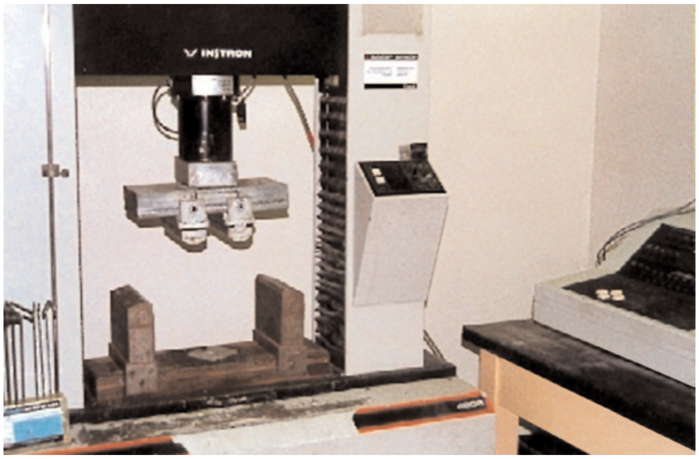

Figure 2.12. Flexural strength testing equipment. (IMG15529)

2.5.2 Characteristics of the Air-Void System

To determine the characteristics of the air-void system, polished 100x100-mm sections were examined microscopically in accordance with the modified point count method described in the ASTM C 457 – *Standard Test Method for the Determination of the Air Content and the Air-Void Characteristics of Hardened Concrete*. The characteristics of the air-void systems were measured initially by considering all air-voids without making any distinction with regard to shape.

For air-entrained RCC mixtures, the sections were examined a second time to determine if the air-entraining admixture had allowed the entrainment of air bubbles in the cement paste. This second observation was performed by separating the spherical air-voids (air bubbles) from the irregularly shaped compaction voids.

2.5.3 Microscopic Observations by Scanning Electron Microscopy

Air-entrained dry concrete mixtures often contain very small spherical air-voids which hardly can be detected by optical microscopy. The diameter of these voids usually ranges from 1 µm or less to 50 µm. These voids can, however, be observed easily using scanning electron microscopy.

To do so, a selected number of RCC mixtures were observed using a scanning electron microscope. For each selected mixture, a 25-mm disc was cut from a hardened RCC sample. The disc was dried at 40°C and then impregnated with an epoxy resin. After a second impregnation, the disc was ground with a diamond paste over a rotating lead plate until the smoothness of the surface was good enough for the microscopical observations.

For each disc, a surface of approximately 1 mm^2 was examined. Observations were made at a magnification of 700X. At this magnification, voids having a diameter of 1 µm can be observed easily. During the observations, the spherical voids were recorded.

2.5.4 Frost Durability

The durability of concrete exposed to freezing and thawing can be assessed using different laboratory tests. Some are designed to test the resistance of concrete to internal microcracking induced by freezing and thawing cycles (ASTM C 666), and others are intended to characterize the resistance to scaling due to freezing in the presence of deicer chemicals. Although these laboratory tests give valuable information on the frost resistance of conventional concretes, none of these tests were developed to assess the frost durability of RCC mixtures. However, a testing procedure (ASTM C 1262) has been designed specifically to assess the freezing and thawing durability of manufactured concrete masonry and related concrete units. Since dry concrete products have an internal pore structure similar to masonry units, this testing procedure may be applied to other types of dry concrete mixtures such as roller-compacted concrete.

2.5.5 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A)

Probably the most efficient way to assess the frost resistance of a concrete is to subject concrete specimens to repeated cycles of freezing and thawing. A selected number of RCC mixtures were subjected to the ASTM C 666 – *Resistance of Concrete to Rapid Freezing and Thawing Cycles (Procedure A)* laboratory test. This test procedure consists of subjecting concrete specimens (in this study, two 75x100x400-mm beams per mixture) to 300 cycles of rapid freezing and thawing in water. The freezing and thawing cycles have to be adjusted so that the temperature decreases from 5°C to -18°C and increases back to 5°C in no less than 2 hours and no more than 5 hours. To conduct the test, the specimens are placed in metal containers and surrounded by approximately 5 mm of clean water. Freezing is generated with a cooling plate at the bottom of the apparatus while thawing is produced by heating elements placed between the containers. The test apparatus is shown in Figure 2.13.

At regular intervals, specimens were removed from the apparatus and length change and pulse velocity (to determine the dynamic modulus of elasticity) measurements were carried out. Pulse velocity results were used to calculate the durability factor of concrete samples. Although optional in the ASTM C666 Standard, the length change of concrete specimens generally is considered as the most sensitive index of internal microcracking due to freezing and thawing cycles. Contrary to pulse velocity measurements, length change values are not affected by scaling occurring at the surface of the test specimens during freezing and thawing cycles in water.

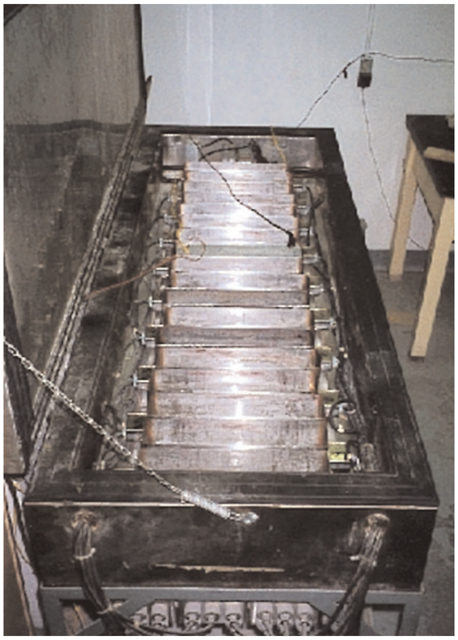

Figure 2.13. Freeze-thaw cabinet. (IMG15530)

2.5.6 Deicer Salt-Scaling Resistance (ASTM C 672)

It is well known that the widespread use of deicing salts during winter roadway maintenance operations is the primary cause of steel reinforcing corrosion and scaling of concrete surfaces. In Chapter 1 (literature review), it was indicated that roller-compacted concretes are particularly susceptible to deicer salt-scaling.

To determine the influence of air entrainment or supplementary cementitious materials on the deicer salt-scaling resistance of RCC, salt-scaling tests were carried out on laboratory-made RCC mixtures in accordance with ASTM C 672 – *Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*. For each RCC mixture, two surfaces (235x355-mm) were tested. The mold used to prepare the specimens is shown in Figure 2.8.

All specimens were cured in lime-saturated water at a temperature of 23°C for a period of 14 days after the initial water-binder contact. After this period, the specimens were stored for another 14 days at the same temperature and at a relative humidity of 45%-55%. During the drying period, a watertight dike was placed on the test surface to retain the salt solution during the test. At 28 days, the top surface of the concrete specimens was covered with approximately 6 mm of pure water for a period of 7 days. After this 7-day period, the pure water was replaced with a salt solution, and the specimens were subjected to freezing and thawing cycles. The salt solution was a 3% sodium chloride solution (i.e., 3 g of NaCl for each 100 ml of water). The specimens were subjected to a minimum of 50 freezing and thawing cycles by alternately placing them in a freezing environment (-17.8°C ± 1.7°C) and a thawing environment (23°C ± 1.7°C). At the end of each series of 5 cycles, the salt solution was renewed and the scaling residues were recuperated, dried, and weighed.

The extent of surface scaling was assessed visually. The visual rating (see Table 2.4) ranges from 0 (concrete surfaces showing no scaling) to 5 (concrete surfaces suffering severe scaling with coarse aggregates visible over the entire test surface).

Table 2.4. Visual Rating of Scaled Surfaces According to ASTM C 672 Standard

Rating	Condition of the surface
0	No scaling
1	Very light scaling (maximum depth of 3 mm, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to sever-scaling
5	Severe scaling (coarse aggregate visible over entire surface)

However, the visual rating can be influenced by the operator's subjectivity. Over the years, the mass of scaled-off particles has been considered as a more rigorous index of surface scaling resistance, although this practice has not been adopted officially by the ASTM C 672 Standard.

2.5.7 Freezing and Thawing Durability (ASTM C 1262)

The ASTM C 1262 – *Evaluating the Freeze-Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units* is a testing procedure used for the determination of the freezing and thawing durability of manufactured concrete masonry and related concrete units. ASTM C 1262 tests were carried out to evaluate the potential use of this method for the determination of the freezing and thawing durability of RCC mixtures.

Each test was carried out on three companion specimens (100x50x200 mm). After 35 days of sealed curing, the nonmolded surface was tested surface down in a 3-mm saline solution (3% NaCl). The first freezing cycle followed a 24-hour saturation period in a saline solution. During the freezing cycle, the temperature was maintained at -17 ± 5°C for a period of no less than 4 hours and no more than 5 hours. After the freezing cycle, the thawing cycle started immediately at a temperature maintained at 24 ± 5°C for a period not less than 2.5 hours and not more than 96 hours. The residues were collected after 10, 20, 35, and 50 cycles. After each measurement, the salt solution was renewed. After 50 cycles, the specimens were placed in an oven and dried for 24 hours at a temperature of 105°C. The mass of the specimens was measured after 7 days of drying. The ratio of the weight of residues to the initial specimen weight was calculated for each measurement.

2.5.8 Pulse Velocity Measurements

The ASTM C 597 Standard – Pulse Velocity Through Concrete is a testing method commonly used to assess the uniformity and relative quality of a given concrete. It also can indicate the presence of voids and cracks in the concrete. The method uses a pulse of compressional waves that are generated by an electro-acoustical transducer (Figure 2.14). The time required for the waves to traverse the specimen represents the transit time and is measured electronically. Knowing the length of the specimen, it is thus possible to evaluate the pulse velocity.

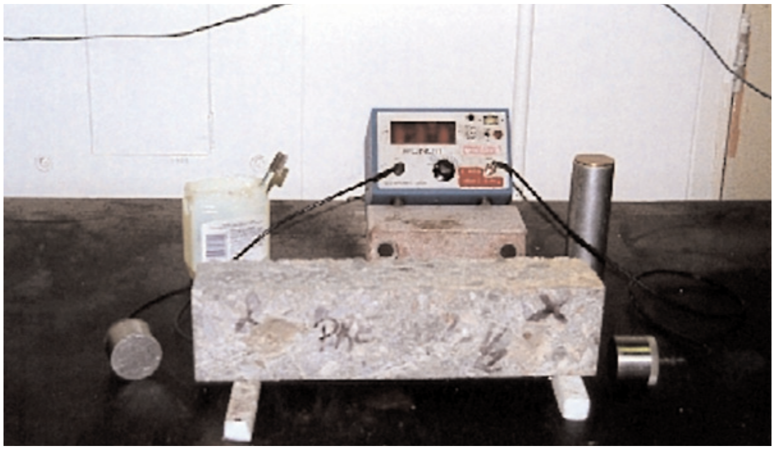

Figure 2.14. Pulse velocity apparatus. (IMG15513)

Based on a classification by E.A. Whitehurst,[1] the quality of the RCC specimens was determined with respect to their pulse velocity (see Table 2.5).

Table 2.5. Classification of the Quality of Concrete on the Basis of Pulse Velocity[1]

Pulse velocity, m/s	Quality of concrete
> 4500	Excellent
3500 – 4500	Good
3000 – 3500	Doubtful
2000 – 3000	Poor
< 2000	Very poor

2.5.9 Chloride Penetration Profiles

Total chloride penetration profiles were determined in accordance with a modified version of ASTM C 1152/C 1152M – *Standard Test Method for Determination of Acid-Soluble Chloride in Mortar and Concrete*. The following procedure was used:

- Hardened RCC slices (5 mm in thickness) were sawed at different depths and milled to powder
- Powdered samples were dried at 105° C for 24 hours
- After drying, 50 ml of deionized water were added to 5 g of the powdered sample in a 100-mL container

- 10 drops of nitric acid (HNO_3) concentration were added into the container followed by heating to 80° C
- Solution was cooled to room temperature
- Powders were filtered through filter paper to collect the chloride-containing acidic solution
- The chloride concentration of the filtered solution was determined by titration

For each selected specimen, the chloride content was determined at different depths, i.e., at 0-5 mm, 10-15 mm, and 20-25 mm measured from the top of the pavement. The total chloride content of the powder was calculated considering the weight of the sample, the volume of the solution, and the measured chloride concentration.

2.5.10 Surface and Internal Microcrack Measurements

The surface and internal microcracks were measured on polished hardened RCC specimens (100x100x25 mm). With the use of a red dye impregnation (applied on the polished surface) and an optical microscope, the presence of microcracks in the RCC specimens can be observed. This nonstandardized test procedure consists of counting the number of microcracks and discontinuities by a linear traverse method. Knowing the number of observation points, it is possible to determine the density of microcracks and discontinuities. This test was carried out on selected specimens.

Chapter 3

ASSESSING THE FROST DURABILITY OF RCC PAVEMENTS

In Canada, and especially in the province of Quebec, exposure conditions for concrete structures are considered to be particularly severe: snow is frequent, the number of freezing and thawing cycles per year is high, temperatures can drop very low, and large amounts of deicer salts are used regularly on roads.

The most efficient method of assessing the resistance of RCC to freezing and thawing cycles and to scaling due to deicer salts is, obviously, to analyze the performance of RCC pavements subjected to natural exposure conditions.

3.1 TEST SECTION SAMPLING AND VISUAL INSPECTION

To assess the frost durability of RCC pavements, 25 test sections from the St. Constant research project were selected and sampled in order to cover as many variables as possible. Test sections were produced during a 4-year period, ranging from 1987 to 1990.

3.1.1 Sampling Procedure

In April 1999, twenty-one 600x600x250-mm RCC samples were taken from pavements produced in 1987, 1988, and 1989 (seven sections sampled in each year) and four 600x600x250-mm sections were sampled in sections cast in 1990. All concrete samples were sawed and then removed from the pavement with the aid of anchors.

The 25 RCC samples then were transported to our laboratory to be sawed, prepared, and subsequently tested. The mixture characteristics of the RCC pavements sampled are given in Table 3.1

3.1.2 Visual Inspection

Immediately before sampling, all test specimens were rated visually to assess the severity of the surface scaling in accordance with ASTM C 672 test procedure. Each RCC sample was rated in accordance with the following system:

0 — No scaling

1 — Very slight scaling

2 — Slight to moderate scaling

3 — Moderate scaling (some coarse aggregate visible)

4 — Moderate to severe scaling

5 — Severe scaling

Table 3.1. RCC Mixture Characteristics of Each Selected Test Section

Section	Year	Cement type	Cement, kg/m^3	Fly ash, kg/m^3	Slag, kg/m^3	Sand, kg/m^3	Aggregate			Aggregate, kg/m^3	Water, L/m^3	W.R., ml/m^3	A.E.A., ml/m^3	S.P., ml/m^3
							10mm	14mm, kg/m^3	20mm					
1	90	10	300	60	–	1015	–	–	–	1000	105	960	1000	–
2	90	10SF	250	–	–	1130	–	–	–	1070	90	960	1000	–
3	90	10SF	300	–	–	1075	–	–	–	1000	105	960	1000	–
4	90	10SF	300	–	–	1075	–	–	–	1000	105	960	–	–
5	87	10	300	–	–	1055	300	500	200	–	100	940	250	–
6	87	10	300	–	–	1055	300	500	200	–	100	940	250	–
7	87	10	370	–	–	1015	300	480	200	–	100	940	–	–
8	87	10	300	–	–	1055	300	500	200	–	100	–	250	–
9	87	10	285	–	–	1065	300	500	200	–	100	940	–	–
10	87	10	300	–	–	1055	300	500	200	–	100	940	–	–
11	87	10	300	–	–	1055	300	500	200	–	100	940	250	–
12	88	10	300	–	–	1260	300	500	–	–	105	960	160	–
13	88	30	300	–	–	1090	300	700	–	–	105	960	160	–
14	88	10	300	–	–	1260	300	500	–	–	105	960	160	–
15	88	10SF	300	–	–	1260	300	500	–	–	105	960	160	–
16	88	10SF	300	–	–	1260	300	500	–	–	105	960	160	–
17	88	10	300	60	–	1200	300	500	–	–	105	960	160	–
18	88	10	300	60	–	1200	300	500	–	–	80	960	160	–
19	89	10	240	–	60	1075	300	700	–	–	105	960	–	–
20	89	10	200	–	50	1130	310	760	–	–	90	–	500	7500
21	89	10	300	–	–	1075	300	700	–	–	105	960	–	–
22	89	10	300	60	–	1015	300	700	–	–	105	960	600	–
23	89	10	250	50	–	1080	310	760	–	–	90	–	500	7500
24	89	10SF	300	–	–	1075	300	700	–	–	105	960	600	–
25	89	10SF	250	–	–	1130	310	760	–	–	90	825	500	–

Results of the visual inspection are given in Table 3.2. Observations of the pavements showed no significant surface scaling deterioration. The surface was mostly uniform and deterioration of the surface was due to abrasion rather than to the effect of deicing salts.

Table 3.2. Visual Ratings of Test Sections

Section	Visual rating	Notes and observations	Section	Visual rating	Notes and observations
1	1			14	1
2	2			15	1
3	1			16	1.5
4	1			17	1
5	2	Mostly from abrasion		18	2
6	2			19	1
7	2.5	Mostly from abrasion		20	1.5
8	1			21	1
9	1			22	2.5
10	1			23	2
11	1			24	3
12	1.5			25	1.5
13	1				

Sections 1 to 4: Mixtures produced in 1990
Sections 5 to 11: Mixtures produced in 1987
Sections 12 to 18: Mixtures produced in 1988
Sections 19 to 25: Mixtures produced in 1989

3.2 TEST PROGRAM AND RESULTS

The actual state of all 25 samples was assessed according to the following test procedures: compressive strength (ASTM C 39), flexural strength (ASTM C 78), pulse velocity (ASTM C 597), chloride profiles (ASTM C 114 modified), and internal microcrack measurements.

Furthermore, micro air-void analyses using a scanning electron microscope were carried out on five concrete specimens. For these samples, the characteristics of the air-void system were determined in accordance to a modified version of ASTM C 457. Furthermore, the frost resistance of selected samples was tested in accordance to ASTM C 1262. All ASTM C 1262 tests were performed using a 3% NaCl solution. The ASTM C 1262 procedure commonly is used to investigate the frost durability of masonry products.

3.2.1 Compressive Strength

The compressive strength of all specimens was determined in accordance with ASTM C 39 – *Compressive Strength of Cylindrical Concrete Specimens*. Specimens were cored from

Table 3.3. Compressive Strength Results

	Compressive Strength, MPa		
Section	**Specimen 1**	**Specimen 2**	**Average**
1	59.9	63.7	61.8
2	53.4	48.8	51.1
3	86.6	82.8	84.7
4	61.4	50.1	55.8
5	81.2	56.6	68.9
6	54.4	66.6	60.5
7	56.0	41.8	48.9
8	84.8	83.2	84.0
9	55.6	52.1	53.9
10	54.3	51.1	52.7
11	49.2	52.3	50.8
12	49.6	45.8	47.7
13	30.8	32.3	31.6
14	45.2	49.8	47.5
15	47.1	48.2	47.7
16	58.2	64.6	61.4
17	72.7	65.5	69.1
18	44.0	36.7	40.4
19	43.5	44.2	43.9
20	46.3	49.3	47.8
21	63.8	73.2	68.5
22	59.2	67.7	63.5
23	63.8	73.1	68.5
24	47.4	41.5	44.5
25	48.4	36.0	42.2

the various selected sections and then stored for 48 hours in a 100% humidity room prior to testing. All tests were carried out on two cylindrical (75x100 mm). Compressive strength test results are given in Table 3.3.

All sampled RCC developed good compressive strengths after more than 9 years of field exposure. Compressive strength values range from 30.8 to 86.6 MPa. For some mixtures, individual results are scattered. This can be explained, at least in part, by the inherent heterogeneity of field RCC mixtures. The presence of a few compaction voids (resulting from improper consolidation) may have a significant influence on the compressive strength of the material.

In the collaborative research study conducted from 1987 to 1990, the compressive strength of RCC sections was not measured systematically. Values obtained on mixtures produced during the third and fourth phases of the project (i.e., in 1989 and 1990) indicate that the compressive strength of 2-month old mixtures ranged from 36 to 69 MPa. Considering the compressive strength values given in Table 3.3, the exposure to severe winter conditions apparently had no detrimental influence on the mechanical properties of the test sections.

3.2.2 Flexural Strength

The flexural strength of selected specimens was determined on 50-mm x 75-mm x 225-mm beams in accordance with ASTM C 78 – *Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. Specimens were sawed from the RCC pavement and kept for 48 hours in a 100% humidity room prior to testing.

Table 3.4. Flexural Strength Results

Section	Flexural strength, MPa				
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average
2	8.1	7.9	7.8	7.9	7.9
4	7.7	7.1	–	–	7.4
6	7.6	5.3	5.5	9.6	7.0*
8	9.4	8.8	8.8	9.8	9.2
9	7.7	8.0	7.8	5.6	7.3
10	7.8	7.3	–	7.3	7.5
11	9.3	9.4	9.9	8.8	9.4
12	6.1	6.4	6.1	7.4	6.5
13	5.3	5.5	–	–	5.4
14	6.5	6.0	6.8	7.5	6.7
18	5.4	5.9	5.7	–	5.7

*** Some variation in the individual results.**

Although flexural strength measurements were not scheduled in the original testing program, these tests were performed on a series of specimens for which the internal microcrack measurements could not be carried out (see later section on Internal Microcrack Measurements). The flexural strength test results are given in Table 3.4. Each value is the average result of several specimens (from two to four specimens).

As can be seen, after more than nine years of field exposure, the selected RCC sections have developed good, if not very high, flexural strengths, with average results ranging from 5.4 to 9.4 MPa. Unfortunately, flexural strength measurements were not performed during the collaborative research study conducted from 1987 to 1990.

3.2.3 Pulse Velocity Measurements

For each section, pulse velocity measurements were carried out on two 75x150x300-mm specimens, in accordance with ASTM C 597 – *Pulse Velocity Through Concrete*. The specimens were sawed from the selected RCC pavement sections and then kept in a 100% relative humidity room until testing. Pulse velocity test results are given in Table 3.5.

The average pulse velocity test results range from 4772 to 5438 m/s. As previously mentioned in Chapter 2, according to the classification proposed by E.A. Whitehurst,[1] the overall quality of a concrete specimen is considered excellent when pulse velocity values are higher than 4500 m/s. These results also indicate that none of the RCC sections had suffered from any frost-related damage over the years.

Table 3.5. Pulse Velocity

Section	Pulse velocity, m/s			Section	Pulse velocity, m/s		
	Specimen 1	Specimen 2	Average		Specimen 1	Specimen 2	Average
1	5053	5267	5160	14	5059	5035	5047
2	5161	5164	5163	15	5089	5118	5104
3	5355	5378	5367	16	5245	5148	5197
4	5210	5201	5206	17	5263	5277	5270
5	5258	5362	5310	18	5060	5031	5046
6	5511	5233	5372	19	5067	5103	5085
7	5214	5230	5222	20	4887	5005	4946
8	5318	5277	5274	21	5236	5211	5224
9	5355	5302	5329	22	5264	5328	5296
10	5336	5316	5326	23	5342	5344	5343
11	5415	5460	5438	24	5092	5087	5090
12	5032	5121	5077	25	5025	4898	4962
13	4776	4768	4772				

3.2.4 Chloride Penetration Profiles

The determination of total chloride content of selected RCC pavement sections was conducted in accordance with a modified ASTM C 1152/C 1152M – *Test Method for Determination of Acid-Soluble Chloride in Mortar and Concrete*.

For each selected specimen, the total chloride content was determined at different depths i.e., at 0-5 mm, 10-15 mm, and 20-25 mm measured from the top of the pavement. Table 3.6 gives the total chloride profile of each RCC section.

Considering that no chloride-based admixture had been used in the preparation of these mixtures, the measured values clearly indicate that samples have been exposed to deicing salts. Some chloride concentration values are even relatively high considering that the threshold value to initiate corrosion in conventional reinforced concrete is around 0.05% by mass of concrete[2-4].

In most cases, the chloride contents close to the exposed surface are usually higher. However, for a few sections, the chloride concentration of the top five millimeters is lower than that of the second and third layers. This probably can be explained by the fact that the concrete has been exposed to numerous wetting and drying cycles that have contributed to leaching the surface portion of the pavement.

Table 3.6. Chloride Penetration Profiles

Section	Depth, mm	Chloride content, wt. %	Section	Depth, mm	Chloride content, wt. %
1	0 – 5 mm	0.02	14	0 – 5 mm	0.03
	10 – 15 mm	0.01		10 – 15 mm	0.06
	20 – 25 mm	0.01		20 – 25 mm	0.02
2	0 – 5 mm	0.02	15	0 – 5 mm	0.05
	10 – 15 mm	0.01		10 – 15 mm	0.03
	20 – 25 mm	0.00		20 – 25 mm	0.01
3	0 – 5 mm	0.04	16	0 – 5 mm	0.17
	10 – 15 mm	0.00		10 – 15 mm	0.06
	20 – 25 mm	0.00		20 – 25 mm	0.01
4	0 – 5 mm	0.04	17	0 – 5 mm	0.12
	10 – 15 mm	0.02		10 – 15 mm	0.09
	20 – 25 mm	0.01		20 – 25 mm	0.01
5	0 – 5 mm	0.08	18	0 – 5 mm	0.04
	10 – 15 mm	0.10		10 – 15 mm	0.05
	20 – 25 mm	0.04		20 – 25 mm	0.05
6	0 – 5 mm	0.06	19	0 – 5 mm	0.12
	10 – 15 mm	0.05		10 – 15 mm	0.08
	20 – 25 mm	0.01		20 – 25 mm	0.01
7	0 – 5 mm	0.06	20	0 – 5 mm	0.13
	10 – 15 mm	0.07		10 – 15 mm	0.11
	20 – 25 mm	0.05		20 – 25 mm	0.02
8	0 – 5 mm	0.06	21	0 – 5 mm	0.17
	10 – 15 mm	0.06		10 – 15 mm	0.10
	20 – 25 mm	0.01		20 – 25 mm	0.01
9	0 - 5 mm	0.07	22	0 - 5 mm	0.12
	10 - 15 mm	0.12		10 - 15 mm	0.12
	20 - 25 mm	0.02		20 - 25 mm	0.02
10	0 - 5 mm	0.04	23	0 - 5 mm	0.11
	10 - 15 mm	0.06		10 - 15 mm	0.09
	20 - 25 mm	0.02		20 - 25 mm	0.02
11	0 - 5 mm	0.03	24	0 - 5 mm	0.08
	10 - 15 mm	0.03		10 - 15 mm	0.07
	20 - 25 mm	0.01		20 - 25 mm	0.01
12	0 - 5 mm	0.04	25	0 - 5 mm	0.06
	10 - 15 mm	0.06		10 - 15 mm	0.09
	20 - 25 mm	0.02		20 - 25 mm	0.02
13	0 - 5 mm	0.08			
	10 - 15 mm	0.08			
	20 - 25 mm	0.05			

3.2.5 Internal Microcrack Measurements

Results of the internal microcrack measurements are given in Table 3.7. It should be mentioned that measurements could not be performed on sections 2, 4, 6, 8, 9, 10, 11, 12, 13, 14, and 18; the high number of discontinuities and defects in these specimens made it impossible to properly prepare the samples and conduct reliable observations.

On the one hand, test results summarized in Table 3.7 indicate that the number of discontinuities observed is very high, their density often being higher than 0.10 discontinuity per millimeters. This may be explained, at least in part, by the presence of compaction voids, which are included in the calculations. On the other hand, the number of microcracks is extremely low. Similar measurements[5] carried out on ordinary concrete samples (i.e., without any compaction voids) subjected to various drying treatments yielded microcrack density values in the order of 0.065 Nc/mm. Clearly, test results summarized in Table 3.7 are in good agreement with strength and pulse velocity measurements and confirm that concrete samples have not suffered from any significant degradation despite their long exposure to severe winter conditions.

Table 3.7. Internal Microcrack Measurements

Section	Total length analyzed, mm	Total count microcracks, N_C	Total count discont., N_D	Density of microcracks, N_C/mm	Density of discont., N_D/mm
1	2700	15	251	0.00556	0.09296
3	2700	5	84	0.00185	0.03111
5	2700	16	304	0.00593	0.11259
7	2700	19	274	0.00704	0.10148
15	2700	12	191	0.00444	0.07074
16	2700	25	316	0.00926	0.11704
17	2700	14	125	0.00519	0.04630
19	2700	33	295	0.01222	0.10926
20	2700	26	219	0.00963	0.08111
21	2700	8	88	0.00296	0.03259
22	2700	11	110	0.00407	0.04074
23	2700	13	87	0.00481	0.03222
24	2700	9	110	0.00333	0.04074
25	2700	5	334	0.00185	0.12370

3.2.6 Characteristics of the Air-Void System

The characteristics of the air-void system of five RCC mixtures (sections 1, 2, 3, 4, and 19) were determined in accordance with ASTM C 457 – *Standard Test Method for the Determination of the Air Content and the Air-Void Characteristics of Hardened Concrete*. The selection of these samples was motivated by the fact that sections 1, 2, and 3 had been produced with an air-entraining admixture, while sections 4 and 19 were not air-entrained. Test results are given in Table 3.8.

Table 3.8. Characteristics of the Air-Void System

Section	Including compaction voids			Excluding compaction voids		
	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm
1[1]	6.5	20.8	142	0.6	26.9	391
2[1]	6.7	19.4	115	0.4	28.0	410
3[1]	4.1	20.8	186	0.3	50.7	272
4[2]	7.8	13.8	130	0.3	26.1	461
19[2]	4.1	19.2	237	0.6	49.1	216

[1] with air-entraining admixture
[2] without air-entraining admixture

For each mixture, the results of the standard measurements, i.e., without distinguishing the voids according to their shape, is given in the first columns (including compaction voids). Results of the second measurement, in which only the spherical air-voids were considered, are given in the last columns (excluding compaction voids).

Overall, test results indicate that air is difficult to entrain in RCC mixtures. In all cases, the spherical air-voids content is lower than 0.6%, and the air-entrained mixtures (sections 1, 2, and 3) do not contain more spherical voids than non-air-entrained mixtures.

Despite the low spherical air-void contents, test results show that the total air content is, for many mixtures, relatively high. Sample 4 for instance has a very low spherical air-void content (0.3%) while its total air content is the highest of all mixtures tested (7.8%). This indicates that most air-voids probably result from consolidation operations.

Table 3.9. Microscopic Observations by Scanning Electron Microscopy

Section	Spherical air-void diameter, µm								
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
	Number of spherical air-voids per square millimeter								
1	–	–	–	1	–	–	–	–	–
2	2	–	–	–	–	1	–	–	–
3	–	–	–	–	–	–	–	–	–
4	–	–	–	–	–	–	–	–	–
19	–	1	2	–	–	–	–	–	–

3.2.7 Micro Air-Void Analysis by Scanning Electron Microscopy

The results of the scanning electron microscope observations are summarized in Table 3.9. As can be seen, very few microscopic bubbles could be observed.

The microscopic observations usually provide significant information with regard to the size of the spherical air-voids. Previous investigations have shown that air-entrained dry concrete mixtures can contain as many as 90 spherical air-voids per mm.[2] [6] The diameter of these voids usually ranges from 2 µm, 0.0004 in., or less to 50 µm, 0.002 in. These very small air-voids hardly can be observed during the standard optical observations and often are present in dry concrete mixtures, particularly when high dosages of air-entraining admixtures are used. The fact that none of these microvoids could be detected tends to indicate that the amount of air-entraining admixtures was not sufficient to entrain spherical air bubbles.

3.2.8 ASTM C 1262 Test Results

To evaluate its reliability to assess the freezing and thawing resistance of RCC mixtures, the frost durability of the selected RCC sections was determined in accordance with ASTM C 1262 – *Evaluating the Freeze-thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units*. As previously mentioned in Chapter 2, this test procedure currently is used by the concrete masonry industry to evaluate the frost durability of dry concrete mixtures.

The ratio of the mass of residues (collected after 50 cycles) to the initial mass of the specimen was calculated for each sample. Since test specimens are not subjected to freezing-thawing cycles in a fully saturated state, the ASTM C 1262 procedure (that can be performed using either tap water or a saline solution) is believed to be less severe than ASTM C 666 and ASTM C 672. Table 3.10 gives the results of the frost-durability test after

Table 3.10. ASTM C 1262 Test Results

Section	Specimen	Mass of scaled-off particles		Mass loss of of initial mass
		grams	kg/m^2	
1	1	2.1	0.077	0.08
	2	2.4	0.088	0.09
	3	6.9	0.267	0.28
	average	3.8	0.144	0.15
2	1	10.2	0.387	0.41
	2	12.1	0.457	0.49
	3	16.1	0.616	0.67
	average	12.8	0.487	0.52
3	1	13.4	0.499	0.53
	2	6.0	0.224	0.24
	3	3.8	0.142	0.15
	average	7.7	0.288	0.31
4	1	7.1	0.272	0.29
	2	6.2	0.236	0.25
	3	6.1	0.226	0.24
	average	6.5	0.245	0.26
19	1	8.8	0.319	0.33
	2	8.7	0.326	0.35
	3	12.6	0.479	0.52
	average	10.0	0.375	0.40

50 freezing and thawing cycles. As mentioned in Chapter 2 in this study, all tests were carried out with the samples partially immersed in a salt solution.

For concrete masonry products, a mass loss of 1% after 40 freezing and thawing cycles in a saline solution usually is considered as the maximum limit for performance. Although values for Sections 1 and 3 are somewhat scattered, all test results are under the 1% limit, with the maximum mass loss being 0.67 %.

Table 3.11. ASTM C 666 and ASTM C 672 Test Results After Construction

Section	Original ID number		ASTM C 672 Mass of scaled-off particles, kg/m²	ASTM C 666	
				Durability factor, %	Length change, μm/m
1	90-FA1A		1.58		
2	90-SF2A		2.30		
3	90-SF1A		1.46		
4	90-SF1N		1.92		
5	87-10A2A	A	7.99	97	393
		M	5.12	95	631
		W	3.63	100	258
6	87-10C2A	A	10.13		
7	87-10A1N	A	4.33	97	381
		M	3.72		
8	87-10A2B		No result		
9	87-10A3N	A	3.5	91	569
		M	4.19		
10	87-10D2N	A	6.5	100	183
11	87-10D2A	A	17.15	94	233
		W	7.6		
12	88-10A1A	A	7.05		
		W	3.32		
		M	Failed	92	197
13	88-30A1A	A	8.67		
		W	12.01		
		M	13.76		
14	88-10B1A	A	4.27	Failed	Failed
		W	3.32	95	271
		M		91	388
15	88-SFA1A	A	4.56		
		M	0.35	98	668
16	88-SFB1A	A	2.04		
		W	4.56		
		M	1.72	64	239
17	88-FAA1A	A	4.02		
		M	0.84	84	767
18	88-FAA2A	A	4.39		
		M	3.32	72	161

A = air curing; M = membrane curing; W = water curing

Table 3.11. ASTM C 666 and ASTM C 672 Test Results After Construction (continued)

Section	Original ID number		ASTM C 672 Mass of scaled-off particles, kg/m^2	ASTM C 666	
				Durability factor, %	Length change, μm/m
19	89-SLN1	M	2.1		
		W	4.84		
20	89-SLS2		No result	97	490
21	89-10N1	M	3.64		
		W	3.75		
22	89-FAA1	M	2.06	100	153
		W	4.28		
23	89-FAS2		No result		
24	89-SFA1	M	1.1	100	145
		W	2.83		
25	89-SFA2	M	1.24	100	109
		W	3.58		

A = air curing; M = membrane curing; W = water curing

Table 3.11 gives the results of the ASTM C 666 and ASTM C 672 tests carried out on companion samples extracted from the pavements a few weeks after casting and tested from 1987 to 1990. As previously mentioned, these tests were performed at Laval University as part of a collaborative research program.

As can be seen, the ASTM C 672 test results obtained on the samples extracted from the experimental pavements a few weeks after casting are markedly different from the ASTM C 1262 values reported in Table 3.10. All ASTM C 672 results but two (mixtures 88-SFA1A-M [or 15 according to the present codification] and 88-FAA1A-M [or mixture 17]) are over the 1 kg/m^2 limit after 50 daily cycles. It also should be emphasized that a few mixtures (e.g., 88-FAA2A-M and 88-10B1A-A) also had been found to be susceptible to frost-induced microcracking when tested according to ASTM C 666.

3.3 DISCUSSION

Normal, good quality concrete can be quite resistant to frost and deicer salt-scaling if properly air-entrained. It is thus normal to expect that air entrainment also is required for RCC mixtures exposed to severe winter conditions. However, as explained in Chapter 1, it can be difficult to entrain air in RCC because of its low water content and paste content, and because of its stiff consistency.[6] This is particularly clear from the results of the measurements made on the samples from the experimental pavement. In the five samples examined, the maximum spherical air-void content is 0.6%. These results are in line with the measurements made immediately following the construction of the experimental pavement. In all cases, the spherical air-void content was, at the time, found to be much lower than 1.5%, the value considered to be a lower limit for RCC.

The various measurements made on the samples extracted from the RCC experimental pavements (mechanical properties, pulse velocity, and microcrack density) clearly indicate that none of the mixtures had suffered any significant degradation by surface scaling or frost-induced microcracking after more than 10 winters of severe exposure. The good field performance of the test sections tends to indicate that unsaturated compaction air-voids offer some protection against frost action. If the spherical air-void content of all RCC samples was quite low (i.e., less than 1%), all had a relatively good air-void spacing factor (i.e., close to or lower than 230 µm), due to the high content in irregularly shaped compaction voids. In the Canadian A23.1 – *Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete*, 230 µm is considered to be the critical value below which concrete is protected intrinsically against frost action.

If the good performance of non-air-entrained RCC exposed to harsh winter conditions is in good agreement with the observations of other authors,[7,8] the absence of any significant sign of deicer salt-scaling is rather surprising. As previously mentioned, ASTM C 672 and ASTM C 666 tests that were conducted from 1987 to 1990 indicated that if some non-air-entrained RCC mixtures were resistant to frost-induced microcracking, almost none of the RCC mixtures performed well in the presence of deicing salts. Since chloride profiles show that RCC pavements were exposed to deicer salts, results from the present investigation and the field performance of the RCC sections clearly emphasize the severity of both procedures, particularly that of ASTM C 672.

The same conclusion cannot be drawn concerning the relative severity of the ASTM C 1262 procedure. As can be seen in Table 3.10, despite small evidence of scaling deterioration, all mixtures tested according to the ASTM C 1262 procedure passed the test (i.e., all mass loss results were under the 1% limit).

It should be emphasized that these results are in good agreement with the field behavior of the test sections, which did not suffer from any significant degradation over the 10-year exposure period. Clearly, the ASTM C 1262 appears to be more reliable than any other standard test method for correctly predicting the ability of dry concrete products to be durable when exposed to severe field conditions. However, further testing is required to establish the reliability of the ASTM C 1262 procedure. As mentioned in Chapter 2, ASTM C 1262 will be used to investigate the frost durability of various mixtures in the next chapters.

3.4 REFERENCES

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Chapter 4

INFLUENCE OF AIR-ENTRAINMENT ON THE FROST DURABILITY OF RCC

It is widely accepted that the presence of a large number of closely spaced air-voids throughout the cement paste represents the most effective way of protecting concrete against frost damage. The incorporation of a large number of small air bubbles into the cement paste usually is obtained by adding an air-entraining admixture to the mixing water. However, some air-entraining agents, meeting the requirements of ASTM C 260 (pertaining to the acceptance of an admixture as a valid air-entraining agent), may be more effective than others in producing a satisfactory air-void system in dry concretes.

To investigate the mechanisms of air entrainment on laboratory-made RCC mixtures, two series of mixtures were produced and tested: a first series of ordinary RCC mixtures (total binder content ≤ 250 kg/m^3) and a second series of high-performance RCC mixtures (total binder content ≥ 300 kg/m^3). For each series of RCC mixtures, three different air-entraining agents were evaluated: a conventional air-entraining agent, a powdered air-entraining agent, and a tensio-active agent. Each agent was tested at two different dosages. For each cement content, one reference mixture also was produced without any air-entraining admixture.

In all, 14 different concrete mixtures were produced in this phase of the program. For all RCC mixtures, the 28-day compressive strength was determined in accordance with ASTM C 39. The air-void characteristics of all mixtures were determined according to a modified version of ASTM C 457. This procedure was described in detail in Chapter 2. For a certain number of mixtures, the amount of micro air-voids (i.e., with diameter < 50 µm) entrained in the concrete also was determined by image analysis on polished sections using a scanning electron microscope.

To assess their frost resistance, specimens from a selected number of RCC mixtures were subjected to ASTM C 666 (Procedure A) test and ASTM C 672 test. In addition, ASTM C 1262 tests were carried out on these selected mixtures.

4.1 MIXTURE CHARACTERISTICS

The mixture characteristics of the two series of RCC made in the laboratory are given in Table 4.1. The RCC mixture codification is shown in Figure 4.1. The dosage of liquid air-entraining admixtures is given in ml/m^3 while the powder air-entraining admixture is expressed as a percentage of the mass of cement.

All air-entrained mixtures were designed with a theoretical air content of 6%. After mixing the reference concrete made with 250 kg/m^3 of cement, the amount of mixing

Table 4.1. RCC Mixture Characteristics

Mixture ID	Cement, kg/m^3	Water, L/m^3	Fine aggregates, kg/m^3	Coarse aggregates, kg/m^3	Water reducer, ml/m^3	Air–entraining agent, ml/m^3	Water–binder ratio
300 – Ref.	296	102	747	1347	1200[1]	–	0.34
300 – MA – 4	301	96	773	1303	1200[2]	1200	0.32
300 – MA – 2	302	98	776	1302	1200[2]	600	0.32
300 – AXL – 1	305	96	782	1319	1200[1]	300	0.31
300 – AXL – 0.5	304	97	780	1314	1200[1]	150	0.32
300 – AMP – 0.4	301	96	773	1302	1200[1]	1200 g/m^3	0.32
300 – AMP – 0.2	297	94	762	1284	1200[1]	600 g/m^3	0.32
250 – Ref.	246	107	758	1355	1000[1]	–	0.43
250 – MA – 4	251	96	786	1323	1000[2]	1000	0.38
250 – MA – 2	246	93	773	1305	1000[2]	500	0.38
250 – AXL – 1	250	89	783	1322	1000[1]	250	0.36
250 – AXL – 0.5	250	94	784	1323	1000[1]	125	0.38
250 – AMP – 0.4	253	92	794	1336	1000[1]	1000 g/m^3	0.36
250 – AMP – 0.2	248	92	779	1315	1000[1]	500 g/m^3	0.37

[1] **Eucon WR-75 manufactured by Euclid Admixtures Canada Inc.**

[2] **Pozzolith 200N manufactured by Master Builders Technologies**

300 – MA – 4

Dosage of Type 10 cement:

300: 300 kg/m^3 of cement;

250: 250 kg/m^3 of cement.

Type of air-entraining agent (AEA):

Ref.: Without AEA

MA: Micro air;

AXL: AireX-L;

AMP: Airmix 200-P

Dosage of the air-entraining admixture:

4: 400 ml per 100 kg of cement;

2: 200 ml per 100 kg of cement

1: 100 ml per 100 kg of cement

0.5: 50 ml per 100 kg of cement

0.4: 0.4% of the weight of cement;

0.2: 0.2% of the weight of cement.

Figure 4.1. RCC mixture codification.

water for the air-entrained RCC mixtures had to be reduced in order to achieve acceptable fresh RCC properties. Consequently, the water-cement ratios for the air-entrained RCC mixtures prepared with 250 kg/m^3 of cement are in the 0.36 to 0.38 range, while their reference RCC has a water-cement ratio of 0.43.

4.2 FRESH CONCRETE PROPERTIES

All mixtures were designed to have a VEBE workability of approximately 60 seconds. Recent experience has shown that the optimum modified VEBE time for RCC mixture for pavement applications should be in the 40-to-90 second range. Such workability generally is required to ensure good placement and consolidation operations for RCC.

The properties of the fresh RCC mixtures are given in Table 4.2. The VEBE test was carried out at different intervals (10, 30, and 60 minutes after mixing) to determine the evolution of the workability of the RCC with time. Thirty minutes is often the maximum specified time for the truck to deliver the concrete to the job site.

Table 4.2. Fresh RCC Properties

Mixture ID	Unit weight, kg/m^3	VEBE time, in seconds		
		10 min.	30 min.	60 min.
300 – Ref.	2493	50	>90	>120
300 – MA – 4	2475	90	>90	>120
300 – MA – 2	2480	50	90	90
300 – AXL – 1	2503	45	75	>90
300 – AXL –0.5	2496	35	60	90
300 – AMP – 0.4	2474	33	45	65
300 – AMP – 0.2	2438	15	30	55
250 – Ref.	2468	25	35	55
250 – MA – 4	2458	25	45	73
250 – MA – 2	2418	65	>90	>90
250 – AXL – 1	2446	25	45	70
250 – AXL – 0.5	2452	40	80	>90
250 – AMP – 0.4	2477	25	65	90
250 – AMP – 0.2	2436	30	50	60

The unit weight of the high-performance RCC mixtures (made with 300 kg/m^3 of cement) ranges from 2438 to 2503 kg/m^3 while the RCC mixtures made with 250 kg/m^3 of cement have a unit weight ranging from 2418 to 2477 kg/m^3. Most RCC mixtures made using an air-entraining agent have a unit weight lower than their reference mixture, clearly indicating that air bubbles probably had been entrained.

Almost all RCC mixtures have a workability that should allow efficient consolidation of the material. Their VEBE time, measured 30 minutes after mixing, ranges from 30 seconds to approximately 90 seconds. The workability also tends to vary in time. Some mixtures have a very low VEBE time at 10 minutes, while their VEBE time measured after 30 minutes is adequate to ensure proper placement and consolidation of the RCC. The loss of workability in time is probably due, at least in part, to the use of dry coarse aggregates (not entirely saturated surface dry) that may have absorbed part of the mixing water, thus reducing the workability of concrete.

For high-performance RCC mixtures, the workability of air-entrained mixtures is often higher (lower VEBE time) than that of the reference concrete. The use of an air-entraining admixture slightly increases the paste volume, and reduces the viscosity of the paste fraction, therefore enhancing the workability of the concrete.

For the RCC mixtures made with a cement content of 250 kg/m^3, the VEBE time of the reference concrete (250-Ref.) is lower than the air-entrained mixtures. This is clearly a result of the adjustments made to the mixing water. As previously mentioned, the mixing water for the mixtures containing an air-entraining agent were prepared with a lower amount of mixing water.

4.3 PROPERTIES OF HARDENED CONCRETE

4.3.1 Mechanical Properties

The 28-day compressive strength and the 28-day flexural strength of each RCC mixture were determined in accordance with ASTM C 39 and ASTM C 78, respectively. Test results are summarized in Table 4.3.

Table 4.3. Mechanical Properties of RCC Mixtures

	Compressive strength, MPa			Flexural strength, MPa		
Mixture ID	Specimen 1	Specimen 2	Average	Specimen 1	Specimen 2	Average
300 – Ref.	52.5	55.7	54.1	6.5	6.7	6.6
300 – MA – 4	45.0	41.3	43.2	5.7	5.6	5.7
300 – MA – 2	43.7	46.4	45.1	5.8	5.4	5.6
300 – AXL – 1	50.8	50.2	50.5	7.6	7.6	7.6
300 – AXL –0.5	39.8*	58.6	58.6	5.6	6.1	5.9
300 – AMP – 0.4	53.6	49.6	51.6	7.0	6.8	6.9
300 – AMP – 0.2	49.5	51.1	50.3	6.4	6.8	6.6
250 – Ref.	44.9	47.9	46.4	6.1	6.5	6.3
250 – MA – 4	39.1	42.0	40.6	5.9	4.8	5.4
250 – MA – 2	28.2	28.7	28.5	4.7	4.4	4.6
250 – AXL – 1	39.3	41.3	40.3	5.7	5.6	5.7
250 – AXL – 0.5	41.0	41.4	41.2	5.8	5.5	5.7
250 – AMP – 0.4	33.6	33.0	33.3	5.6	5.5	5.6
250 – AMP – 0.2	42.6	44.2	43.4	6.2	5.6	5.9

*** Presence of numerous compaction voids, which may be the cause of the lower compressive strength. The result was omitted in the calculation of the average compressive strength.**

All RCC mixtures developed good mechanical properties. The average 28-day compressive strength of the high-performance RCC mixtures (300 kg/m^3 of cement) ranges from 43 to 54 MPa. The 250 kg/m^3 series also developed good compressive strengths, with average results ranging from 29 to 46 MPa. The 28-day flexural strength of all RCC mixtures ranges from 4.6 to 6.9 MPa.

As expected, a variation in the cement content influences the mechanical properties of concrete. The compressive and flexural strengths of the high-performance RCC mixtures (300 kg/m^3 of cement) were systematically higher than those prepared at a lower (250 kg/m^3) cement content. This can be explained by the lower water/cement ratio of the high-performance RCC mixtures.

For both series, the air-entrained RCC mixtures developed lower mechanical properties. Even if the influence of air-entraining admixtures on the flexural strength is not significant, their use has contributed to markedly reducing the compressive strength values of all mixtures.

The compressive strength test results for mixture 250-MA-2 are remarkably lower than those of other air-entrained mixtures. These results are due to a high number of compaction voids, which were observed on the specimens immediately after testing. These specimens probably were not consolidated properly.

4.3.2 Characteristics of the Air-Void System

The characteristics of the air-void system of all RCC mixtures, determined according to a modified version of ASTM C 457, are given in Table 4.4. The first columns give the results of the standard measurements, i.e., without distinguishing the voids according to shape (including compaction voids). The three remaining columns give the results of the second observation in which only the spherical air-voids were recorded (excluding compaction voids).

Overall, test results clearly show that air bubbles were entrained in the RCC mixtures made in the laboratory. Even if air entrainment in dry concrete mixtures is difficult, the spherical air-void content is systematically higher for the air-entrained mixtures than for the reference concretes. The spherical air-void content of both non-air-entrained RCC is 0.6 % while that of the high-performance mixtures ranges from 1.2% to 2.9%, and from 2.3% to 3.9% for the RCC mixtures made with 250 kg/m^3 of cement. These results are similar to those of a previous test series.[1]

The air content of all RCC mixtures made with 250 kg/m^3 of cement is higher than for the high-performance RCC. Air-entraining admixtures are usually more efficient in mixtures having a higher paste volume. In the present case, the greater amount of water available to form air bubbles in the lower cement content was probably the reason more air was entrained in those concretes.

With the exception of mixture 250-MA-2, 40% – 60% of the total air content of the air-entrained mixtures is associated with spherical air-voids (total air content excluding compaction voids/total air content including compaction voids ratio). The total air-void content of the 250-MA-2 mixture is unusually high (9.5%), however, and may result from poor consolidation.

Table 4.4. Characteristics of the Air-Void System

Mixture ID	Including compaction voids			Excluding compaction voids		
	Air content, %	Specific surface, mm⁻¹	Spacing factor, µm	Air content, %	Specific surface, mm⁻¹	Spacing factor, µm
300 – Ref.	2.2	10.2	541	0.6	20.1	482
300 – MA – 4	5.2	19.2	182	1.9	37.1	168
300 – MA – 2	4.2	17.9	207	2.1	27.2	206
300 – AXL – 1	5.6	15.5	202	2.4	28.1	200
300 – AXL –0.5	3.9	20.2	197	2.2	28.2	195
300 – AMP – 0.4	2.6	13.7	375	1.2	23.9	309
300 – AMP – 0.2	4.4	24.2	153	2.9	31.1	157
250 – Ref.	1.6	10.0	624	0.6	16.9	595
250 – MA – 4	6.5	24.8	93	3.2	40.2	113
250 – MA – 2	9.5	11.5	107	2.5	24.2	192
250 – AXL – 1	6.1	18.1	142	3.6	25.6	172
250 – AXL – 0.5	5.3	14.6	192	2.8	21.8	224
250 – AMP – 0.4	6.1	19.8	114	3.9	25.8	116
250 – AMP – 0.2	4.7	19.4	136	2.3	27.7	174

The spacing factor is considered the most important parameter in regard to frost resistance. Although the critical spacing factor required to protect concrete against frost action depends on the type of concrete, the most widely recognized value is 230 µm. This is, for instance, the limit accepted by the Canadian standard A23.1. In Table 4.4, the spacing factors of the non-air-entrained RCC mixtures are all higher than 230 µm. The air-entrained mixtures have good spacing factors: For the RCC mixtures made with 250 kg/m^3 of cement, the values range from 93 to 192 µm when all compaction voids are considered, while those of the high-performance RCC range from 153 to 375 µm.

4.3.3 Microscopic Observations by Scanning Electron Microscopy

Air entraining agents may, in certain instances, contribute to producing a large number of microbubbles in the concrete without entraining any bigger spherical voids. These microbubbles may have a beneficial influence on the frost durability of RCC mixtures. The microscopic observations carried out on both non-air-entrained RCC mixtures and on the air-entrained RCC made with 250 kg/m^3 of cement are summarized in Table 4.5.

These observations clearly confirm that the use of the air-entraining admixtures was sufficient to entrain microscopic air bubbles. A significant number of microvoids (with a diameter lower than 50 µm) were detected. However, the number of microvoids observed in these mixtures is somewhat lower than what has been detected in a previous study (see reference 1).

Table 4.5. Microscopic Observations by Scanning Electron Microscopy

Mixture ID	Spherical air–void diameter, µm									
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	>91
	Number of spherical air-voids per square millimeter									
300 – Ref.	0	0	0	0	0	0	0	0	0	1
250 – Ref.	0	0	0	0	0	0	0	0	0	0.5
250 – MA – 4	8	11	8	6	1	1	0	0	0	2
250 – MA – 2	10	14	4	3	0.5	1	0	0	0.5	0
250 – AXL – 1	3	2	0	2	0.5	1	0.5	0	0	0
250 – AXL – 0.5	0	0.5	0.5	0.5	0	0	0	0	0	3
250 – AMP – 0.4	11	20	8	4	1	0.5	1	0	1	1
250 – AMP – 0.2	16	22	4	1	0	0	0.5	0	0.5	0

The most microscopic spherical voids were recorded for RCC mixtures made with the powdered air-entraining admixture. The Air XL air-entraining admixture was the least efficient in entraining small air bubbles, particularly air-voids having a diameter less than 20 µm.

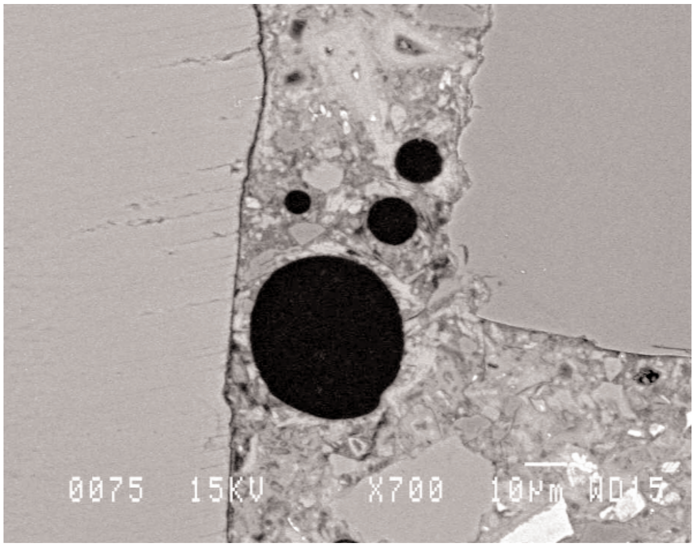

Figure 4.2. Typical SEM observations (X700). (IMG15531)

4.3.4 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A)

The results of the ASTM C 666 rapid freezing and thawing test are summarized in Table 4.6 which gives both the residual length change and the durability factor after 300 cycles. Prior to testing, all specimens were sealed cured for 14 days.

The non-air-entrained RCC mixtures were not resistant to rapid freezing and thawing cycles in water; both reference concretes failed before reaching 300 cycles. The residual

Table 4.6. ASTM C 666 Test Results After 300 Cycles

Mixture ID	Durability factor, %	Length change, µm/m
300 – Ref.	43[1]	4270
250 – Ref.[2]	0	11670
250 – MA – 4	100	39
250 – MA – 2	100	114
250 – AXL – 1	100	115
250 – AXL – 0.5	100	48
250 – AMP – 0.4	100	104
250 – AMP – 0.2	100	153

[1] **Durability factor was 61% after 268 cycles.**
[2] **Specimens failed after 268 cycle.**

length changes of the air-entrained RCC are lower than 200 µm/m, with results ranging from 39 to 153 µm/m. For most concretes, it generally is assumed that microcracking becomes significant when the length change exceeds approximately 200 µm/m.[2] The durability factors obtained corroborate these results; the air-entrained mixtures have a durability factor of 100%, while those of the non-air-entrained RCC mixtures are lower than 60%. A concrete is considered frost resistant when its durability factor is higher than or equal to 60%. However, values lower than 90% indicate the onset of deterioration.

Results clearly show that, no matter the type or the dosage used, the incorporation of an air-entraining admixture in the RCC mixtures tested has a beneficial influence on their frost resistance. *Data also clearly show that very little air is needed to protect RCC against frost-induced microcracking.*

4.3.5 Deicer Salt-Scaling Resistance (ASTM C 672)

Salt-scaling tests were carried out on a selected number of RCC mixtures in accordance with ASTM C 672 Standard. The mass of scaled-off particles and the ASTM rating after 50 freezing and thawing cycles are given in Table 4.7. Each individual test result is shown in brackets.

Concrete generally is considered to have an adequate scaling resistance if the mass of scaled-off particles does not exceed 1 kg/m^2 after 50 cycles of freezing and thawing. The loss of mass after 50 cycles of the non-air-entrained RCC mixtures is higher than the 1 kg/m^2 limit; the mass of scaled-off particles for the high-performance RCC is 2.06 kg/m^2, and 9.00 kg/m^2 for the RCC made with 250 kg/m^3 of cement.

Considering that the mass loss of the reference RCC made with 250 kg/m^3 of cement is extremely high (9.00 kg/m^2), the influence of the use of air-entraining admixtures on the salt-scaling resistance is shown clearly in Figure 4.3. Almost all air-entrained RCC

Table 4.7. ASTM C 672 Test Results After 50 Cycles

Mixture ID	Mass of scaled–off particles, kg/m²	Rating
300 – Ref.	2.06 (0.90 ; 3.23)	4.5 (4 ; 5)
250 – Ref.	9.00 (8.53 ; 9.45)	4.5 (4 ; 5)
250 – MA – 4	0.57 (0.52 ; 0.61)	2.5 (2 ; 3)
250 – MA – 2	0.72 (0.82 ; 0.62)	3.5 (4 ; 3)
250 – AXL – 1	0.45 (0.55 ; 0.35)	3 (3 ; 3)
250 – AXL – 0.5	1.58 (2.06 ; 1.09)	5 (5 ; 5)
250 – AMP – 0.4	0.97 (1.40 ; 0.53)	4 (4 ; 4)
250 – AMP – 0.2	0.52 (0.49 ; 0.54)	4 (4 ; 4)

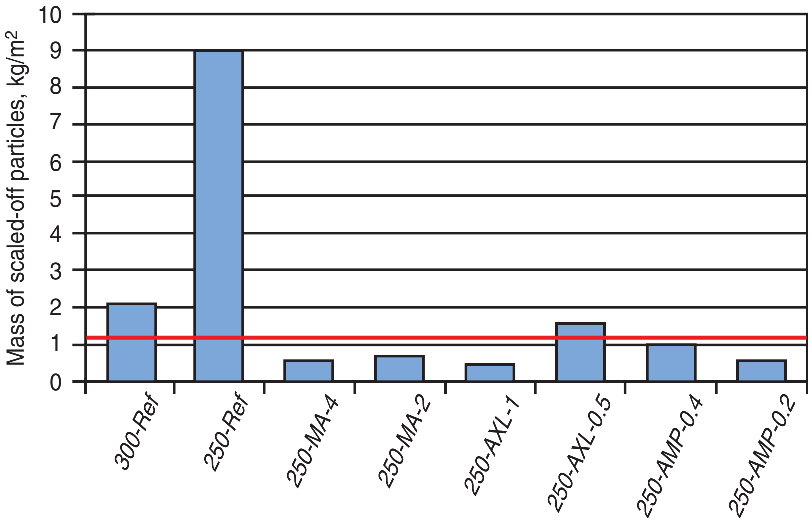

Figure 4.3. ASTM C 672 test results after 50 daily cycles.

mixtures made with 250 kg/m³ of cement have a good scaling resistance to deicer salts. Only the air-entrained RCC mixture made with the very low dosage of Air XL admixture (250-AXL-0.5) has a mass of scaled-off particles higher than the 1 kg/m² limit.

4.3.6 ASTM C 1262 Test Results

Frost-durability tests also were carried out in accordance with ASTM C 1262 Standard. Test results after 50 freezing and thawing cycles are given in Table 4.8.

Test results also are presented in Figure 4.4. As can be seen, the reference (non-air-entrained) mixture prepared with a binder content of 250 kg/m^3 is the only one that

Table 4.8. ASTM C 1262 Test Results After 50 Cycles

Mixture ID	Mass of scaled–off particles, kg/m^2	Mass loss, % of the initial dry mass
300 – Ref.	0.37 (0.39 ; 0.54 ; 0.20)	0.40 (0.41 ; 0.58 ; 0.20)
250 – Ref.	1.84 (1.65 ; 1.54 ; 2.33)	1.96 (1.72 ; 1.70 ; 2.45)
250 – MA - 4	0.20 (0.19 ; 0.19 ; 0.22)	0.21 (0.20 ; 0.20 ; 0.23)
250 – MA - 2	0.21 (0.15 ; 0.22 ; 0.25)	0.23 (0.16 ; 0.24 ; 0.28)
250 – AXL - 1	0.36 (0.46 ; 0.40 ; 0.21)	0.38 (0.48 ; 0.43 ; 0.22)
250 - AXL - 0.5	0.14 (0.22 ; 0.07 ; 0.14)	0.15 (0.23 ; 0.08 ; 0.15)
250 - AMP - 0.4	0.20 (0.19 ; 0.21 ; 0.19)	0.20 (0.20 ; 0.23 ; 0.16)
250 - AMP - 0.2	0.46 (0.49 ; 0.16 ; 0.72)	0.48 (0.52 ; 0.17 ; 0.76)

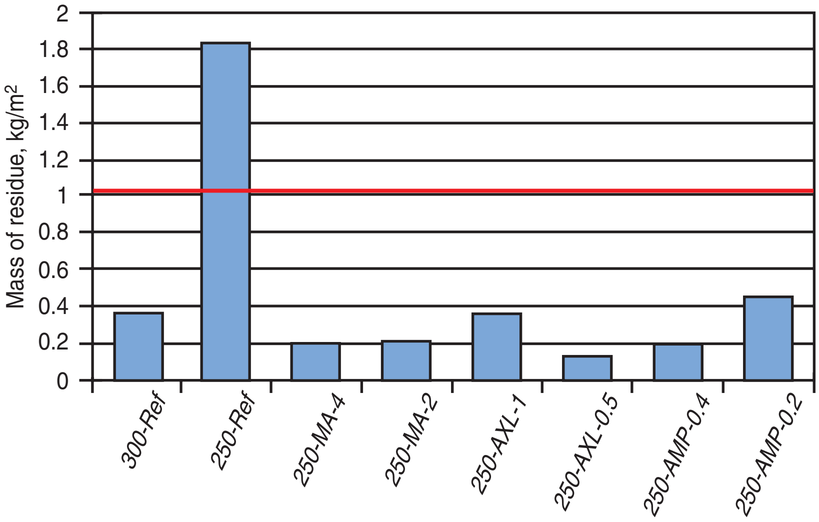

Figure 4.4. Mass of residues after 50 cycles (ASTM C 1262).

failed the test. All the others have a mass of residues of less than 1% after 50 daily cycles. It is easy to see the beneficial influence of the air-entraining admixture in RCC with a binder content of 250 kg/m^3. It appears that a non-air-entrained RCC with a binder content of 300 kg/m^3 performs well under this test.

4.4 DISCUSSION

Test results show that it was possible to entrain a certain amount of spherical air bubbles in all mixtures containing an air-entraining admixture. Globally, ASTM C 457 data and the SEM observations indicate that, although difficult, air entrainment in RCC is not totally impossible. These encouraging results probably can be explained by the fact that all mixtures were batched in a countercurrent pan mixer. Previous experience has shown that pan mixers can exhibit a much higher kneading energy than other types of mixers.[1] This high energy certainly facilitates the introduction of air during the mixing period and the subsequent action of the air-entraining admixture.

The use of an air-entraining admixture clearly resulted in an improved air-void network. There is, however, no clear influence of the dosage and the type of air-entraining agent used. These results contradict those of previous studies during which it was found that the type of air-entraining admixture had a direct bearing on air entrainment in dry concrete mixtures.[1,3] More research is needed to understand the real influence of the type of admixture.

As previously mentioned in Chapter 1, air-voids offer good protection against frost action when they are spherical in shape and fairly well dispersed in the cement paste. With the exception of one RCC mixture (300-AMP-0.4), all the spacing factors obtained for the air-entrained RCC were lower than 230 µm when only the spherical air-voids were taken into account. 230 µm often is considered the critical spacing factor below which concrete mixtures are considered to be protected properly against frost action.

These spacing factor values should, however, be considered with some caution.[1] The fact that the air-void system of most mixtures was found to consist, to a large fraction, of compaction voids underlines the somewhat ambiguous application of the ASTM C 457 standard to RCC. The irregular shape of these air-voids and their random distribution throughout the paste seem to lead to large variations of the air-void characteristics. It is also clear that the characterization of an air-void system made of large irregularly shaped compaction voids using a method designed for spherical air-voids of various sizes is not appropriate, especially if it is considered that no one has ever clearly established the role played by these voids in the protection against frost damage.[4] Compaction voids may be interconnected: if so, when they become saturated (if enough water is available), their influence on frost resistance may be detrimental.

Globally, test results emphasize the overwhelming influence of air entrainment on the frost durability of RCC. Test data also demonstrate that very little entrained air is required to adequately protect RCC against frost-induced microcracking and deicer salt-scaling. These results are in good agreement with those of a previous investigation.[5] It should be noted that the influence of air entrainment on the deicer salt-scaling resistance of RCC (tested according to ASTM C 672) is particularly encouraging. As discussed in Chapter 1, RCC has been found in the past to be particularly sensitive to this type of deterioration.

Finally, results summarized in Table 4.8 and illustrated in Figure 4.3 tend to confirm the ability of ASTM C 1262 to discriminate between durable and nondurable mixtures. The poor performance of mixture 250-Ref. suggests that the test is severe enough to induce degradation to mixtures not adequately protected against frost action.

4.5 CONCLUDING REMARKS

Test results show that it was possible to entrain a certain amount of spherical air bubbles in all mixtures containing an air-entraining admixture. Although difficult, air entrainment in RCC is not totally impossible.

Test results emphasize the overwhelming influence of air entrainment on the frost durability of RCC. Test data also demonstrate that very little entrained air is required to adequately protect RCC against frost-induced microcracking and deicer salt-scaling.

Finally, results tend to confirm the ability of ASTM C 1262 to discriminate between durable and nondurable mixtures.

4.6 REFERENCES

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Chapter 5

INFLUENCE OF SILICA FUME AND FLY ASH ON THE FROST DURABILITY OF RCC

In North America, most RCC pavements typically are made of Type 10 (ASTM Type I) cement and fly ash. When used as partial replacement for cement, fly ash can contribute to reducing the cost of production. The use of fly ash also is believed to improve the consolidation of the concrete by increasing the percentage of fines in the mixture. The filler effect of fly ash particles may influence the packing density of the mixture, which enhances the overall performance of RCC. The addition of fly ash also has been found to improve the wearing surface finish of RCC pavements. To increase the amount of fine particles in RCC mixtures, supplementary cementing materials, such as fly ash, often are used as partial sand replacement.

Although widely used in Europe, other supplementary cementing materials such as slag and silica fume are not added commonly in western Canada or the United States. Silica fume has, however, been used over the past 10 years in eastern Canada for the construction of high-performance RCC pavements.[1] Silica fume not only improves the mechanical properties of RCC mixtures but also speeds up their mechanical strength development. Silica fume is used mostly in blended cements, at a level of replacement of approximately 7%. Recent studies have shown that the use of silica fume contributes to improving the frost durability and deicer salt-scaling resistance of RCC mixtures.[2,3]

To study the influence of supplementary cementing materials on the frost durability of RCC, two series of mixtures were produced: a first series of ordinary RCC mixtures (total binder content ≤ 250 kg/m^3) and a second series of high-performance RCC mixtures (total binder content ≥ 300 kg/m^3). For each series, one RCC mixture was made using a Class C fly ash, a second mixture was produced with a Class F fly ash, and a third mixture was made with a blended silica fume cement. Both fly ashes were used as partial cement replacement and therefore considered in the total binder content (25% of the total mass of binder).

As previously mentioned, the blended cement contained 7% silica fume. The ordinary and high-performance non-air-entrained RCC mixtures produced in the previous chapter (Chapter 3) served as reference mixtures for this test series.

The 28-day compressive and flexural strengths of all mixtures were determined in accordance with ASTM C 39 and ASTM C 78, respectively. The air-void characteristics of all mixtures were determined according to a modified version of ASTM C 457. The amount of micro air-voids (diameter < 50 µm) entrained in the concrete also was determined by image analysis on polished sections using a scanning electron microscope. All mixtures were tested according to ASTM C 666 – Procedure A, ASTM C 672, and ASTM C 1262.

5.1 MIXTURE CHARACTERISTICS

The characteristics of all mixtures are given in Table 5.1. The mixture codification used throughout this chapter is given in Figure 5.1.

Table 5.1. Characteristics of RCC Mixtures

Mixture ID	Cement, kg/m^3	Fly ash, kg/m^3	Water, L/m^3	Fine aggregate, kg/m^3	Coarse aggregate, kg/m^3	Water reducer[1], ml/m^3	Water/ binder
300 – T	296[2]	–	102	747	1347	1200	0.34
300 – T10SF	298[3]	–	98	765	1338	1200	0.33
300 – FA – C	225[2]	75	100	761	1343	1200	0.33
300 – FA – F	225[2]	75	100	739	1347	1200	0.33
250 – T	246[2]	–	107	758	1355	1000	0.43
250 – T10SF	249[3]	–	103	781	1348	1000	0.41
250 – FA – C	187[2]	62	101	776	1358	1000	0.41
250 – FA – F	189[2]	63	100	763	1357	1000	0.40

[1] Eucon WR-75 manufactured by Euclid Admixture Canada Inc.
[2] CSA – Type 10 cement.
[3] CSA – Silica fume blended cement.

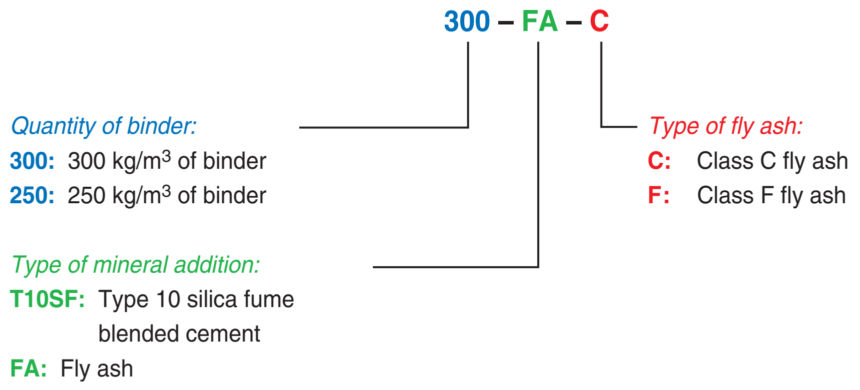

Figure 5.1. Codification for RCC mixtures.

5.2 TEST RESULTS AND DISCUSSION

5.2.1 Fresh Concrete Properties

The properties of the fresh RCC mixtures (unit weight and VEBE time) are given in Table 5.2. The Modified Proctor test was carried out to determine the unit weight of the fresh RCC. The test was performed in accordance with ASTM D 1557 – *Modified Proctor Method (Method D)*. VEBE measurements were conducted in accordance with ASTM C 1170 – *Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table (Method A)*. The VEBE Time was measured at different intervals (10, 30, and 60 minutes

Table 5.2. Fresh Concrete Properties

Mixture ID	Unit weight, kg/m³	VEBE time, in seconds		
		10 min.	30 min.	60 min.
300 – Ref.	2493	50	>90	>120
300 – T10SF	2454	45	60	> 90
300 – FA – C	2458	25	35	45
300 – FA – F	2477	35	30	40
250 – Ref.	2468	25	35	55
250 – T10SF	2458	50	60	> 90
250 – FA – C	2443	55	61	70
250 – FA – F	2504	35	55	–

after the initial water-binder contact), providing valuable information on the influence of supplementary cementing materials on the time evolution of the RCC workability.

Although the VEBE time increases with time for all RCC mixtures, the use of silica fume accelerates the loss of workability, which subsequently can affect the consolidation operations. By increasing the percentage of fines in the mixtures, both fly ashes tend to improve the fluidity of the RCC mixtures. The workability of the RCC mixtures containing fly ash, and particularly the high-performance RCC series, was found to be more constant with time.

5.2.2 Compressive and Flexural Strengths

The 28-day compressive and flexural strengths are given in Table 5.3. As can be seen, the partial replacement of cement by silica fume or fly ash had a beneficial effect on the mechanical properties of RCC mixtures.

With the exception of mixture 300 – T10SF, RCC mixtures containing supplementary cementing materials developed better compressive strengths than the non-air-entrained reference RCC mixtures. Unexpectedly, the high-performance RCC mixture containing silica fume (300 – T10SF) developed fairly low mechanical strengths. Both the 28-day compressive and flexural strength test results were lower than those of the reference concrete. Observations made on the ruptured specimens after testing revealed an unusually high amount of compaction voids, which could explain the surprising test results. The casting of RCC specimens was difficult, considering the rapid loss of workability. Test results of the 250 – 10SF are more consistent with results found in the literature; the silica fume usually improves the mechanical strength of RCC mixtures.[3,4]

Although their effect on the 28-day flexural strength is less obvious, the addition of both fly ashes improved the 28-day compressive strengths of all RCC mixtures. Tests results are quite variable from one fly ash to the other.

Table 5.3. Compressive and Flexural Strengths of RCC Mixtures

	Compressive strength, MPa			Flexural strength, MPa		
Mixture ID	Specimen 1	Specimen 2	Average	Specimen 1	Specimen 2	Average
300 – Ref.	52.5	55.7	54.1	6.5	6.7	6.6
300 – T10SF	47.0	46.0	46.5	6.1	6.1	6.1
300 – FA – C	60.8	63.2	62.0	6.1	6.3	6.2
300 – FA – F	70.9	70.5	70.7	7.1	6.5	6.8
250 – Ref.	44.9	47.9	46.4	6.1	6.5	6.3
250 – T10SF	61.1	62.8	62.0	6.8	7.2	7.0
250 – FA – C	57.2	55.7	56.5	5.9	6.6	6.3
250 – FA – F	50.5	47.1	48.8	5.5	6.0	5.8

5.2.3 Characteristics of the Air-Void System

The characteristics of the air-void system of all mixtures are given in Table 5.4. The results of the standard measurements of ASTM C 457 (including compaction voids) are given in the first columns while the last three columns present the results of the observations in which only the spherical air-voids were recorded (excluding compaction voids).

The RCC mixtures containing the different supplementary cementing materials were produced without an air-entraining agent. Results given in Table 5.4 are typical of non-air-entrained RCC mixtures. There is no influence of either the silica fume or fly ash on the characteristics of the air-void system when mixtures are not air-entrained. It is clear that most, if not all, of the air-voids observed resulted from the consolidation operations.

Table 5.4. Characteristics of the Air-Void System

	Including compaction voids			Excluding compaction voids		
Mixture ID	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm
300 – Ref.	2.2	10.2	541	0.6	20.1	482
300 – T10SF	2.9	13.1	390	1.0	15.0	544
300 – FA –C	3.2	11.8	399	0.9	12.3	699
300 – FA – F	3.5	11.2	419	0.4	27.1	450
250 – Ref.	1.6	10.0	624	0.6	16.9	595
250 – T10SF	3.9	10.1	433	0.9	18.9	446
250 – FA – C	3.7	9.1	477	0.6	11.2	857
250 – FA – F	4.4	10.8	342	0.4	14.5	835

5.2.4 Microscopic Observations by Scanning Electron Microscopy

Results of the scanning electron microscope observations are summarized in Table 5.5. As expected, there is no significant influence of silica fume or fly ash on the content in micro air-voids. These observations are in good agreement with those presented in the previous subsection.

Table 5.5. Microscopic Observations by Scanning Electron Microscopy

Mixture ID	Spherical air–void diameter, µm/mm^2									
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	>91
	Number of spherical air-voids per square millimeter									
300 – Ref.	–	–	–	–	–	–	–	–	–	1
300 – T10SF	1	8	–	–	–	–	–	–	–	1
300 – FA – C	1	7	1	1	–	–	–	–	1	–
300 – FA – F	–	–	–	–	–	–	–	–	–	–
250 – Ref.	–	–	–	–	–	–	–	–	–	0.5
250 – T10SF	1	–	1	–	–	–	–	–	–	–
250 – FA – C	–	–	–	–	–	–	–	–	–	–
250 – FA – F	–	–	–	–	–	–	–	–	–	–

5.2.5 Resistance to Rapid Freezing and Thawing (ASTM C 666 – Procedure A)

ASTM C 666 test results are summarized in Table 5.6. The residual length change and the durability factor after 300 cycles are given. When appropriate, the maximum number of cycles withstood by the specimens before failure appears in brackets. Since surface scaling may influence the durability factor, the residual length change usually is considered to be the most reliable indicator of internal cracking. When ordinary concrete freezes in water, a length change value in excess of approximately 200 µm/m generally indicates the onset of significant microcracking.[5]

Table 5.6. ASTM C 666 Test Results After 300 Cycles

Mixture ID	Number of cycles	Durability factor, %	Length change, µm/m
300 – Ref.	300	43[1]	4270
300 – T10SF	300	100	1430
300 – FA – C	Failed (147)	0	0
300 – FA – F	300	47	1510
250 – Ref.	Failed (268)	0	11670
250 – T10SF	300	77	1770
250 – FA – C	300	100	120
250 – FA – F	Failed (164)	0	1250

[1] The durability factor was 61% after 268 cycles.

As can be seen, most RCC mixtures were found to be susceptible to frost-induced microcracking. These results were to be expected considering the relative severity of the ASTM C 666 procedure and the fact that none of the mixtures of this test series could benefit from the protection offered by entrained air.

It should be noted that the addition of silica fume was sufficient to protect the high-performance concrete mixture (produced with a binder content of 300 kg/m^3 of cement type 10SF) against frost action. The durability factor of this mixture remained at 100% after 300 consecutive cycles of freezing and thawing. The beneficial influence of silica fume is in good agreement with previous test results.[3,6]

As can be seen in Table 5.6, the length change of mixture 300 – T10SF reached 1430 µm/m after the same number of cycles. Similar results (i.e., good durability factor and high length change) were observed in a previous investigation,[3,6] and were explained by local degradation of the material. As previously emphasized, the microstructure of RCC can be highly heterogeneous. Zones of high water-binder (or water-cement) ratio often are distributed unevenly across the material. In a non-air-entrained matrix, these zones are likely to suffer from internal microcracking while those characterized by a lower water-binder ratio may remain sound.

The beneficial influence of silica fume on the resistance of RCC to frost-induced microcracking should be considered with caution. Test results indicate that the partial replacement of cement by silica fume did not improve the behavior of mixture 250 – T10SF. Apparently, there exists a critical binder (cement) content (hence a maximum water-binder ratio) below which it is extremely difficult to produce frost-durable non-air-entrained RCC.

Globally, the addition of fly ash did not seem to have any significant effect on the resistance of concrete to frost-induced microcracking. Three of the four mixtures suffered important degradation after a limited number of cycles. Curiously, mixture 250 – FA – C managed to resist to 300 consecutive cycles of freezing and thawing without any significant deterioration. This result is particularly surprising considering that mixture 300 – FA – C, produced at a higher binder content, was found to be frost susceptible. The good performance of mixture 250 – FA – C is hard to explain and cannot be linked to any influence of the Class C fly ash on the air-void network characteristics of RCC.

5.2.6 ASTM C 672 Test Results

Deicer salt-scaling tests were carried out on all RCC mixtures in accordance with ASTM C 672. For each mixture, the mass of scaled-off particles after 50 daily freezing and thawing cycles is given in Table 5.7 together with the corresponding ASTM rating. Test results also are summarized in Figure 5.1.

As mentioned in the previous chapter, the scaling resistance of concrete generally is considered satisfactory if, after the completion of the 50 freezing and thawing cycles, the mass of scaled-off particles is lower than or equal to 1 kg/m^2.

Table 5.7. ASTM C 672 Test Results After 50 Cycles

Mixture ID	Mass of scaled-off particles, kg/m^2	Rating
300 – Ref.	2.06 (0.90 ; 3.23)	4.5 (4 ; 5)
300 – T10SF	0.22 (0.26 ; 0.17)	2 (2 ; 2)
300 – FA – C	6.17 (7.66 ; 4.68)	5 (5 ; 5)
300 – FA – F	4.52 (4.76 ; 4.27)	5 (5 ; 5)
250 – Ref.	9.00 (8.53 ; 9.45)	4.5 (4 ; 5)
250 – T10SF	0.53 (0.81 ; 0.25)	4 (5 ; 3)
250 – FA – C	8.98 (9.65 ; 8.31)	5 (5 ; 5)
250 – FA – F	2.69 (4.17 ; 1,21)	5 (5 ; 5)

Test results clearly emphasize the susceptibility of non-air-entrained RCC mixtures to deicer salt-scaling. In most cases, the mass of scaled-off particles after 50 cycles is well above the 1 kg/m^2 limit. These results are in good agreement with those of previous investigations.[2,6-8]

Results appearing in Table 5.7 also emphasize the very beneficial influence of silica fume. As can be seen, whatever the binder content (i.e., whatever the water-binder ratio), the addition of silica fume was sufficient to reduce the mass of scaled-off particles below the 1 kg/m^2 limit. These results confirmed observations made in previous studies in which the positive influence of silica fume was attributed to its influence on the microstructure of RCC.[2] The addition of silica fume was found to reduce the heterogeneity of the paste fraction of RCC.[9] It is believed that the enhancement of the paste homogeneity contributes to improving the resistance of RCC to surface scaling.

Finally, the partial replacement of cement with fly ash did not have any significant influence on the deicer salt-scaling resistance of RCC. These results are also in good agreement with the results of a previous investigation.[2]

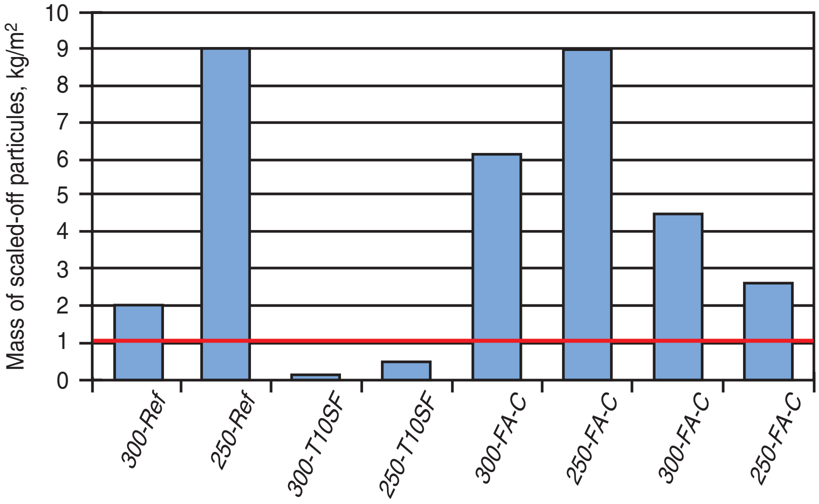

Figure 5.2. ASTM C 672 test results.

5.2.7 ASTM C 1262 Test Results

ASTM C 1262 test results after 50 freezing and thawing cycles are given in Table 5.8 and in Figure 5.3.

Globally, test results summarized in Table 5.8 clearly confirm that the ASTM C 1262 procedure is much less severe than the ASTM C 672 method. Six out of 8 results are

Table 5.8. ASTM C 1262 Test Results After 50 Cycles

Mixture ID	Mass of scaled-off particles, kg/m²	Mass loss, % of the initial dry mass
300 – Ref.	0.37 (0.39 ; 0.54 ; 0.20)	0.40 (0.41 ; 0.58 ; 0.20)
300 – T10SF	0.09 (0.09 ; 0.035 ; 0.13)	0.09 (0.10 ; 0.04 ; 0.14)
300 – FA – C	0.34 (0.46 ; 0.33 ; 0.22)	0.34 (0.45 ; 0.35 ; 0.23)
300 – FA – F	0.43 (0.46 ; 0.33 ; 0.49)	0.49 (0.52 ; 0.37 ; 0.57)
250 – Ref.	1.84 (1.65 ; 1.54 ; 2.33)	1.96 (1.72 ; 1.70 ; 2.45)
250 – T10SF	0.10 (0.15 ; 0.08 ; 0.06)	0.10 (0.16 ; 0.08 ; 0.06)
250 – FA – C	0.78 (0.88 ; 0.67 ; 0.79)	0.86 (0.93 ; 0.74 ; 0.90)
250 – FA – F	3.67 (3.76 ; 3.63 ; 3.62)	4.02 (4.12 ; 4.12 ; 3.83)

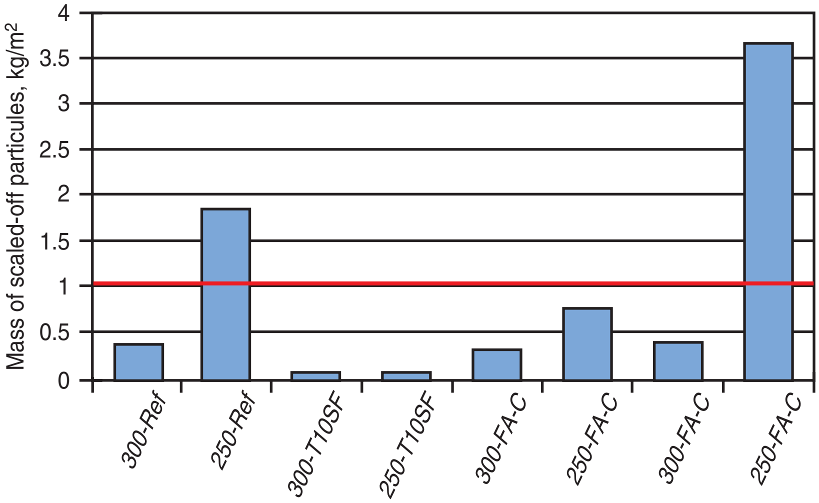

Figure 5.3. ASTM C 1262 test results after 50 cycles – mass of scaled-off particles.

below the 1% mass loss limit. Test data also emphasize the marked influence of binder content (water-binder ratio) on the durability of RCC. An increase of the total binder content from 250 kg/m^3 to 300 kg/m^3 (and therefore a reduction of the water-binder ratio from 0.41 to 0.34) has contributed to substantially reducing deterioration.

Test results confirm the very beneficial influence of silica fume addition. As can be seen, the partial replacement of cement by silica fume has contributed to limiting the degradation of both mixtures to negligible values. As for the ASTM C 672 test data, the use of both classes of fly ash had very little influence on the performance of RCC.

5.3 CONCLUDING REMARKS

Most RCC mixtures were found to be susceptible to frost-induced microcracking. These results were to be expected considering the relative severity of the ASTM C 666 procedure and the fact that none of the mixtures of this test series was air-entrained.

Test results also clearly emphasize the susceptibility of non-air-entrained RCC mixtures to deicer salt-scaling. However, whatever the binder content (i.e., whatever the water-binder ratio), the addition of silica fume was sufficient to reduce the mass of scaled-off particles below the 1 kg/m^2 limit. The use of fly ash had very little influence on the scaling resistance of RCC. The beneficial influence of silica fume and the limited effect of fly ash were confirmed by the ASTM C 1262 test results.

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Chapter 6

INFLUENCE OF MIXER TYPE ON THE PRODUCTION OF FROST-DURABLE RCC MIXTURES

The formation of air bubbles is only possible if there is, in the mixture, enough water available to form a film around each spherical void and if the energy of the mixer is sufficient. Air entrainment also requires a sufficient mixing time. As shown in Chapter 4, the fact that it was possible to entrain a certain amount of spherical air bubbles for mixtures batched in the laboratory tends to indicate that, even if difficult, air entrainment in RCC is possible. Countercurrent pan-mixers, such as the one used in this study, are known for their high kneading energy, which certainly facilitates the introduction of air during the mixing period. But can air be entrained in RCC mixtures produced in large-scale industrial plants?

6.1 TEST PROGRAM

In this part of the study, eight additional RCC mixtures were produced and tested: a first series of four RCC mixtures was prepared in October 1999 in a twin shaft continuous flow pugmill mixer and a second series was produced in a central concrete batch plant in May 2000. For each series, one reference mixture (without any air-entraining admixture) was prepared and three different air-entraining agents were tested at a single dosage. All RCC mixtures were made with a blended silica fume cement.

Continuous flow pugmill mixers are high production units known to provide a vigorous mixing action that facilitates the homogeneous dispersion of the water. The first series of RCC mixtures was produced in a volumetric proportioning pugmill mixer (see Figure 6.1) which was completely calibrated prior to production.

The feeding rate of the aggregates was controlled by a speed belt, calibrated to accurately deliver the specified quantity of material within the required tolerance (see Table 6.1). The blended silica fume cement was stored in a separate silo, which was equipped and operated so that feeding was within the specified tolerances. The water and each admixture were stored, measured, and introduced separately. When needed, the powdered air-entraining agent was manually introduced onto the speed belt and protected from the wind, and all dry materials were incorporated into the mixer at the same time.

The second series of four RCC mixtures was prepared in a central concrete batch plant according to a mixing sequence similar to that found in practice. Although the mixing energy is significantly lower than that of continuous flow pugmill mixers, the mixing time is higher, usually allowing the production of a more homogeneous RCC mixture.

For each series of RCC mixtures, a number of specimens were prepared: 150x300 mm cylinders for compressive strength tests; 100x100x400-mm beams for ASTM C 1262 tests,

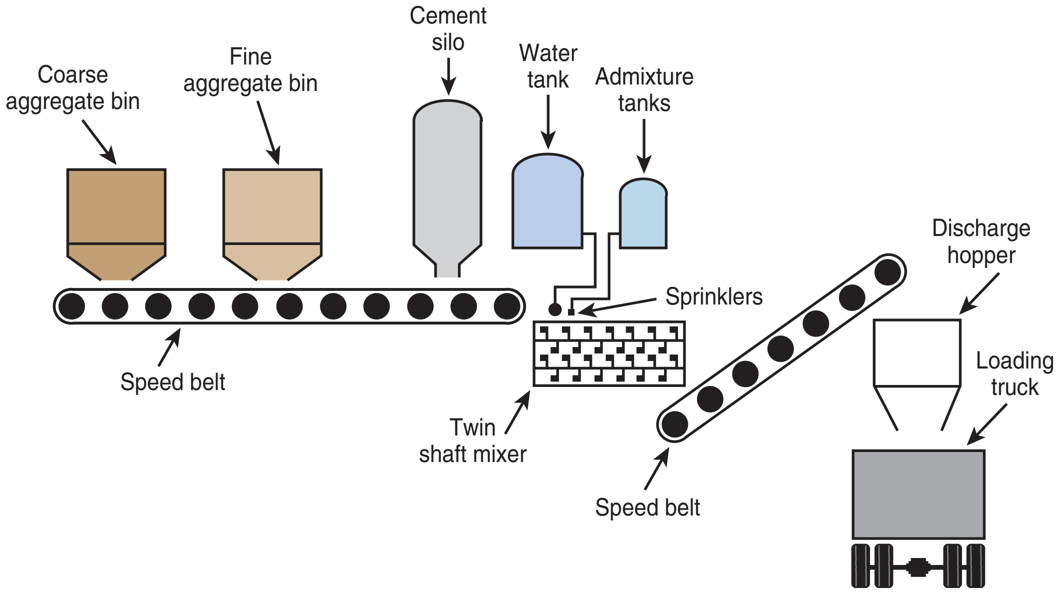

Figure 6.1. Configuration of the continuous flow pugmill mixer used.[1]

Table 6.1. Batching Tolerances

Constituent	Tolerance, % by mass
Cement	± 2 %
Water	± 3 %
Each admixture	± 3 %
Each aggregate	± 2 %

ASTM C 666 tests, and ASTM C 457 tests; and 225x350x75-mm slabs for ASTM C 672 tests. All specimens (cylinders, beams, and slabs) were consolidated on-site with a Kango percussion hammer. Prior to testing, all specimens were moist cured until the day of testing.

Immediately after the mixing process, the properties of the fresh RCC mixtures produced were measured. The 28-day compressive strength was determined in accordance with ASTM C 39. The air-void characteristics of all mixtures were determined according to the modified version of ASTM C 457 and microscopic observations using a scanning electron microscope were carried out. All RCC mixtures were subjected to the ASTM C 666 (Procedure A) test, the ASTM C 672 test, and the ASTM C 1262 frost-durability test.

6.2 MATERIALS

With the exception of the aggregates, all materials used for the large-scale production of RCC were similar to those used for the laboratory-made RCC mixtures. Their properties were described in Chapter 2. Fresh drinking water from the city of Montreal was used since the large-scale production of RCC was carried out in that area.

Both coarse and fine aggregates were from the St. Gabriel quarry located in the Montreal area. A crushed granitic aggregate, with a nominal maximum size of 20 mm, was used as coarse aggregate. The aggregate particles are shaped partly by attrition and have rounded edges. The coarse aggregates had a specific gravity of 2.69 and a 24-hour absorption of 0.71 %. The fine aggregate used was a natural granitic sand with a specific gravity of 2.70, a 24-hour absorption of 0.56%, and a fineness modulus of 2.7. Figure 6.2 gives the grading curves of the coarse aggregate and the fine aggregate.

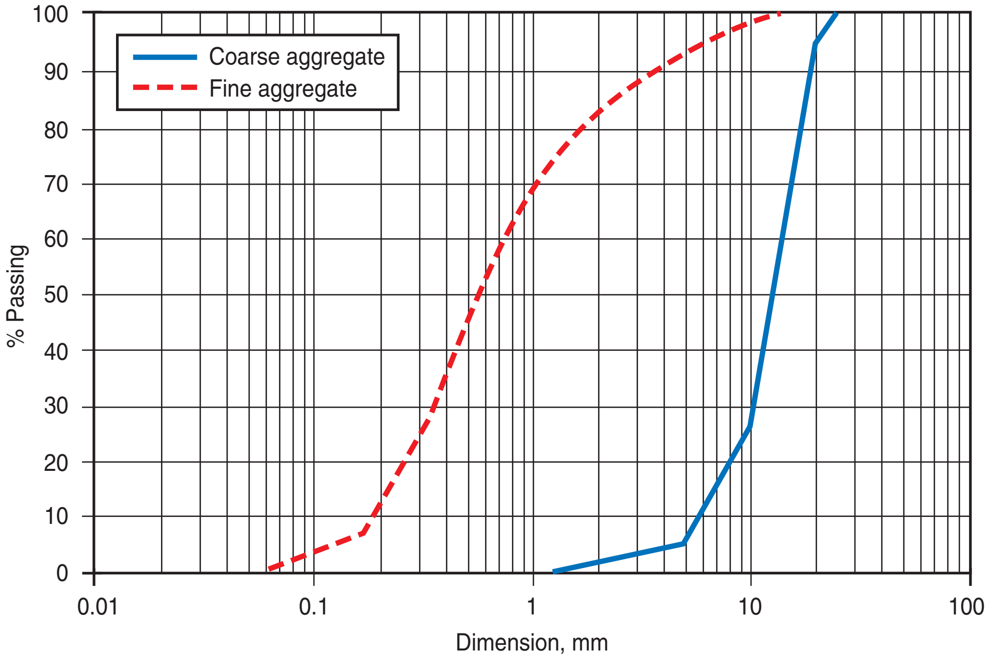

Figure 6.2. Coarse and fine aggregates grading curves.

6.3 MIXTURE CHARACTERISTICS

Table 6.2 presents the mixture characteristics of the RCC mixtures produced in the continuous flow pugmill mixer and in the central concrete batch plant. All RCC mixtures were designed using the Solid Suspension Model. During the design calculation, the air content of the air-entrained mixtures was assumed to be equal to 6%. The mixture codification is shown in Figure 6.3.

Table 6.2. RCC Mixture Characteristics

Mixture ID	Silica fume blended cement, kg/m^3	Water, L/m^3	Fine aggregates, kg/m^3	Coarse aggregates, kg/m^3	Water reducer, ml/m^3	Air entraining agent, ml/m^3	Water/ binder ratio
PUG – Ref.	301	108	761	1331	1200[4]	–	0.36
PUG – MA	291	94	798	1289	1200[4]	1200[1]	0.32
PUG – AXL	293	89	807	1304	1200[4]	600[2]	0.30
PUG – AMP	309	102	784	1267	1200[4]	1200[3,5]	0.33
PRE – Ref.	303	96	784	1340	1200[4]	–	0.32
PRE – MA	297	95	800	1256	1200[4]	1200[1]	0.32
PRE – AXL	304	88	793	1270	1200[4]	600[2]	0.29
PRE – AMP	303	92	814	1256	1200[4]	1200[3,5]	0.30

[1] Micro Air manufactured by Master Builders Technologies
[2] AireX-L manufactured by Euclid Admixture Canada Inc.
[3] Airmix 200-P manufactured by Euclid Admixture Canada Inc.
[4] Eucon WR-75 manufactured by Euclid Admixture Canada Inc.
[5] The value is in g/m^3

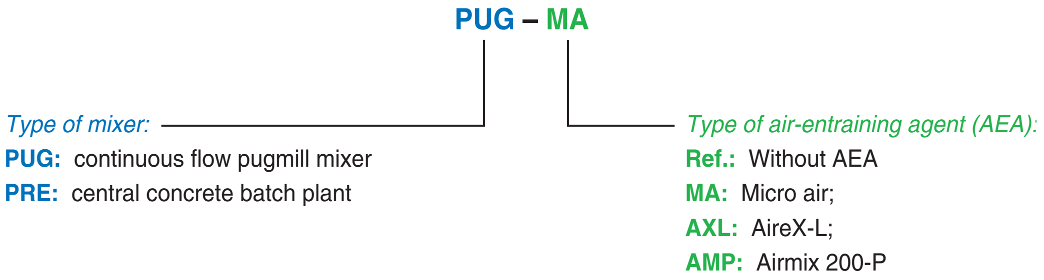

Figure 6.3. RCC mixture codification.

6.4 FRESH RCC PROPERTIES

The properties of the fresh RCC mixtures are given in Table 6.3. The unit weight was measured immediately after the mixing process in accordance with ASTM D 1557. VEBE tests, performed in accordance with ASTM C 1170, were carried out 10 minutes after the initial water-binder contact. All mixtures were designed to have a VEBE workability of approximately 60 seconds.

The unit weight of all RCC mixtures ranges from 2478 to 2540 kg/m^3. Most RCC mixtures made using an air-entraining agent have a unit weight slightly lower than their reference mixture, indicating that air bubbles probably were entrained in these mixtures.

In general, most RCC mixtures had VEBE times comprised between 30 and 50 seconds. Results indicate that the use of an air-entraining admixture did not have a significant influence on the workability of the mixtures. Similarly, the type of production unit did not have any significant effect on the workability of the mixtures. All RCC mixtures have

Table 6.3. Fresh RCC Properties

Mixture ID	Unit weight, kg/m^3	VEBE time, in seconds 10 minutes
PUG – Ref.	2520	40
PUG – MA	2506	31
PUG – AXL	2491	38
PUG – AMP	2478	15
PRE – Ref.	2540	46
PRE – MA	2514	36
PRE – AXL	2514	39
PRE – AMP	2514	50

a workability that allowed for an efficient consolidation of the material. Although the VEBE time measured on mixture PUG-AMP was quite low, its workability was adequate to ensure proper placement and consolidation of the RCC at the time of casting (approximately 30 minutes after mixing).

6.5 HARDENED RCC PROPERTIES

6.5.1 Compressive Strength

The 28-day compressive strength was determined in accordance with ASTM C 39. Test results are given in Table 6.4.

Good compressive strengths generally were obtained for both series of RCC mixtures. Most values are higher than 50 MPa. With the exception of mixture PUG-Ref., no significant differences can be seen between strengths obtained from mixtures prepared with a continuous flow pugmill mixer and those produced in the central batch plant.

Table 6.4. Compressive Strength of RCC Mixtures

Mixture ID	Compressive strength, MPa		
	Specimen 1	Specimen 2	Average
PUG – Ref.	23.6	24.3	24.0
PUG – MA	54.1	55.9	55.0
PUG – AXL	61.2	67.1	64.2
PUG – AMP	58.3	55.9	57.1
PRE – Ref.	69.2	79.6	74.4
PRE – MA	51.6	64.0	57.8
PRE – AXL	73.3	61.1	67.2
PRE – AMP	53.8	58.6	56.2

The 28-day compressive strength test results for mixture PUG-Ref. are surprisingly low. These results are due to the presence of a high number of compaction voids, which could be observed on the specimens immediately after testing. These samples had not been consolidated properly.

6.5.2 Characteristic of the Air-Void System

The characteristics of the air-void system of both series of RCC mixtures, determined according to a modified version of ASTM C 457, are given in Table 6.5. Results of the standard measurements (including compaction voids) and results of the modified version of the standard (excluding compaction voids) are presented.

These results confirm that it is possible to entrain a little (but significant) volume of air under normal plant conditions (without altering the batching sequence of the mixer), even with a continuous flow pugmill mixer. The spherical air-void contents of the non-air-entrained RCC are relatively low (0.2 % for the mixture produced in a pugmill mixer and 0.7 % for the one prepared in a concrete batch plant) while those of the air-entrained mixtures range from 1.0% to 2.1%. As for the results reported in Chapter 4, of the type of air-entraining admixture used has no significant influence.

Although the best results were obtained with the central concrete batch plant, the addition of an air-entraining agent was found to reduce the spacing factor of RCC in all cases. The average results of the air-entrained RCC mixtures (when all compaction voids are considered) range from 246 to 327 µm for the first series, and 209 to 290 µm for the second series. As can be seen in Table 6.5, whatever the type of admixture used, the spacing factors of the mixtures produced in the pugmill mixer are all close to or higher than 230 µm. As previously emphasized in Chapter 4, 230 µm often is considered to be the critical spacing factor below which concrete mixtures are believed to be protected intrinsically against frost action. This is, for instance, the value considered in the Canadian standard A23.1.

Table 6.5. Characteristics of the Air-Void System

	Including compaction voids			Excluding compaction voids		
Mixture ID	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm	Air content, %	Specific surface, mm^{-1}	Spacing factor, µm
PUG – Ref.	5.6	11.7	292	0.2	40.5	437
PUG – MA	2.8	15.2	327	1.0	23.8	337
PUG – AXL	2.6	17.7	317	1.5	21.4	335
PUG – AMP	2.8	20.8	246	2.0	23.9	253
PRE – Ref.	1.4	12.9	680	0.7	20.4	559
PRE – MA	3.4	26.1	209	2.1	38.8	176
PRE – AXL	3.0	20.1	290	1.5	35.1	229
PRE – AMP	3.5	26.8	209	1.6	53.6	149

As emphasized in Chapter 4, spacing factor values measured for RCC mixtures should, however, be considered with some caution[1]. The fact that the air-void system of most mixtures was found to consist, to a large fraction, of compaction voids underlines the somewhat ambiguous application of the ASTM C 457 standard to RCC. The characterization of an air-void system made of large irregularly-shaped compaction voids using a method designed for spherical air-voids of various sizes is not rigorously appropriate, especially if it is considered that no one has ever clearly established the role played by these voids in the protection against frost damage. Compaction voids may be interconnected; if so, when they become saturated (if enough water is available), their influence on frost resistance may be detrimental.

6.5.3 Microscopic Observations Using Scanning Electron Microscopy

The microscopic observations carried out on both series of RCC mixtures are summarized in Table 6.6.

During the observations, very few spherical air-voids could be detected. These results are somewhat unexpected considering that air entrainment was found to have a beneficial influence on the volume of spherical air-voids measured by the ASTM C 457 method. It should however be remembered that the volume of entrained air reported in Table 6.5 was minimal. It is therefore possible that air entrainment has resulted in the formation of a few larger air-voids.

Table 6.6. Microscopic Observations (Scanning Electron Microscopy)

Mixture ID	Spherical air–void diameter, µm									
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	>91
	Number of spherical air-voids per square millimeter									
PUG – Ref.	5	5	3	2	–	1	–	–	–	–
PUG – MA	–	–	–	–	1	–	–	–	–	–
PUG – AXL	1	6	1	–	–	–	–	–	–	–
PUG – AMP	–	1	2	1	–	–	–	–	–	–
PRE – Ref.	–	2	–	–	–	–	–	–	–	1
PRE – MA	–	–	1	2	2	–	–	–	–	–
PRE – AXL	3	3	2	1	1	2	1	2	1	6
PRE – AMP	–	1	0	0	1	1	1	0	0	1

6.5.4 ASTM C 666 (Procedure A) Test Results

The ASTM C 666 rapid freezing and thawing test results are summarized in Table 6.7. The results of the residual length change and the durability factor after 300 cycles are included in the table.

Table 6.7. ASTM C 666 Test Results After 300 Cycles

Mixture ID	Durability factor, %	Length change, µm/m
PUG – Ref.	100	170
PUG – MA	100	20
PUG – AXL	100	-90
PUG – AMP	100	-110
PRE – Ref.	100	190
PRE – MA	100	200
PRE – AXL	100	30
PRE – AMP	100	90

All RCC mixtures were found to be resistant to rapid freezing and thawing cycles in water, even the non-air-entrained mixtures. The residual length changes measured after 300 cycles are lower than 200 µm/m. As emphasized in the previous chapters, 200 µm/m is the critical length change above which concrete is considered to have been damaged by frost attack[2]. The durability factors obtained were 100% for all mixtures. These results tend to confirm the very beneficial influence of the partial replacement of cement by silica fume[3,4]. Silica fume was found in the previous chapter to have a positive influence on the frost durability of non-air-entrained concrete.

6.5.5 ASTM C 672 Test Results

The ASTM C 672 deicer salt-scaling tests results are summarized in Table 6.8. The table presents the mass of scaled-off particles and the ASTM rating after 50 freeze-thaw cycles. Individual test results are shown in brackets.

Table 6.8. ASTM C 672 Test Results After 50 Cycles

Mixture ID	Mass of scaled-off particles, kg/m^2	Rating
PUG – Ref.	0.111 (0.098 ; 0.210 ; 0.025)	2
PUG – MA	0.572 (0.282 ; 0.749 ; 0.685)	4
PUG – AXL	0.691 (1.018 ; 0.753 ; 0.302)	4
PUG – AMP	0.989 (0.785 ; 0.937 ; 1.245)	5
PRE – Ref.	0.350 (0.377 ; 0.454 ; 0.220)	3
PRE – MA	0.033 (0.127 ; 0.072 ; 0.026)	2
PRE – AXL	0.389 (0.540 ; 0.434 ; 0.194)	3
PRE – AMP	0.052 (0.065 ; 0.039 ; 0.052)	1

Overall, the test results clearly indicate that it is possible to produce RCC mixtures that have a good resistance to deicer salt-scaling. For both series, the loss of mass after 50 cycles is lower than the 1 kg/m^2 limit. The average results range from 0.03 to 0.99 kg/m^2.

Although the best results were obtained for mixtures prepared in the central concrete batch plant, the type of production unit did not have a significant effect on the durability of the concrete. As can be seen, the use of air-entraining admixtures or the type of air-entraining agent did not have any effect on the behavior of concrete. The good performance of all mixtures are in good agreement with the ASTM C 666 test results reported in the previous subsection, although the durability of the non-air-entrained mixtures is surprising. This can be attributed to the beneficial influence of silica fume. As emphasized in the two previous chapters, non-air-entrained mixtures produced with a blended silica fume cement were found in the past to be systematically deicer salt-scaling durable.[3,5]

6.5.6 ASTM C 1262 Test Results

ASTM C 1262 test results after 50 freezing and thawing cycles are given in Table 6.9.

Globally, the ASTM C 1262 test results confirm those obtained with the two other procedures (i.e., ASTM C 666 and ASTM C 672). All mixtures but one, mixture PUG-Ref., were found to be durable. As can be seen in Table 6.9, the mass loss of mixture PUG-Ref. is a little over the 1% limit. This result could be explained by the fact that this mixture was not air-entrained. Curiously, the absence of air bubbles did not have any influence on the ASTM C 666 and ASTM C 672 test results.

Table 6.9. ASTM C 1262 Test Results After 50 Cycles

Mixture ID	Mass of scaled-off particles, g/m^2	Mass loss, % of the initial dry moss
PUG – Ref.	1.12 (0.886 ; 1.045 ; 1.437)	1.38 (0.98 ; 1.13 ; 2.03)
PUG – MA	0.24 (0.221 ; 0.278 ; 0.209)	0.24 (0.23 ; 0.28 ; 0.22)
PUG – AXL	0.16 (0.135 ; 0.272 ; 0.062)	0.17 (0.14 ; 0.29 ; 0.07)
PUG – AMP	0.11 (0.070 ; 0.112 ; 0.133)	0.11 (0.08 ; 0.12 ; 0.14)
PRE – Ref.	0.082 (0.115 ; 0.019 ; 0.111)	0.08 (0.11 ; 0.02 ; 0.11)
PRE – MA	0.159 (0.262 ; 0.087 ; 0.128)	0.17 (0.29 ; 0.09 ; 0.13)
PRE – AXL	0.163 (0.165 ; 0.093 ; 0.232)	0.17 (0.17 ; 0.10 ; 0.24)
PRE – AMP	0.068 (0.019 ; 0.015 ; 0.170)	0.08 (0.02 ; 0.02 ; 0.19)

It is probable that the presence of nonconnected compaction voids was just sufficient to protect the mixture against frost-induced microcracking and deicer salt-scaling but, for some odd reason, not enough to reduce the loss of mass during the ASTM C 1262 test under the 1% limit.

6.6 CONCLUDING REMARKS

Test results confirm that it is possible to entrain a little (but significant) volume of air under normal plant conditions (without altering the batching sequence of the mixer), even with a continuous flow pugmill mixer. The spherical air-void contents of the non-air-entrained RCC are relatively low (0.2 % for the mixture produced in a pugmill mixer and 0.7 % for the one prepared in a concrete batch plant) while those of the air-entrained mixtures range from 1.0% to 2.1%. As with the results reported in Chapter 4, the type of air-entraining admixture used has no significant influence.

All RCC mixtures were found to be resistant to rapid freezing and thawing cycles in water, even the non-air-entrained mixtures. The residual length changes measured after 300 cycles are lower than 200 µm/m. The durability factors obtained were 100% for all mixtures. These results tend to confirm the very beneficial influence of the partial replacement of cement by silica fume.

Finally, ASTM C 672 and ASTM C 1262 test results clearly indicate that it is possible to produce RCC mixtures that have a good scaling resistance to deicing salts. The good frost durability of non-air-entrained mixtures in the presence of deicing salts is a little surprising. This can be attributed to the beneficial influence of silica fume.

6.7 REFERENCES

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Chapter 7

SUMMARY AND CONCLUSIONS

The results presented in this report include a series of measurements performed on RCC samples extracted from experimental test sections that had been subjected to more than 10 winters of severe exposure (Chapter 3). The report also contains results from two test series on laboratory-made RCC mixtures (Chapter 4 and 5), and one test series on RCC mixtures produced using two types of industrial mixers (Chapter 6). The global analysis of these data is presented in this chapter. This analysis quite clearly points out that RCC can be frost-and deicer salt-scaling resistant, and indicates the conditions under which this can be achieved.

7.1 AIR ENTRAINMENT

Normal good quality concrete can be quite resistant to frost and deicer salt-scaling if it is properly air-entrained. It is thus normal to expect that air entrainment also is required for RCC mixtures exposed to severe winter conditions. However, as discussed in the previous chapters, it can be difficult to entrain air in RCC because of its low water content and paste content, and its stiff consistency.[1] This is particularly clear from the results of the measurements made on the samples from the experimental pavement (Chapter 3). In the five samples examined, the maximum spherical air-void content was limited to 0.6%, which is much lower than the value of 1.5% considered to be a lower limit for frost-durable RCC.

Results from mixtures prepared specifically for this project (Chapters 4 and 6) indicate that air entrainment can be achieved if the mixtures are properly designed and adequate air-entraining admixtures are selected. As described in Chapter 4, 14 mixtures were prepared: 2 reference (non-air-entrained) mixtures, and 12 air-entrained mixtures. With only a single exception, the air-void spacing factor (excluding the compaction voids, or including these voids) of the air-entrained mixtures was very close to or lower than 230 µm, and that of the two reference mixtures was found to be much higher. These results show that it is possible to entrain air in RCC produced with a laboratory pan-mixer using a substantial dosage of air-entraining admixture.

However, this conclusion only applies to the mixtures tested, i.e., made with 250 kg/m^3 or 300 kg/m^3 of normal portland cement, and with aggregate gradings selected to facilitate placement and minimize compaction air-void content.

The results from the mixtures prepared in a premix plant and in a pugmill mixer (Chapter 6) confirm that it is also possible to entrain air under normal constraints of industrial production conditions. However, at least for the type of mixture tested, i.e., containing silica fume, adequate spacing factors (i.e., below 230 µm) were obtained only in the mixtures prepared in a premix plant. As explained by Powers[1] and Whiting,[2] air entrainment requires a mechanical action to draw air into the mixture. The two basic processes are kneading, in which air is entrapped as concrete falls on itself, and stirring, in which the vortex created draws air into the mixture. Air entrainment also requires a sufficient amount of time. In the pugmill mixer, both the mechanical action and the length of time were probably not sufficient to produce the required number of spherical air bubbles.

Considering both the results obtained from the ASTM C 457 measurements and the observations made using the scanning electron microscope, it is not possible to draw a definitive conclusion concerning the type of air-entraining admixture which would be most suited for RCC. All apparently can be efficient. It should be emphasized that the limited influence of the type of admixtures is in apparent contradiction with the results of previous studies where the type of air-entraining admixtures was found to have a direct bearing on air entrainment in dry concrete mixtures.[2,3]

As pointed out at the beginning of this section, the results obtained in this project indicate that air entrainment in RCC mixtures can be achieved. However, as is the case for normal consistency concrete, it must always be verified before placement that the (RCC) mixture under consideration has been designed properly for the type of mixer that will be used, and that the hardened mixture will have an adequate spacing factor. This of course can only be verified by a trial batch and subsequent measurement of the air-void characteristics of the hardened concrete.

Finally, it is important to emphasize that spacing factor values measured for RCC mixtures should be considered with some caution.[3] The fact that the air-void system of most mixtures was found to consist, to a large fraction, of compaction voids underlines the somewhat ambiguous application of the ASTM C 457 standard to RCC. The characterization of an air-void system made of large irregularly shaped compaction voids using a method designed for spherical air-voids of various sizes is not rigorously appropriate, especially if it is considered that no one has ever clearly established the role played by these voids in the protection against frost damage. Compaction voids may be interconnected; if so, when they become saturated (if enough water is available), their influence on frost resistance may be detrimental.

7.2 FROST RESISTANCE – ASTM C 666

The various measurements made on the samples extracted from the experimental RCC sections (mechanical properties, pulse velocity, and microcrack density) clearly indicate that none of the selected mixtures had suffered any degradation after more than 10 years of exposure to severe winter conditions. The good field performance of the test sections tends to indicate that unsaturated compaction air-voids offer some protection against frost action. As previously mentioned, the air-void characteristics of five of these mixtures were determined. Although the spherical air-void content was quite low in all cases (i.e., less than 1%), all had a relatively good air-void spacing factors (i.e., close to or lower than 200 µm), due to the high content of irregularly shaped compaction voids. The good frost resistance of non-air-entrained RCC is in good agreement with results of previous field investigations.[4,5]

The first series of tests on laboratory RCC mixtures described in Chapter 4 was made on RCC mixtures containing only normal (type I) portland cement. Test results emphasize the beneficial importance of air entrainment. *Test data also demonstrate that very little entrained air is required to adequately protect RCC against frost-induced microcracking.* This is a very important point if one considers that, even when large dosages are used, the addition of an air-entraining admixture to RCC rarely contributes to entrain more than a few percent of spherical air bubbles in the mixture.

The second series of tests on laboratory RCC mixtures was made on non-air-entrained concretes containing silica fume or fly ash. Only one mixture (containing fly ash) was found to be completely frost-resistant. Encouraging results also were obtained for the high-performance silica fume mixture. The remaining mixtures were found to be frost-susceptible. All mixtures had similar air-void spacing factors (of the order of 400 µm) with air contents ranging from 2.9% to 4.4%.

The last series of laboratory tests was made on RCC mixtures containing silica fume and prepared under normal plant or field conditions. All were found to be fully frost-resistant, including the non-air-entrained mixture with a spacing factor of 680 µm (559 µm considering only the spherical voids) with a total air content of only 1.4%.

When concrete is properly compacted and made with good quality aggregates, three basic parameters determine the resistance to freezing and thawing cycles: the paste porosity (i.e., total porosity and pore size distribution), the air-void spacing factor, and, of course, the characteristics of the freezing and thawing cycle (basically the freezing rate, the minimum temperature, and the length of the freezing period). This implies, as clearly explained in previous publications[6], that for a given paste subjected to a given freezing and thawing test, there exists a critical value of the air-void spacing factor (above which frost deterioration will occur). For the mixtures made with normal portland cement at a water-cement ratio of 0.4 (containing 250 kg/m^3 of cement) and tested according to ASTM C 666, this value is less than 600 µm. The results from the experimental pavement subjected to more than 10 winters of exposure do not contradict this conclusion, since no deterioration was observed on mixtures made with normal portland cement and spacing factors of around 200 µm.

For the mixtures made with silica fume, the results reported in Chapter 5 indicate that the critical air-void spacing factor is close to 400 µm, but those from Chapter 6 show that it is higher than 600 µm. This apparent (yet small) contradiction could be explained by various factors, including, for instance, the influence of the mixer on the homogeneity of the paste. For the mixtures containing fly ash, the results are similar: The critical air-void spacing factor is around 400 µm. Again, the results from the experimental pavement subjected to more than 10 winters of exposure do not contradict this conclusion, since no deterioration was observed on mixtures made with silica fume or fly ash and a spacing factor of around 200 µm.

Globally, and unsurprisingly, all the results available thus indicate that good quality RCC with a low air-void spacing factor is frost-resistant, although non-air-entrained RCC containing silica fume can be frost-resistant under certain circumstances which are not all clearly defined at the present time. This good frost resistance of mixtures with spacing factors as high as 600 µm is not surprising, if one considers the data published on the frost resistance of high performance concrete.[6] A number of publications describe test results, which show that 0.40 or 0.35 water-cement ratio concrete containing silica fume can be frost-resistant even if the spacing factor is around 600 µm.[6]

7.3 DEICER SALT-SCALING – ASTM C 672

After more than 10 winters of severe exposure, the test sections were found to be free of any degradation by surface scaling. These observations are particularly interesting considering that ASTM C 672 tests run a few months after construction on samples extracted from the experimental pavements had shown that most RCC mixtures were not resistant to deicer salt-scaling. Furthermore, chloride profiles measured on the various samples taken from the sections in 1999 clearly indicate that most mixtures had been in contact with deicing salts. Globally, results reported in Chapter 3 tend to demonstrate the severity of the ASTM C 672 procedure.

Table 7.1 summarizes the results of the ASTM C 672 tests performed on the first series of laboratory RCC mixtures (containing only normal, ASTM Type I – CSA Type 10, portland cement), on the second series of laboratory RCC mixtures (all non-air-entrained and containing silica fume or fly ash), and on the series of RCC mixtures prepared using two types of industrial mixers. The value of the air-void spacing factor and of the total air content for each mixture tested also is included in Table 7.1.

These results clearly indicate that RCC mixtures can be quite resistant to deicer salt-scaling (as measured under severe laboratory conditions). For all air-entrained mixtures, except in one case, the mass of residues after 50 cycles of freezing and thawing in the presence of a salt solution is equal to or lower than 1 kg/m^2. Furthermore, for all mixtures containing silica fume, both air-entrained and non-air-entrained, the mass of residues after 50 cycles is equal to or lower than 1 kg/m^2. In fact, the only mixtures that can be considered nonresistant to scaling are the non-air-entrained ones containing fly ash or made with normal portland cement.

Although a number of parameters other than the mixture composition and the air-void spacing factor can influence the deicer salt-scaling resistance determined in the laboratory (such as certain surface phenomena, for instance), it is nevertheless interesting to compare the results obtained in this study to data obtained from tests on normal consistency mixtures. Globally, on the basis of a large number of tests performed at Laval University during the last 15 years, it can be said that the scaling resistance of RCC is not very different from that of normal concrete. For the non-air-entrained RCC mixtures made with normal portland cement, for instance, the mass of residues after 50 cycles is 2.1 kg/m^2 at a water-cement ratio of 0.35 (mixture 300 – T) and 9.0 kg/m^2 at 0.40 (mixture 250 – T). For the non-air-entrained mixtures containing fly ash (at water-cement ratios of 0.35 and 0.40), the mass of residues ranges between 2.7 and 9.0 kg/m^2. For the non-air-entrained mixtures containing silica fume (again at water-cement ratios of 0.35 and 0.40), the mass of residues is lower than 0.5 kg/m^2. These results are all quite typical of those that would be obtained with normal consistency concrete.

Table 7.1. Frost-Durability Test Results

	ASTM C 666		ASTM C 672		ASTM C 457
Mixture ID	**Durability factor, %**	**Axial deformation, µm/m**	**Mass of residue, kg/m²**	**Rating**	**Spacing factor, µm**
Chapter 4					
300 – T	43	4270	2.06	4.5	541
250 – T	0	11670	9.00	4.5	624
250 – MA – 4	100	39	0.57	2.5	93
250 – MA – 2	100	114	0.72	3.5	107
250 – AXL – 1	100	115	0.45	3	142
250 – AXL – 0.5	100	48	1.58	5	192
250 – AMP – 0.4	100	104	0.97	4	114
250 – AMP – 0.2	100	153	0.52	4	136
Chapter 5					
300 – T10SF	100	1430	0.22	2	390
250 – T10SF	77	1770	0.53	4	433
300 – FA –C	60	1110	6.17	5	399
250 – FA – C	100	120	8.98	5	477
300 – FA – F	47	1510	4.52	5	419
250 – FA – F	59	1250	2.69	5	342
Chapter 6 – Premix					
PRE – Ref	100	190	0.350	3	680
PRE – MA	100	200	0.033	2	209
PRE – AXL	100	30	0.389	3	290
PRE – AMP	100	90	0.052	1	209
Chapter 6 – Pugmill					
PUG – Ref	100	170	0.111	2	292
PUG – MA	100	20	0.572	4	327
PUG – AXL	100	-90	0.691	4	317
PUG – AMP	100	-110	0.989	5	246

In our view, this is extremely significant, since it shows that the homogeneity of the paste in the RCC mixtures tested is quite similar to that in normal concretes. Since that was not the case for the RCC mixtures in the experimental pavement built from 1987 to 1990, it further emphasizes that the method of mixture design developed recently, which allows reduction of the number of compaction voids while increasing the mechanical strength and also causing a significant improvement in the structure of the paste.

7.4 DEICER SALT-SCALING – ASTM C 1262

In Chapter 3, all mixtures tested according to the ASTM C 1262 procedure passed the test (i.e., all mass loss results were under the 1% limit). These results are in good agreement with the field behavior of the test sections, which did not suffer from any significant degradation over the 10-year exposure period. On the basis of these data, the ASTM C 1262 appears to be more reliable than any other standard test method to correctly predict the ability of dry concrete products to be durable when exposed to severe field conditions.

Finally, results reported in Chapters 4 to 6, particularly those of Chapter 4, tend to confirm the ability of ASTM C 1262 to discriminate between durable and nondurable mixtures. The poor performance of mixtures suggests that the test is severe enough to induce degradation to mixtures not protected adequately against frost action.

Globally, test results discussed in this report strongly suggest that the ASTM C 1262 should be considered seriously as a reliable method to assess the frost durability of RCC. Already used to test masonry products, the method is relatively simple and could be applied directly to RCC pavements.

7.5 CONCLUDING REMARKS AND RECOMMENDATIONS

The observations of the experimental pavements built more than 10 years ago indicate that they are still in good condition. They have not significantly suffered from internal cracking or surface scaling. Although it was not possible at the time to systematically entrain air in the RCC mixtures, the air-void spacing factor was generally good, due to the high amount of compaction voids, which probably explains in good part its resistance to frost-induced internal cracking.

The lack of severe surface scaling is more surprising, since the tests performed after the construction of the pavement did not indicate a very good resistance to this type of frost deterioration. Globally, results reported in Chapter 3 tend to demonstrate the severity of the ASTM C 672 procedure.

Results from the mixtures prepared specifically for this project (Chapters 4 and 6) indicate that air entrainment can be achieved if mixtures are properly designed and adequate air-entraining admixtures are selected.

Test results indicate that RCC mixtures should be air-entrained to be protected adequately against frost-induced internal cracking and, particularly, deicer salt-scaling. Data also clearly show that as little as 1.5% of spherical air bubbles can have a very beneficial influence on the frost durability of RCC. In that respect, air entrainment appears to be a relatively simple and cost-effective way to protect RCC against frost degradation.

Results obtained in this project also tend to show that air entrainment is not required in "high-performance" silica fume RCC (i.e., prepared at a binder content of 300 kg/m^3 or more).

Results also indicate that fly ash has, on average, very little beneficial influence on the frost durability of RCC. More tests should be made before RCC containing fly ash is systematically used in areas where the exposure conditions are very severe.

Finally, test results discussed in this report strongly suggest that the ASTM C 1262 should be seriously considered as a reliable method to assess the frost durability of RCC. Already used to test masonry products, the method is relatively simple and could be applied directly to RCC pavements.

7.6 REFERENCES

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5. Ragan, S.A., *Evaluation of the Frost Resistance of Roller-Compacted Concrete Pavements,* SL-86-16, U.S. Army Corps of Engineers, Washington, D. C., USA, October, 1986.
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APPENDIX A
ASTM C 666 PLOTTED TEST RESULTS

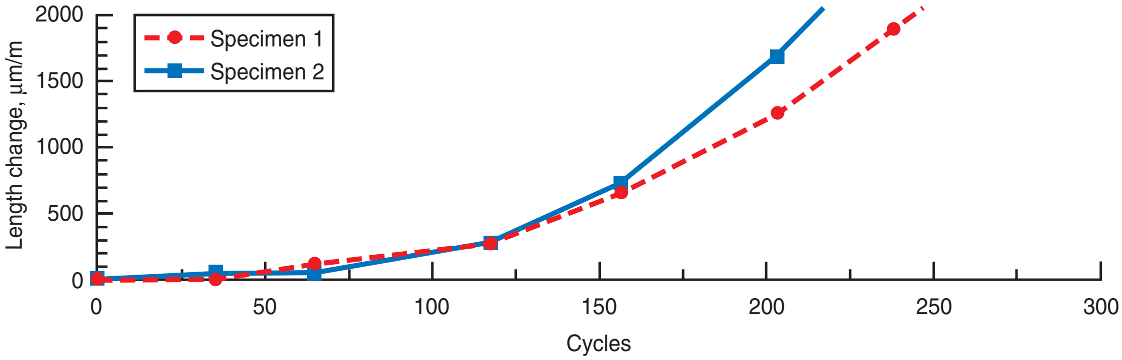


Figure A-1. ASTM C 666 results – mix 300T.

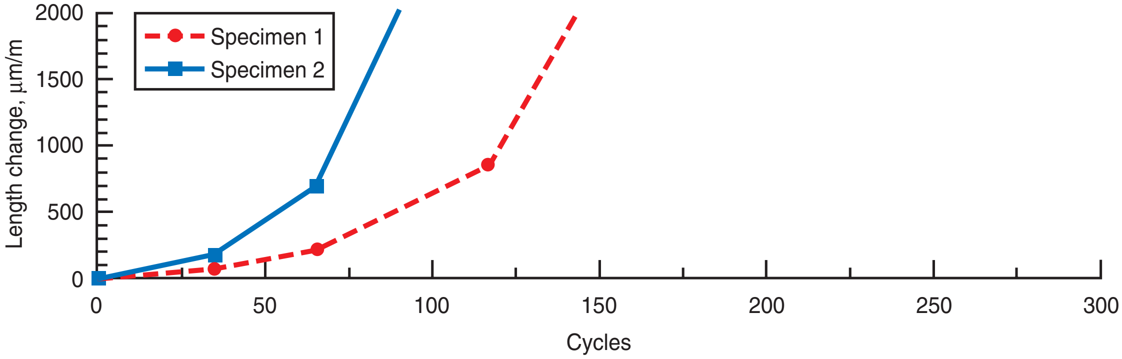


Figure A-2. ASTM C 666 results – mix 250T.

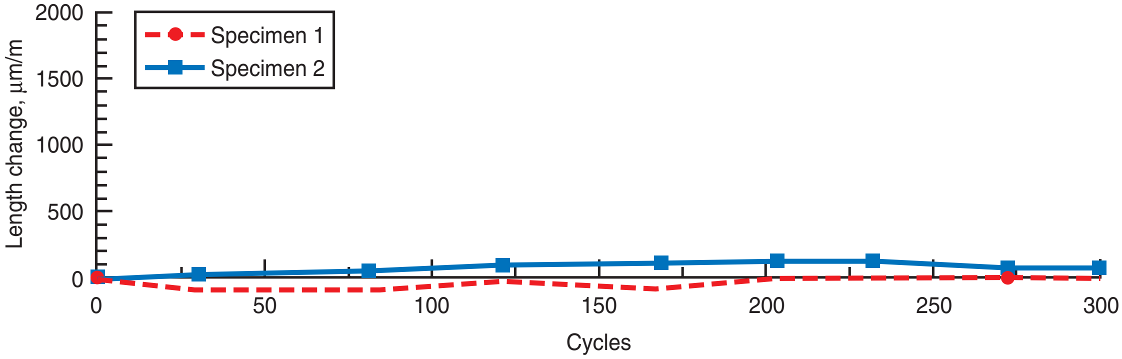


Figure A-3. ASTM C 666 results – mix 250 – MA – 4.

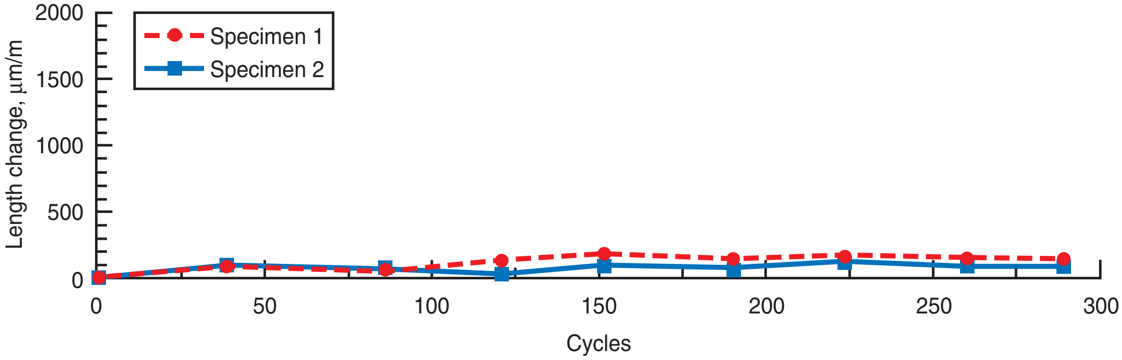


Figure A-4. ASTM C 666 results – mix 250 – MA – 2.

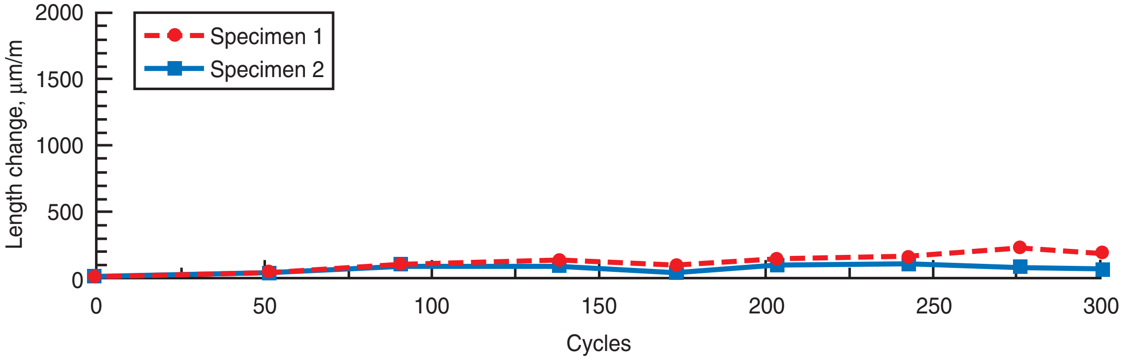


Figure A-5. ASTM C 666 results – mix 250 – AXL – 1.

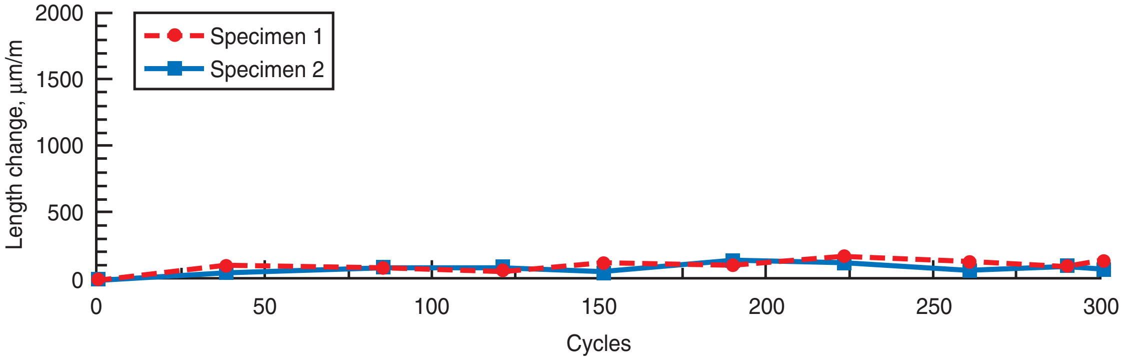


Figure A-6. ASTM C 666 results – mix 250 – AXL – 0.5.

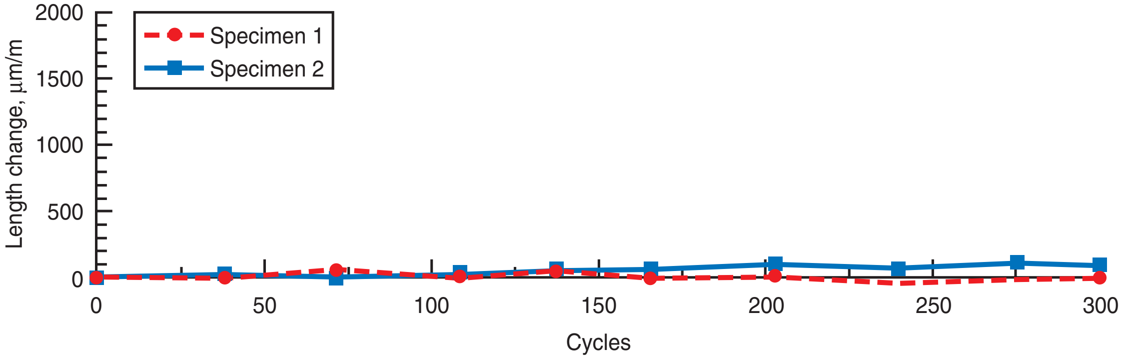


Figure A-7. ASTM C 666 results – mix 250 – AMP – 0.4.

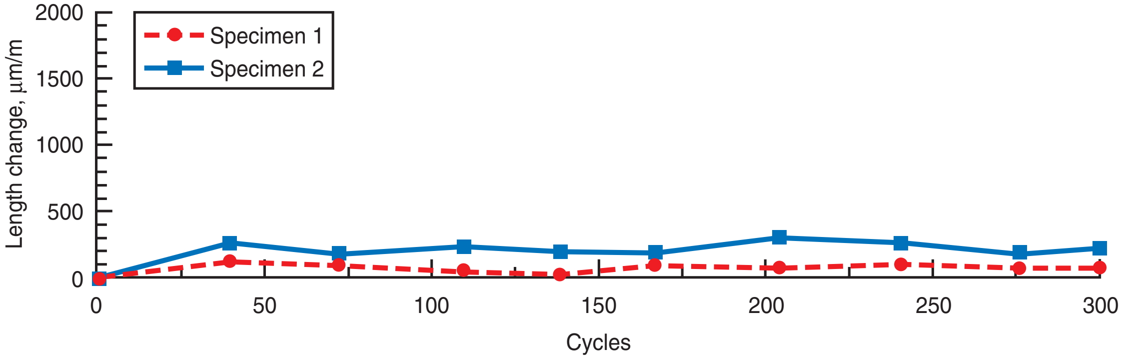


Figure A-8. ASTM C 666 results – mix 250 – AMP – 0.2.

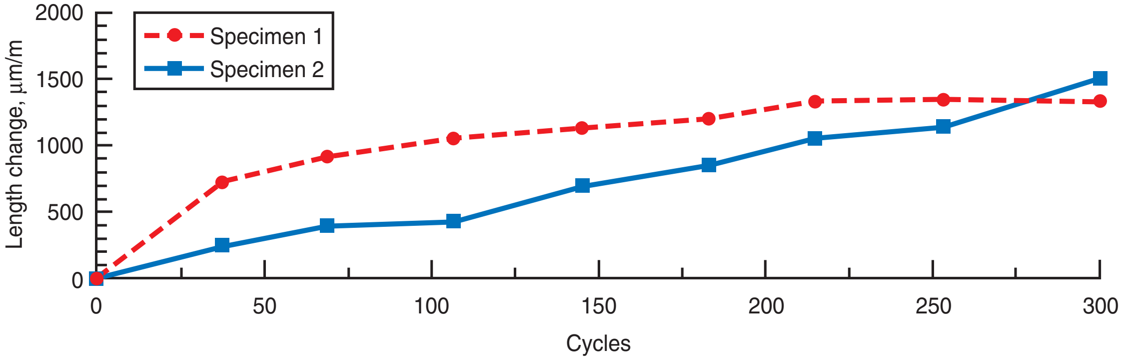


Figure A-9. ASTM C 666 results – mix 300 SF.

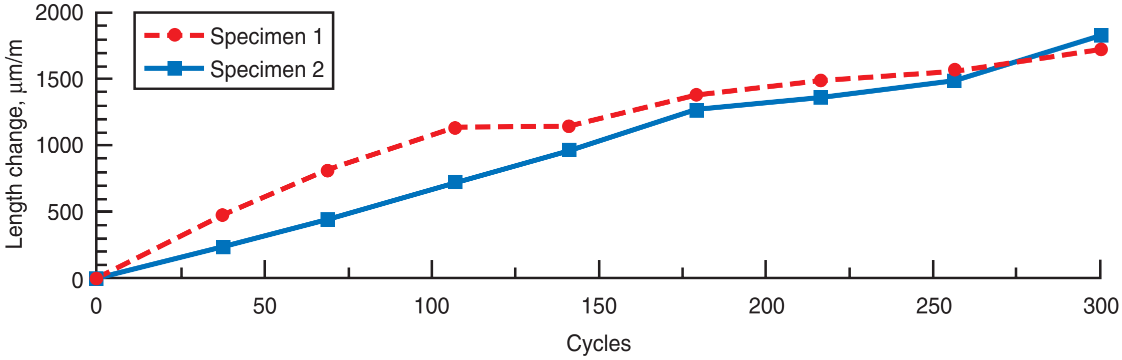


Figure A-10. ASTM C 666 results – mix 250 SF.

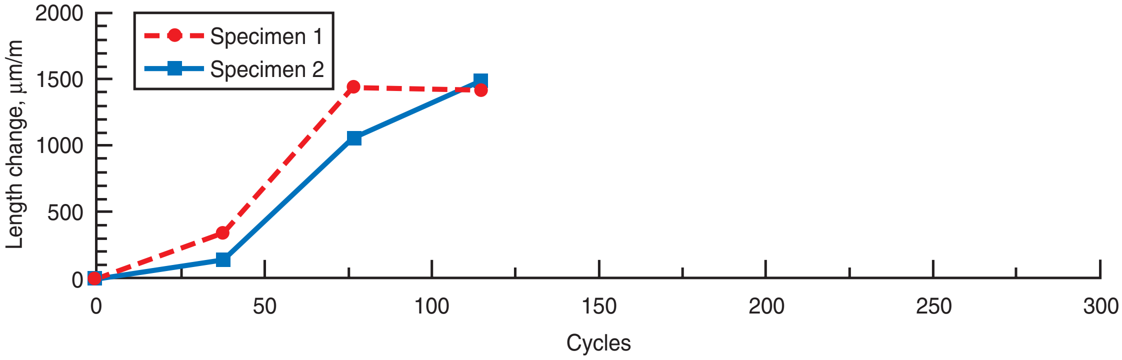


Figure A-11. ASTM C 666 results – mix 300 – FA – C.

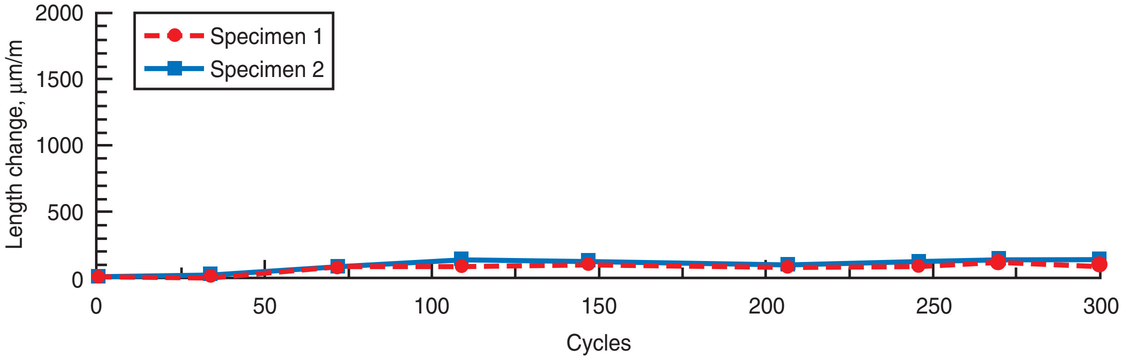


Figure A-12. ASTM C 666 results – mix 250 – FA – C.

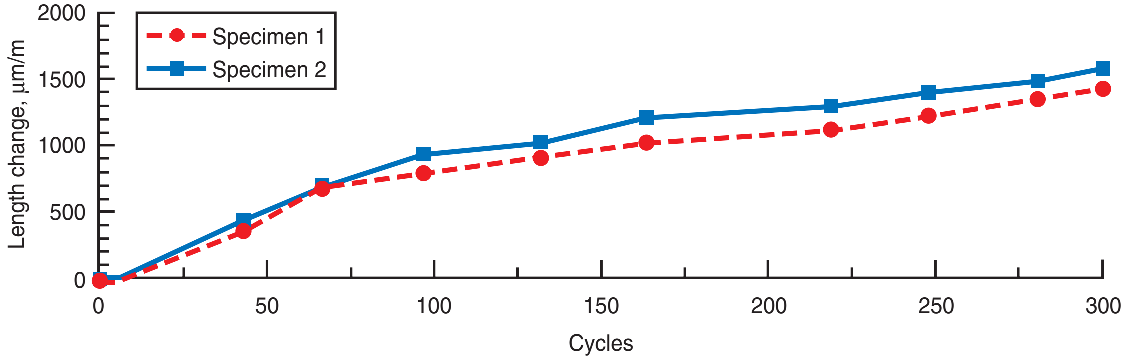


Figure A-13. ASTM C 666 results – mix 300 – FA – F.

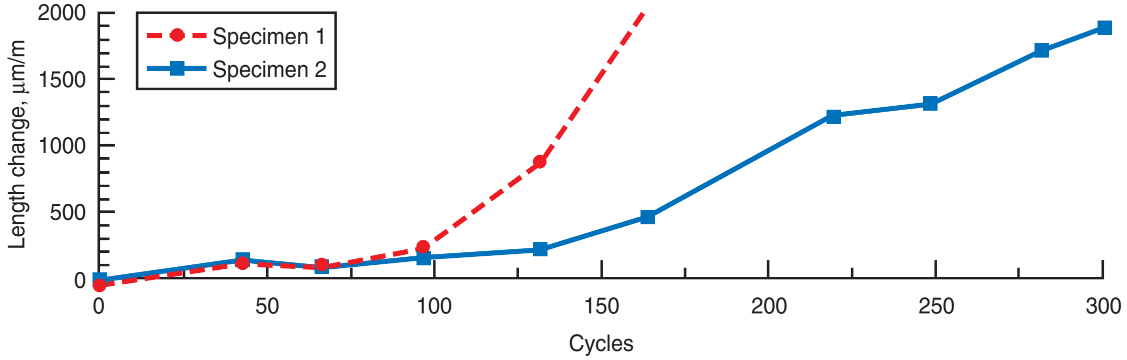


Figure A-14. ASTM C 666 results – mix 250 – FA – F.

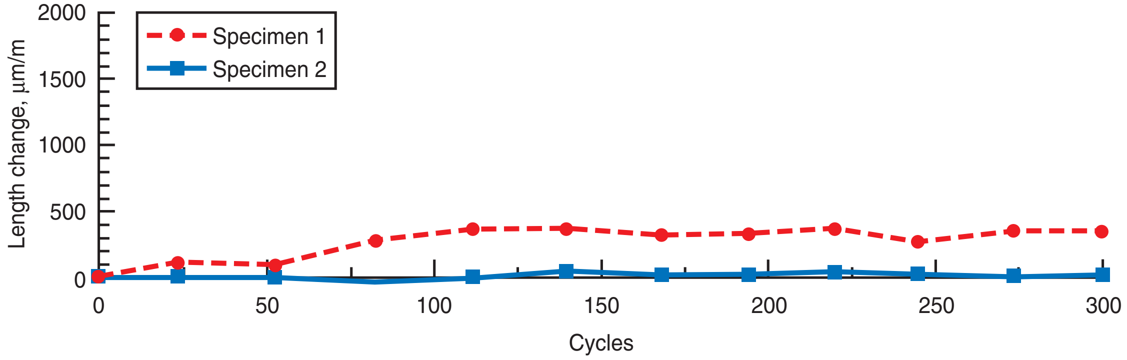


Figure A-15. ASTM C 666 results – premix reference.

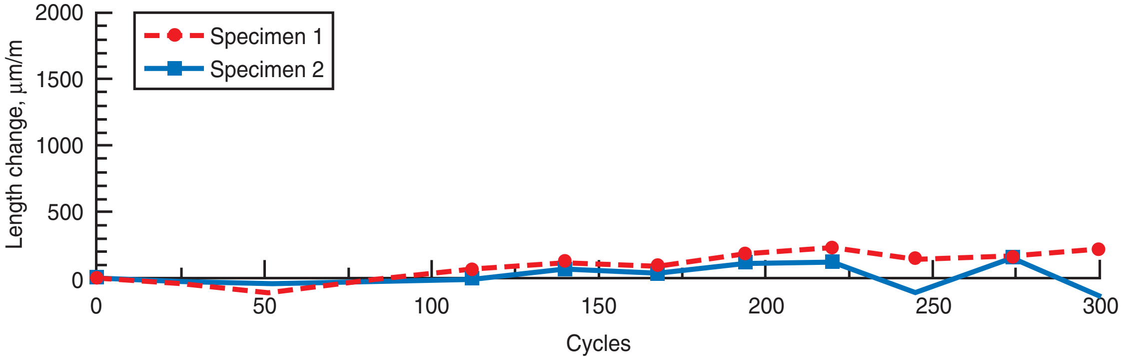


Figure A-16. ASTM C 666 results – premix micro air.

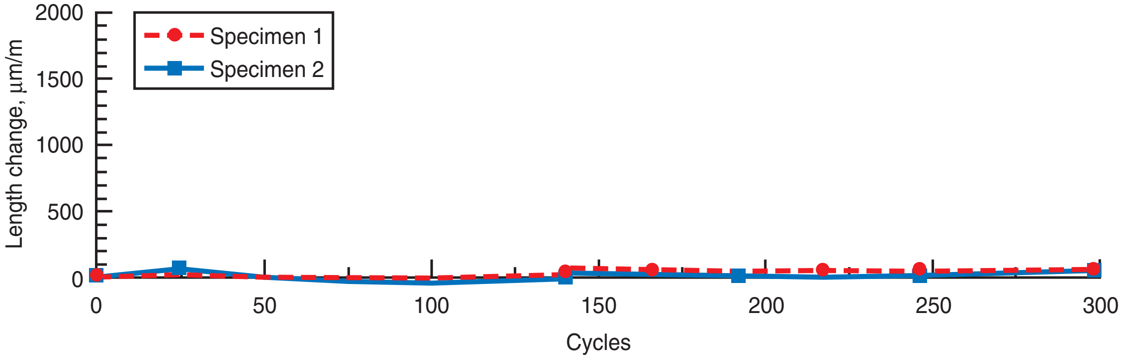


Figure A-17. ASTM C 666 results – premix AireX–L.

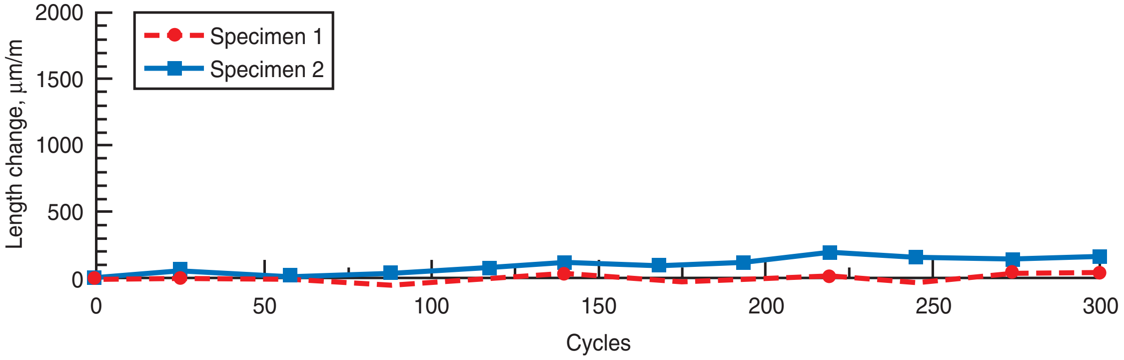


Figure A-18. ASTM C 666 results – premix Airmix – P.

APPENDIX B

ASTM C 672 PLOTTED TEST RESULTS AFTER 50 CYCLES

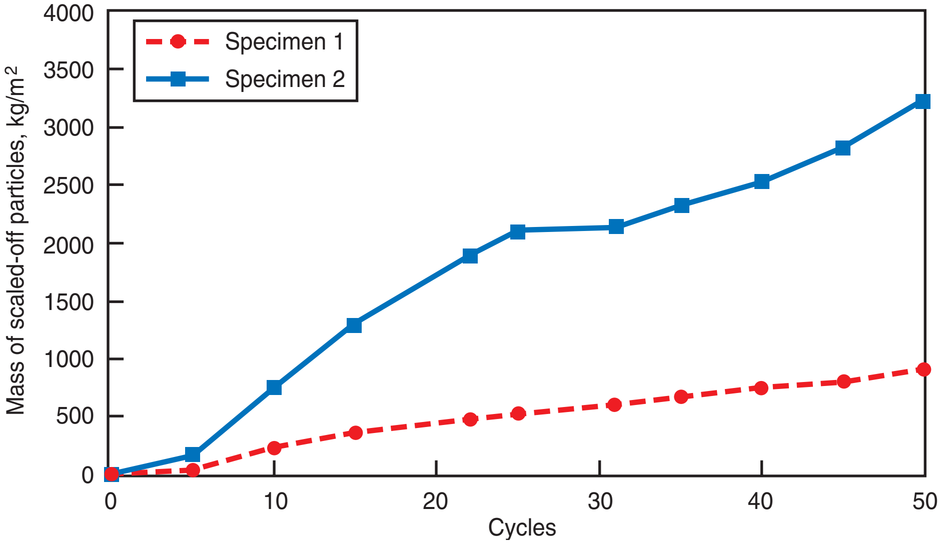


Figure B-1. ASTM C 672 results – mix 300 Ref.

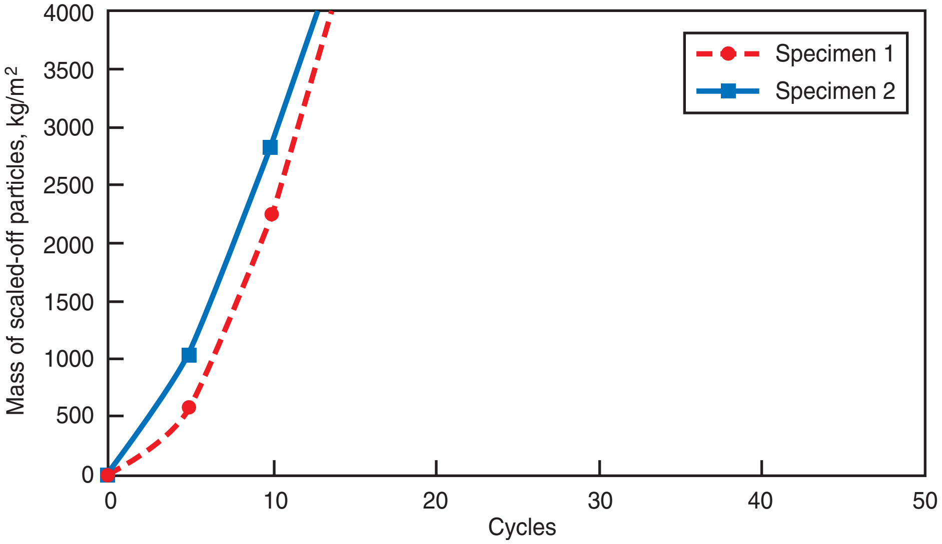


Figure B-2. ASTM C 672 results – mix 250 Ref.

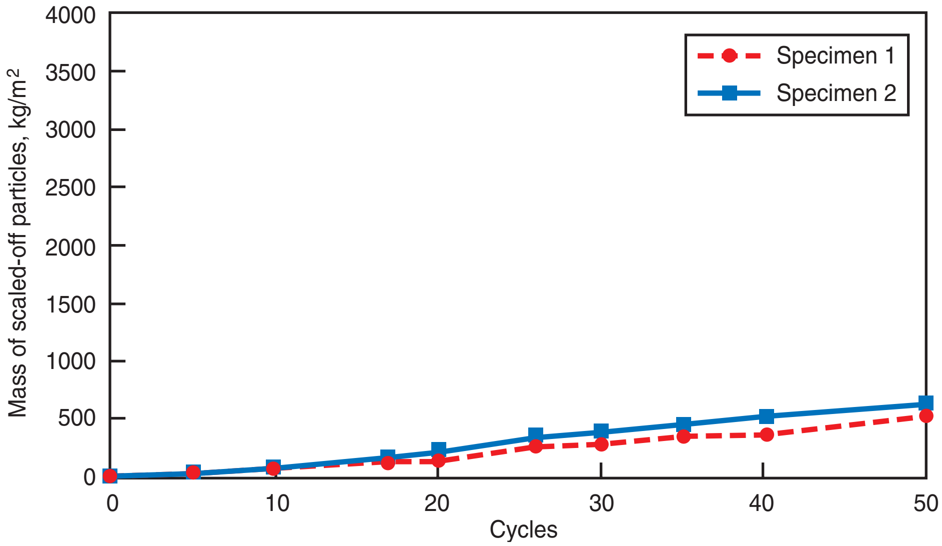


Figure B-3. ASTM C 672 results – mix 250 – MA – 4.

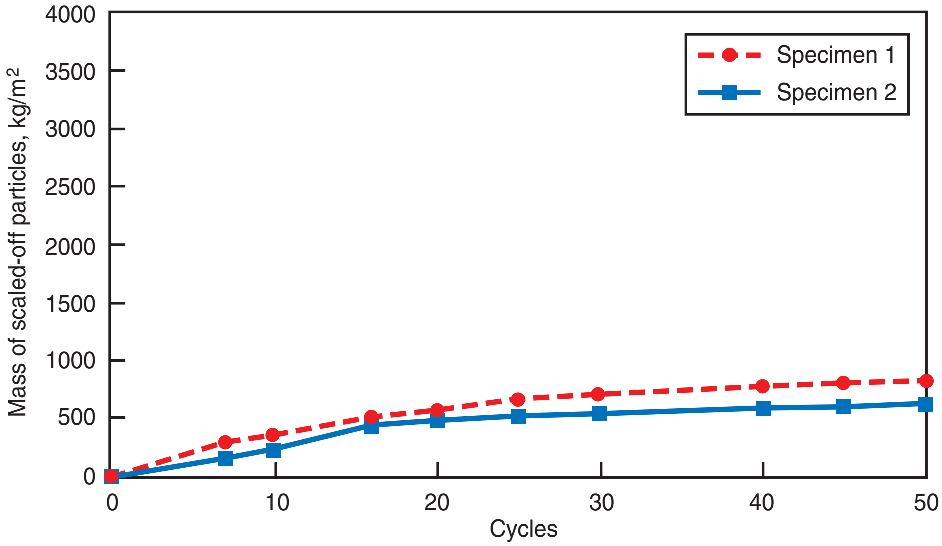


Figure B-4. ASTM C 672 results – mix 250 – MA - 2.

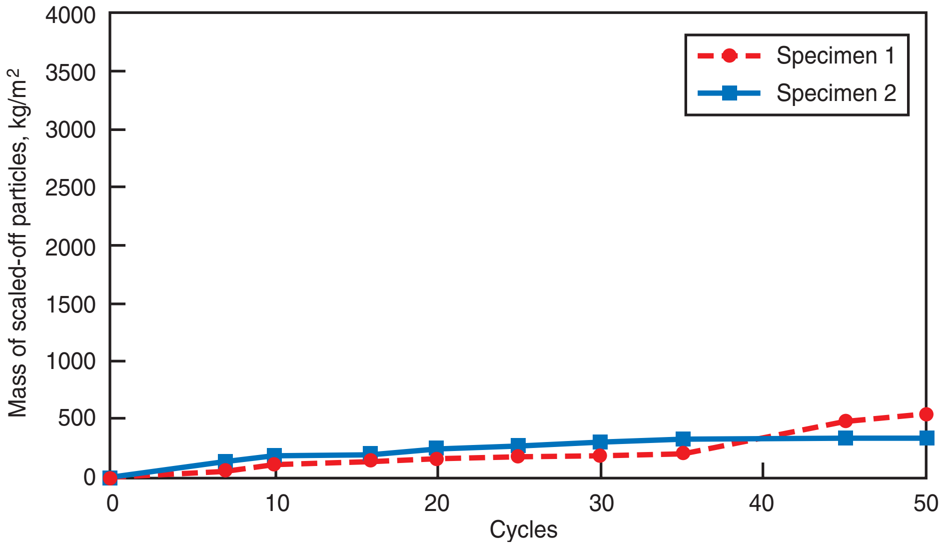


Figure B-5. ASTM C 672 r4results – mix 250 – AXL – 1.

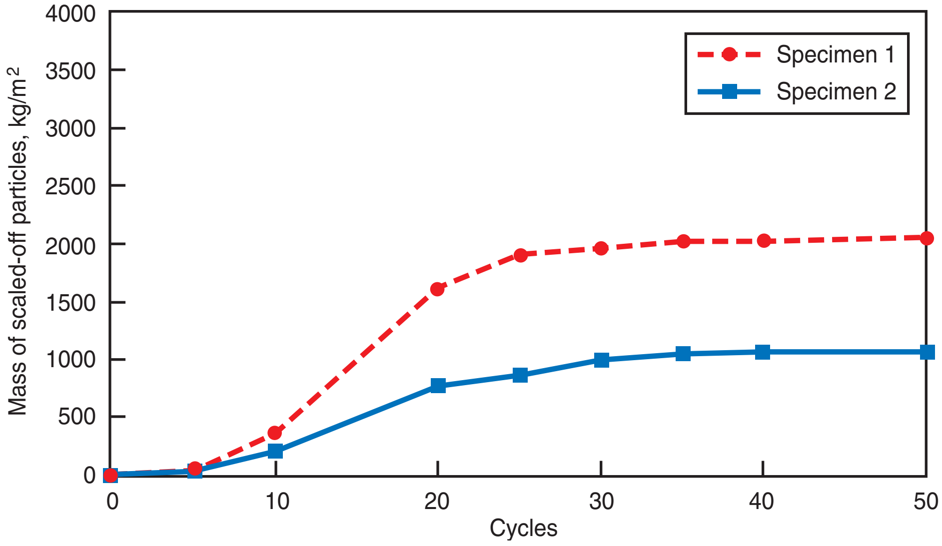


Figure B-6. ASTM C 672 results – mix 250 – AXL – 0.5.

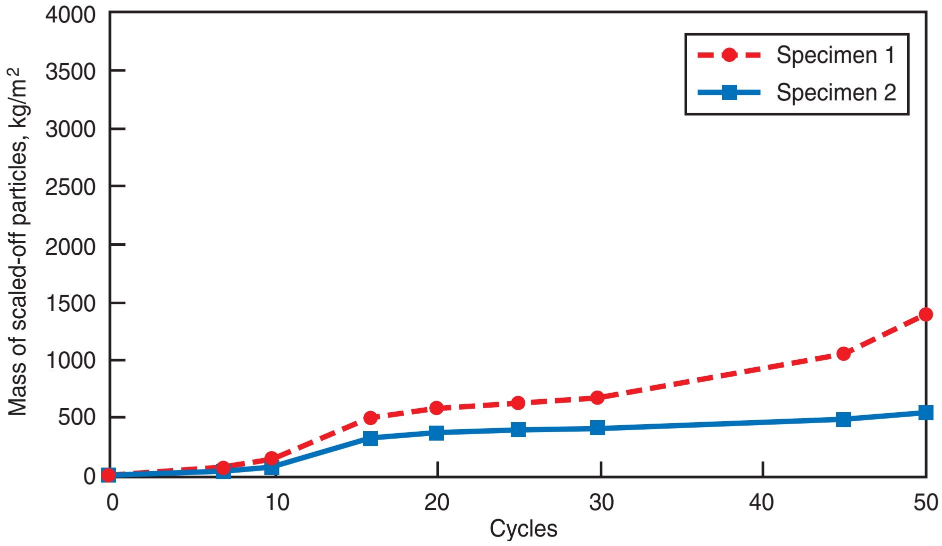


Figure B-7. ASTM C 672 results – mix 250 – AMP – 0.4.

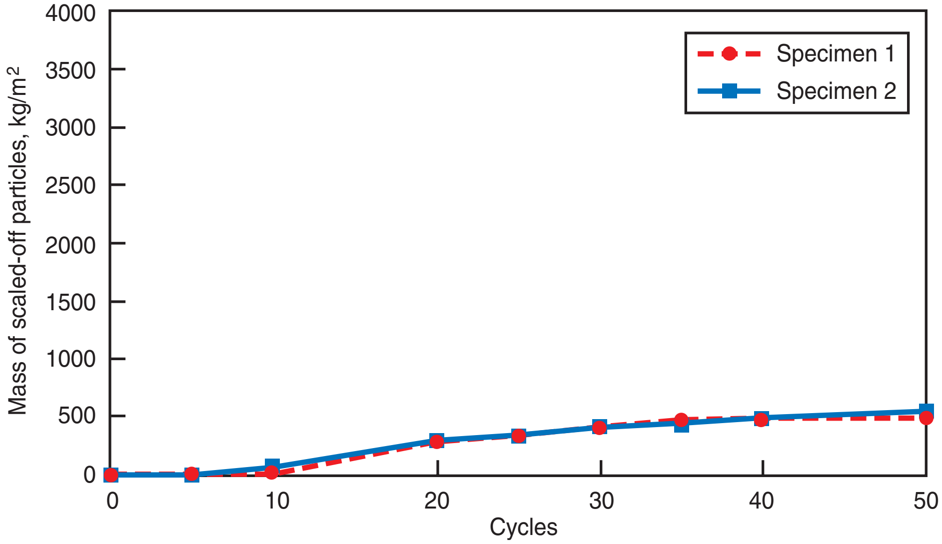


Figure B-8. ASTM C 672 results – mix 250 – AMP – 0.2.

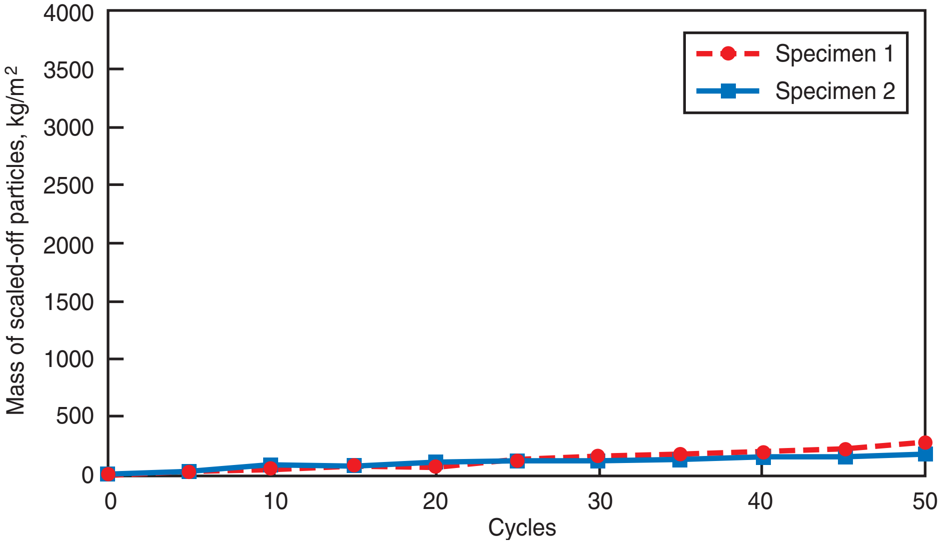


Figure B-9. ASTM C 672 results – mix 300 SF.

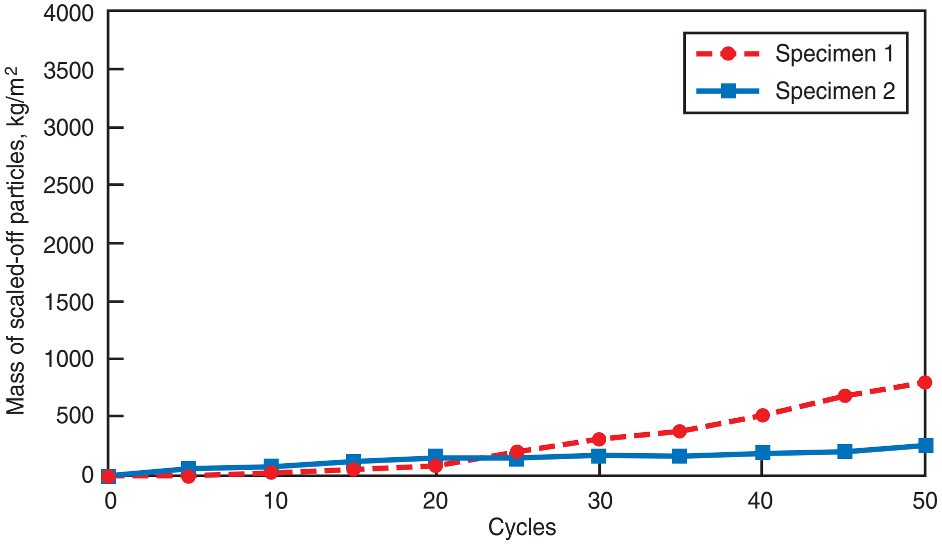


Figure B-10. ASTM C 672 results – mix 250 SF.

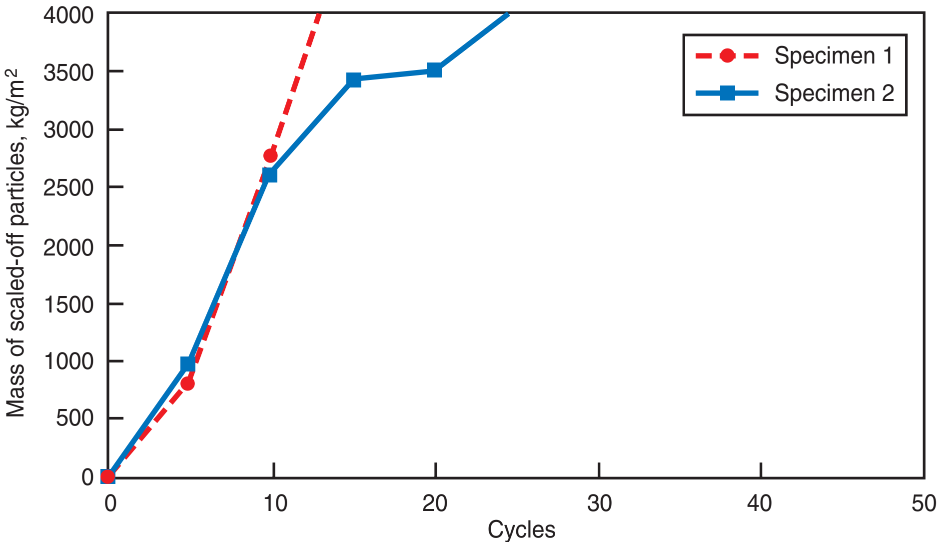
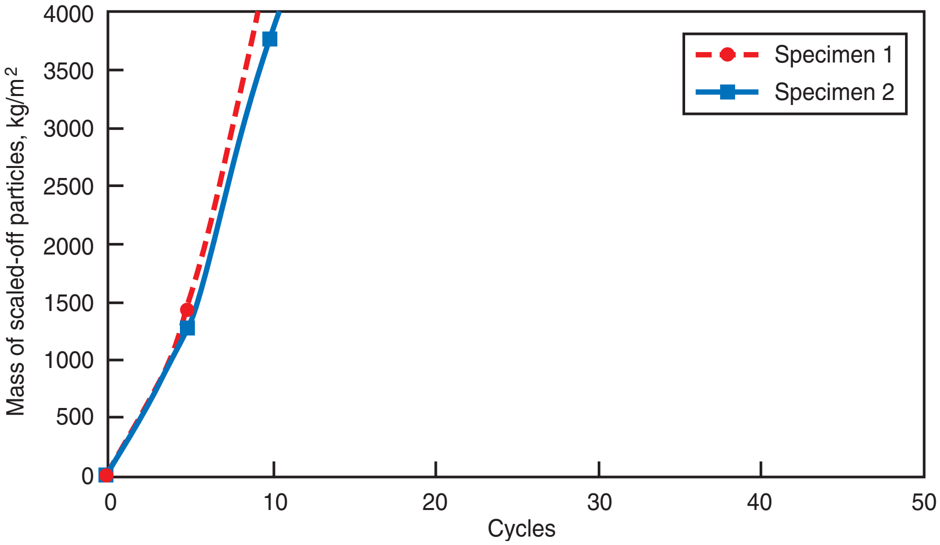


Figure B-11. ASTM C 672 results – mix 300 – FA – C.



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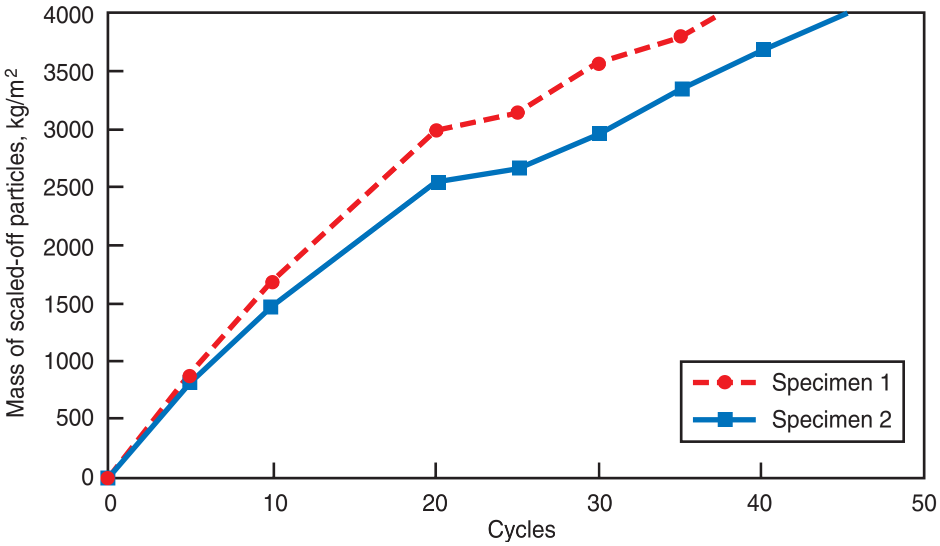

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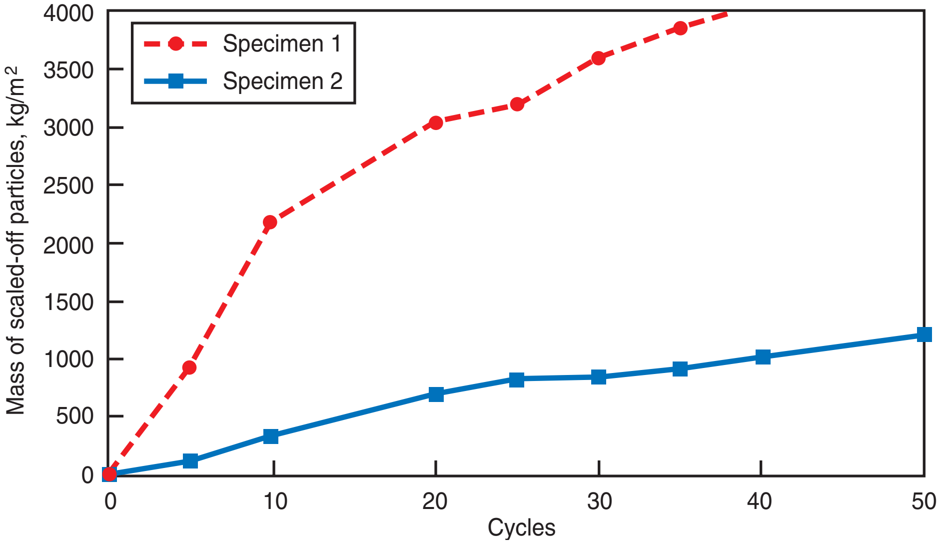

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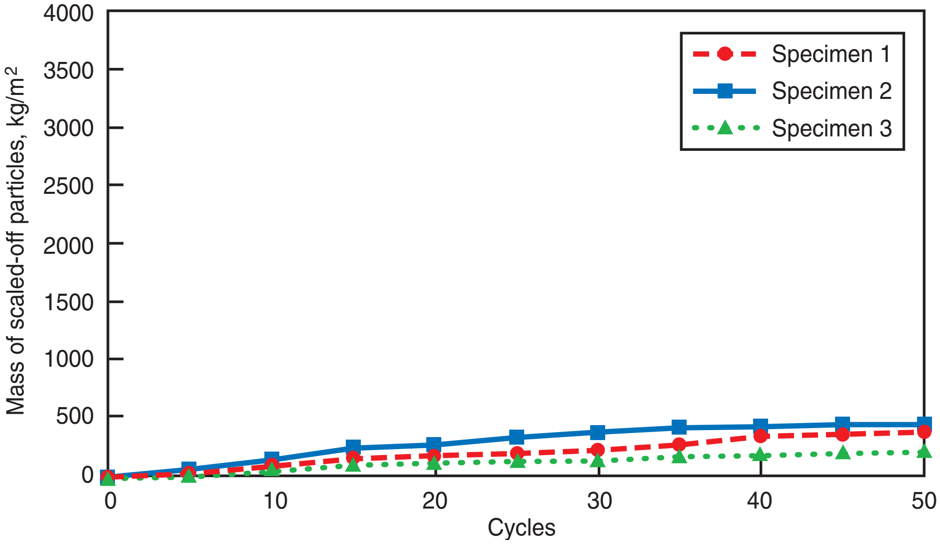

Figure B-15. ASTM C 672 results – mix premix Ref.

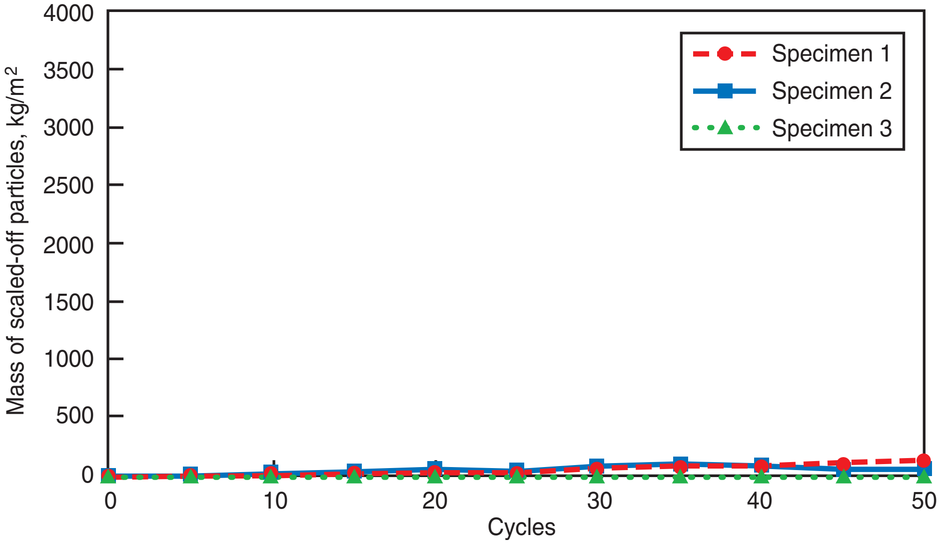

Figure B-16. ASTM C 672 results – mix premix micro air.

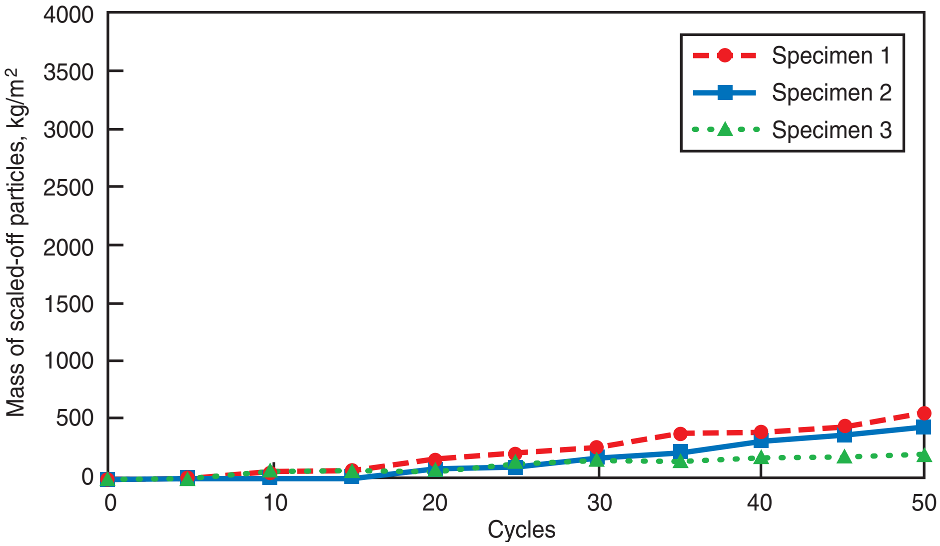

Figure B-17. ASTM C 672 results – mix premix AireX–L.

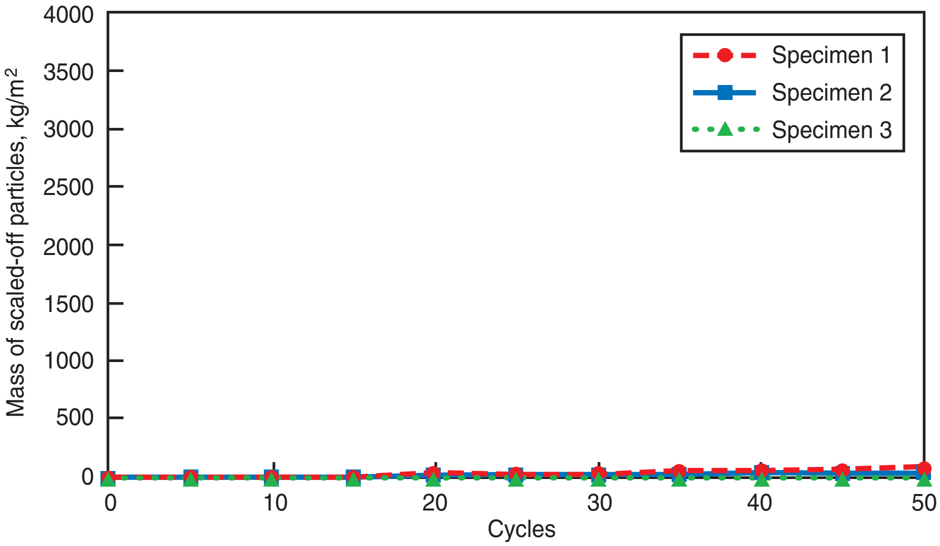

Figure B-18. ASTM C 672 results – mix premix Airmix 200 – P.

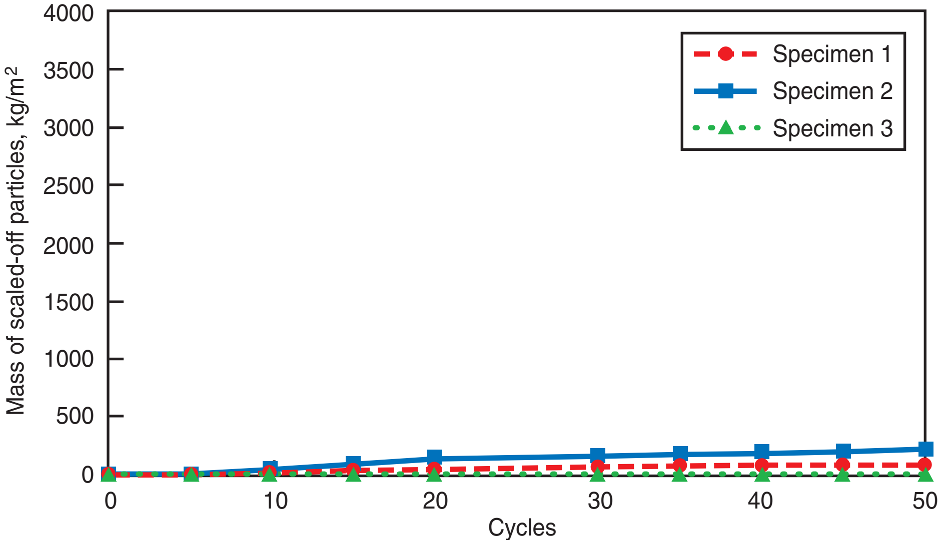

Figure B-19. ASTM C 672 results – mix pugmill Ref.

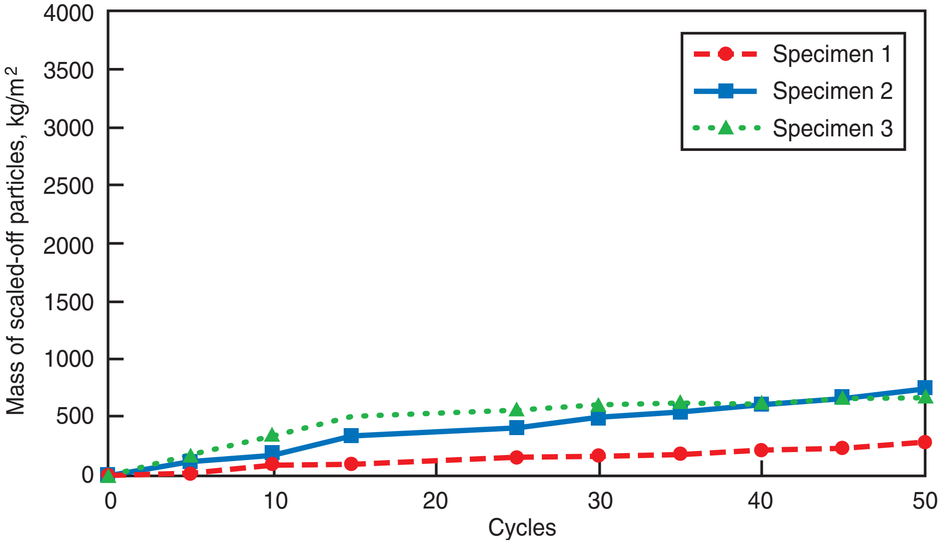

Figure B-20. ASTM C 672 results – mix pugmill micro air.

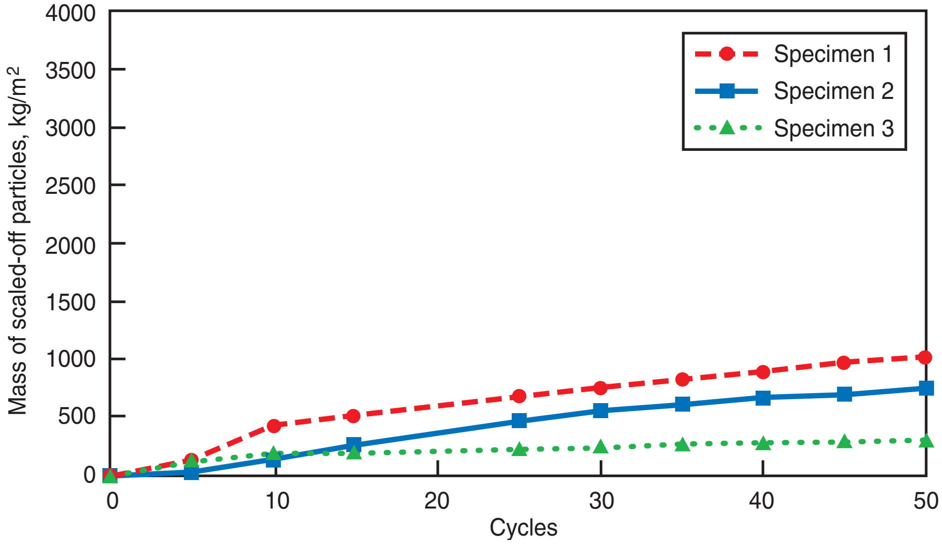

Figure B-21. ASTM C 672 results – mix pugmill AireX–L.

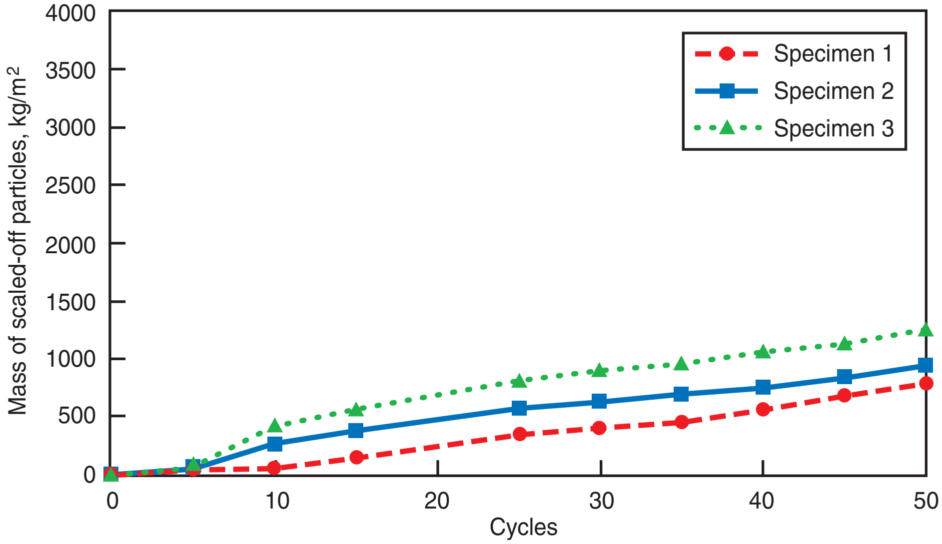

Figure B-22. ASTM C 672 results – mix pugmill Airmix 200 – P.

APPENDIX C

ASTM C 1262 PLOTTED TEST RESULTS

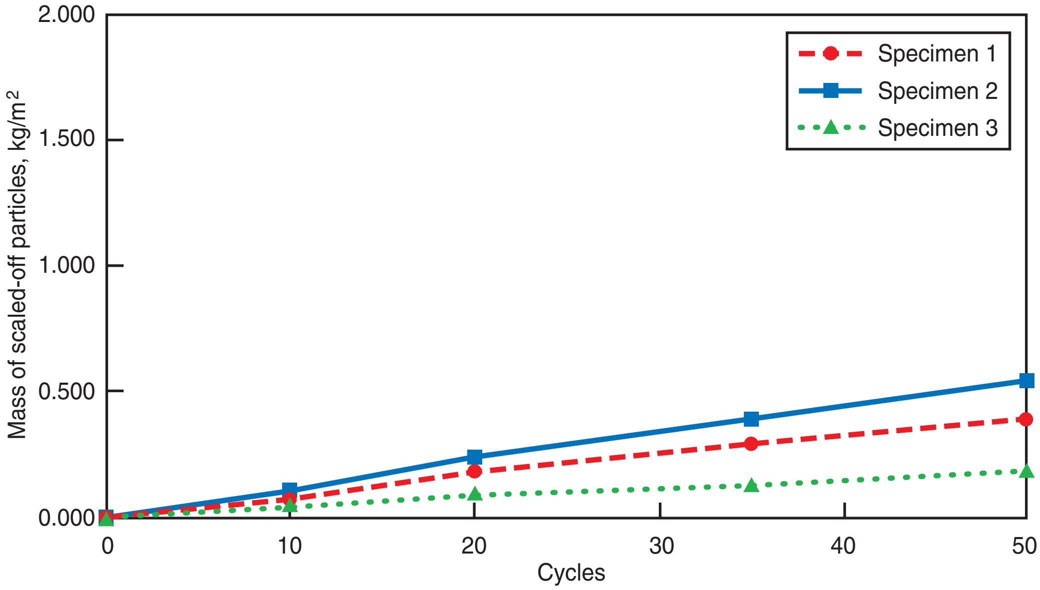

Figure C-1. ASTM C 1262 results – mix 300 Ref.

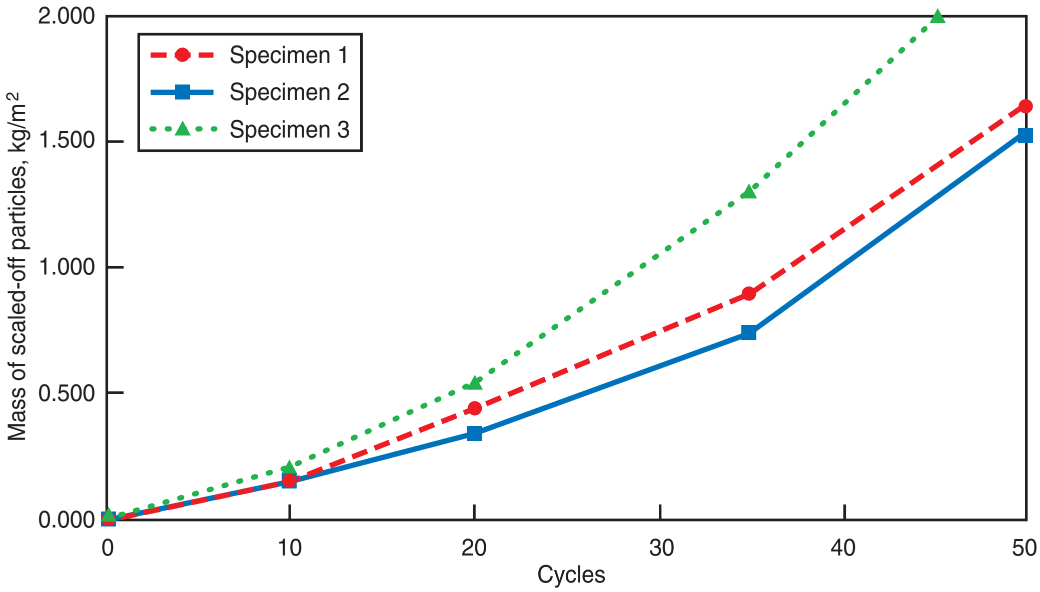

Figure C-2. ASTM C 1262 results – mix 250 Ref.

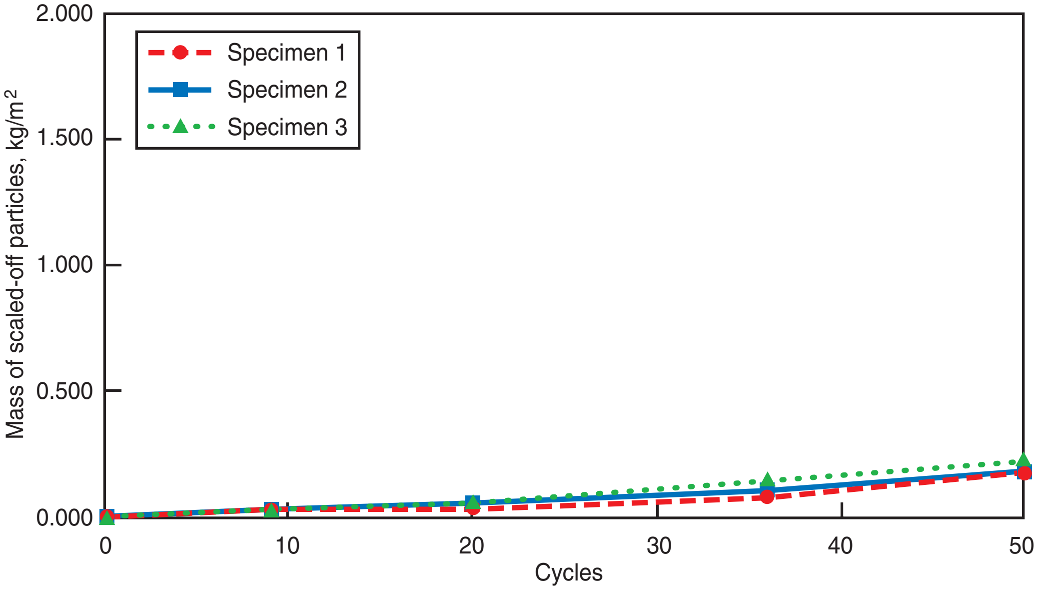

Figure C-3. ASTM C 1262 results – mix 250 – MA – 4.

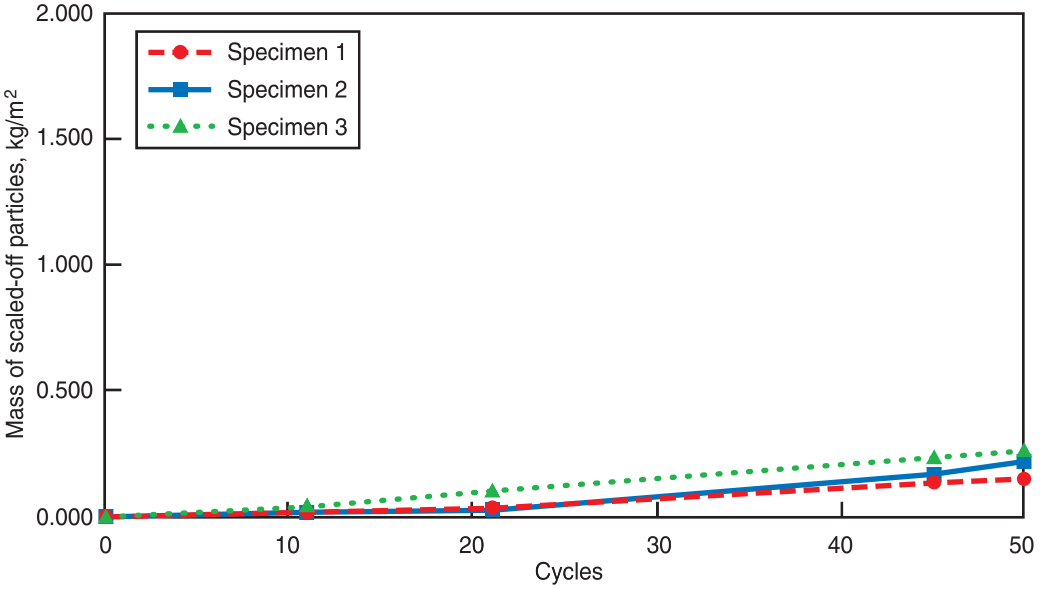

Figure C-4. ASTM C 1262 results – mix 250 – MA – 2.

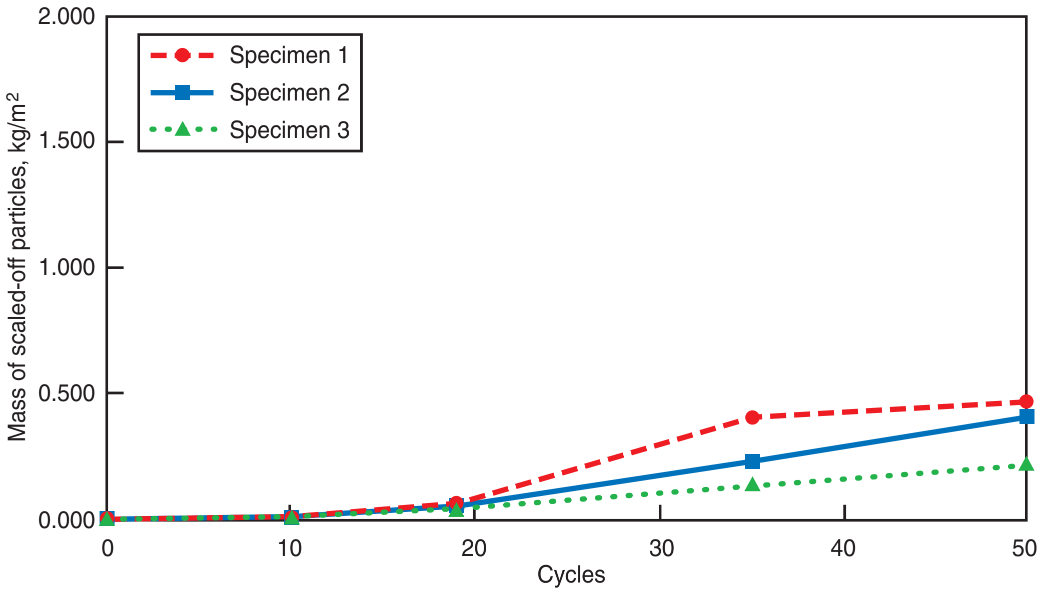

Figure C-5. ASTM C 1262 results – mix 250 – AXL–1.

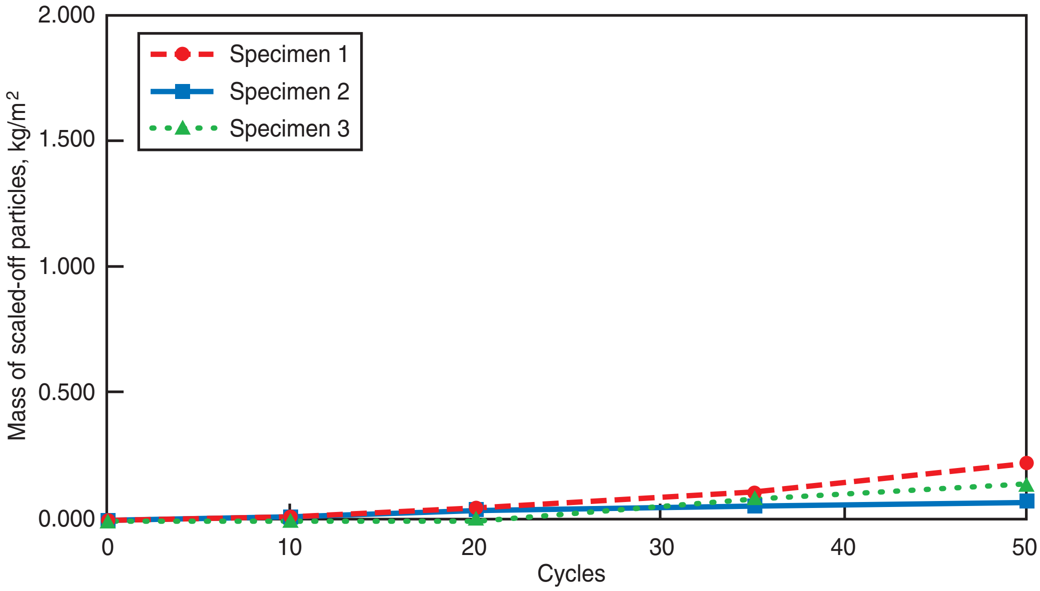

Figure C-6. ASTM C 1262 results – mix 250 – AXL–0.5.

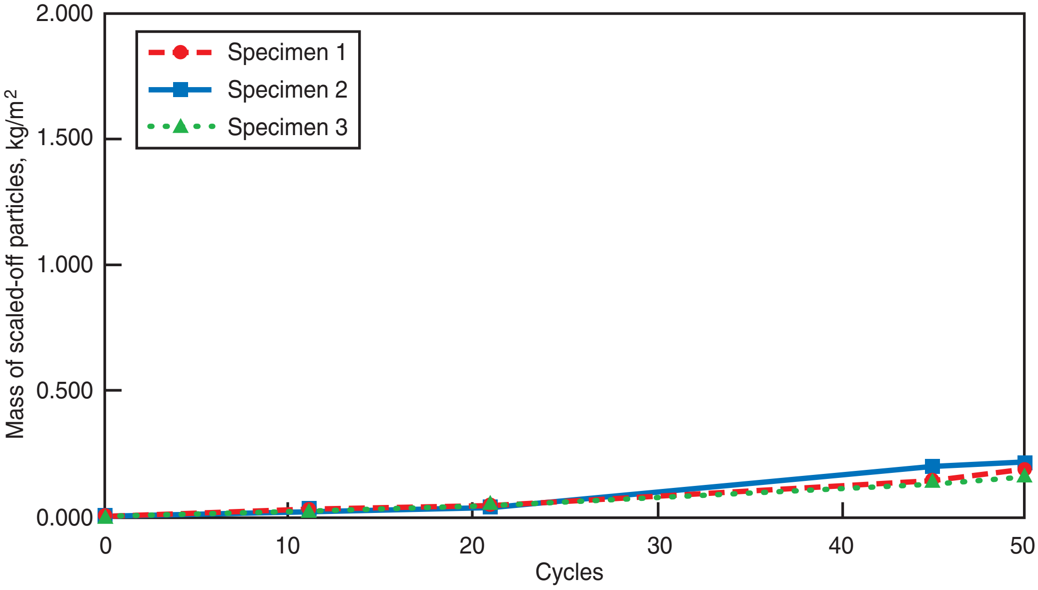

Figure C-7. ASTM C 1262 results – mix 250 – AMP–0.4.

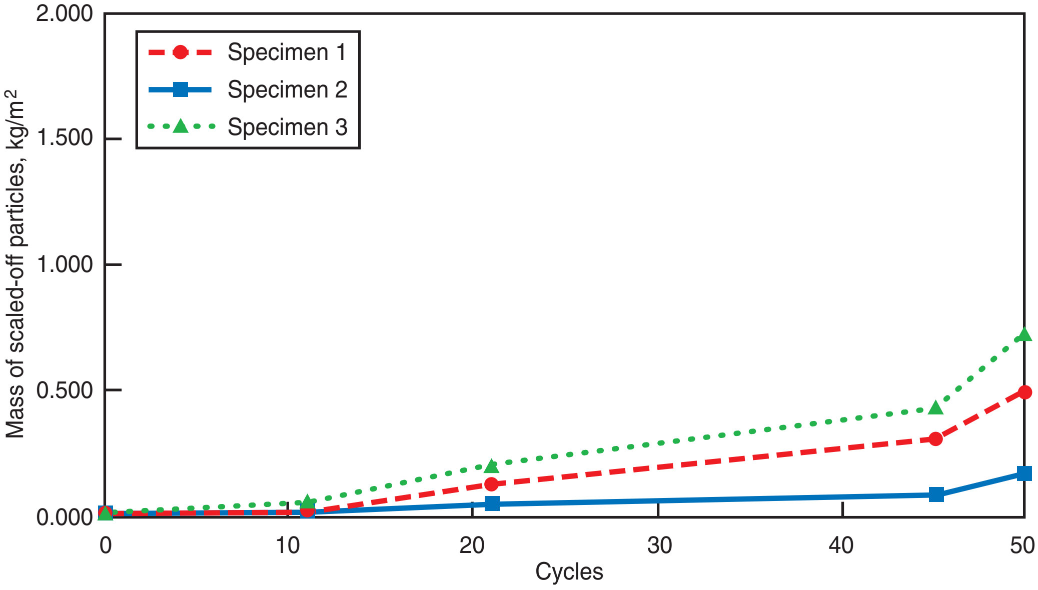

Figure C-8. ASTM C 1262 results – mix 250 – AMP–0.2.

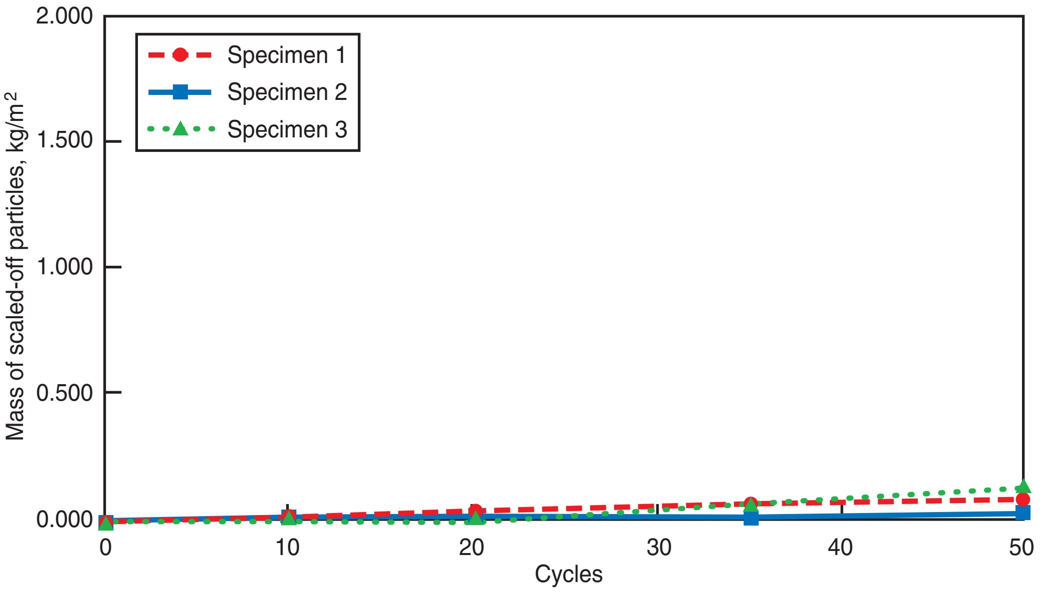

Figure C-9. ASTM C 1262 results – mix 300 SF.

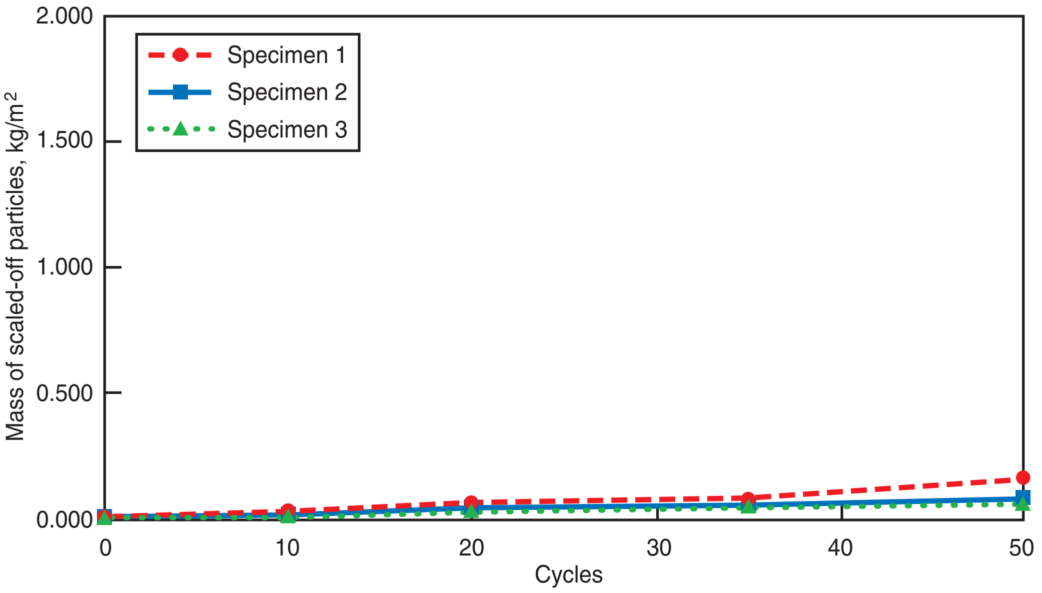

Figure C-10. ASTM C 1262 results – mix 250 SF.

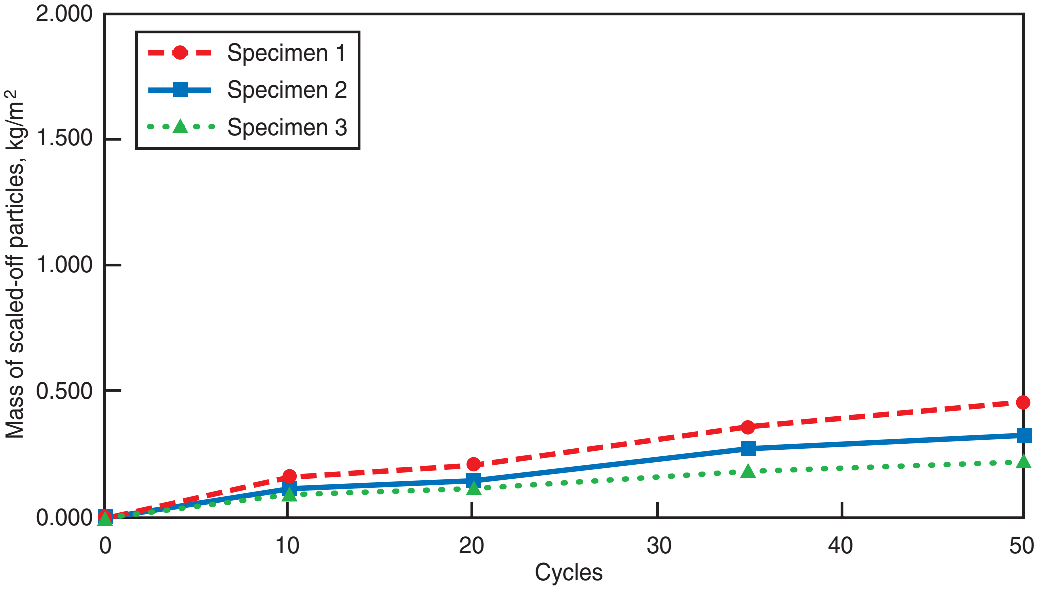

Figure C-11. ASTM C 1262 results – mix 300 – FA – C.

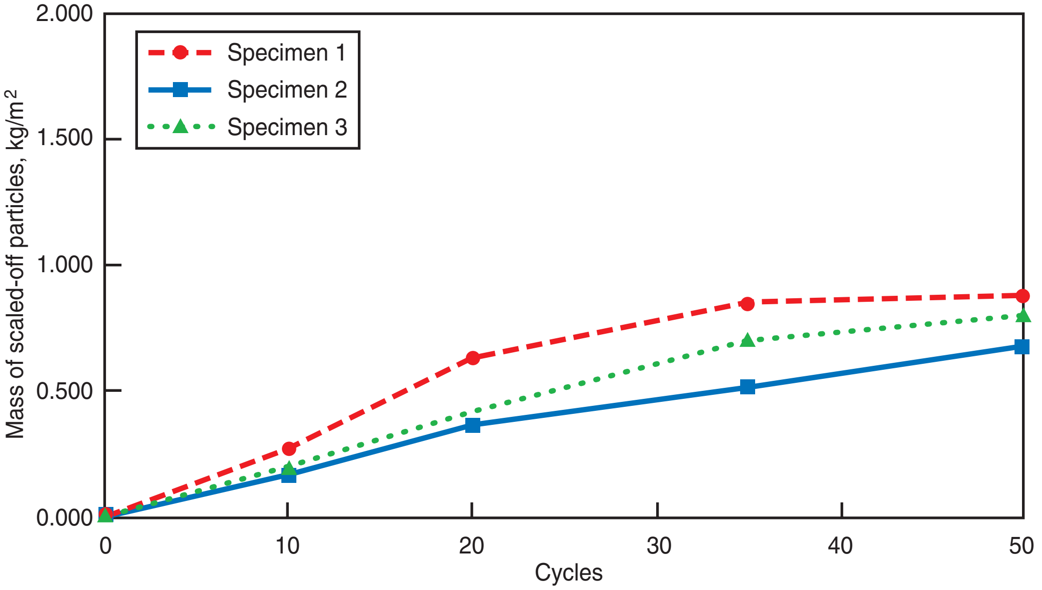

Figure C-12. ASTM C 1262 results – mix 250 – FA – C.

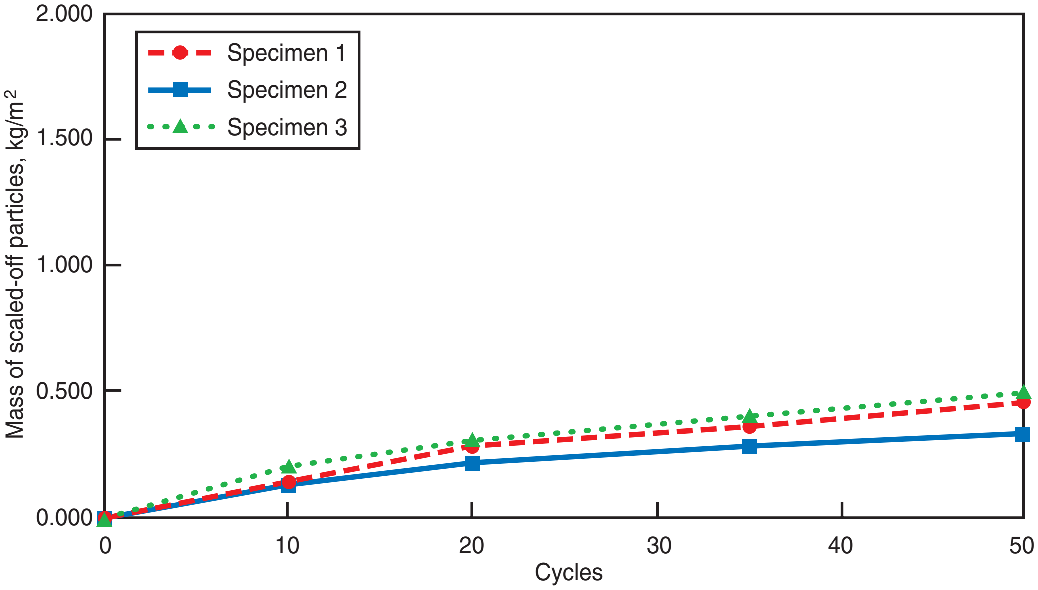

Figure C-13. ASTM C 1262 results – mix 300 FA – F.

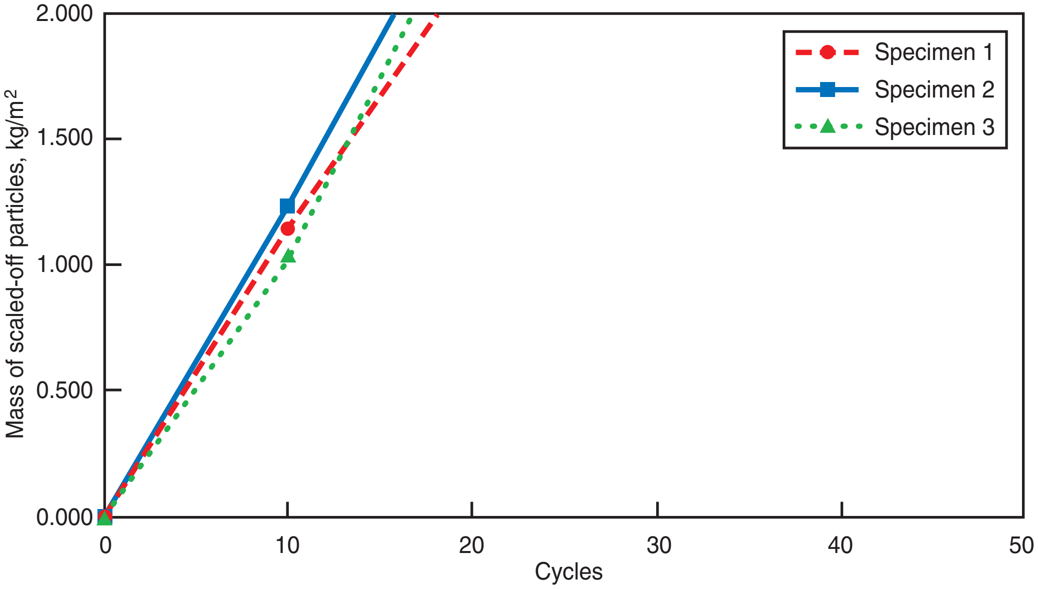

Figure C-14. ASTM C 1262 results – mix 250 FA – F.

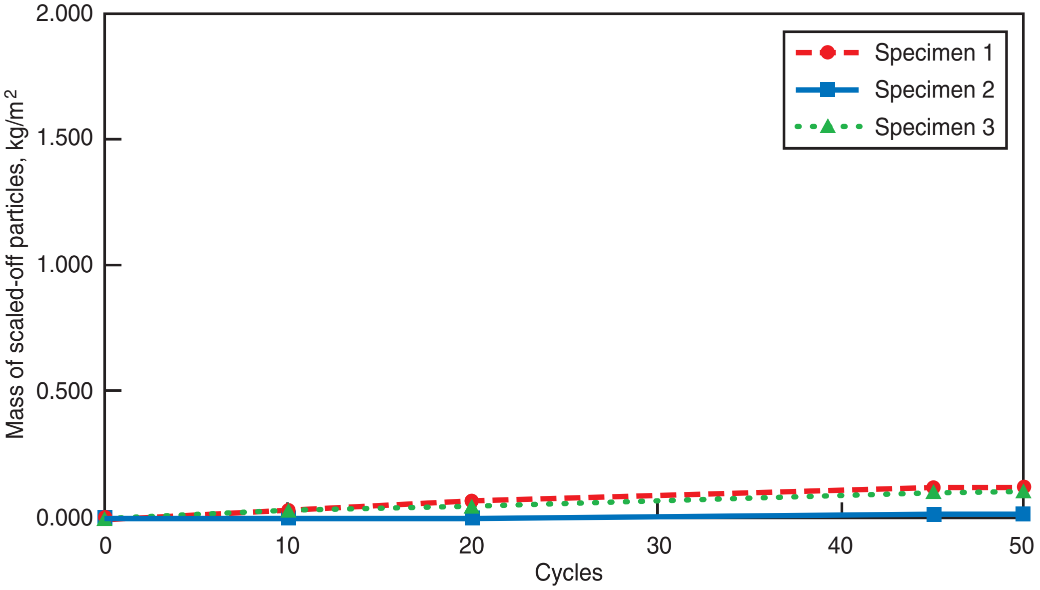

Figure C-15. ASTM C 1262 results – mix premix Ref.

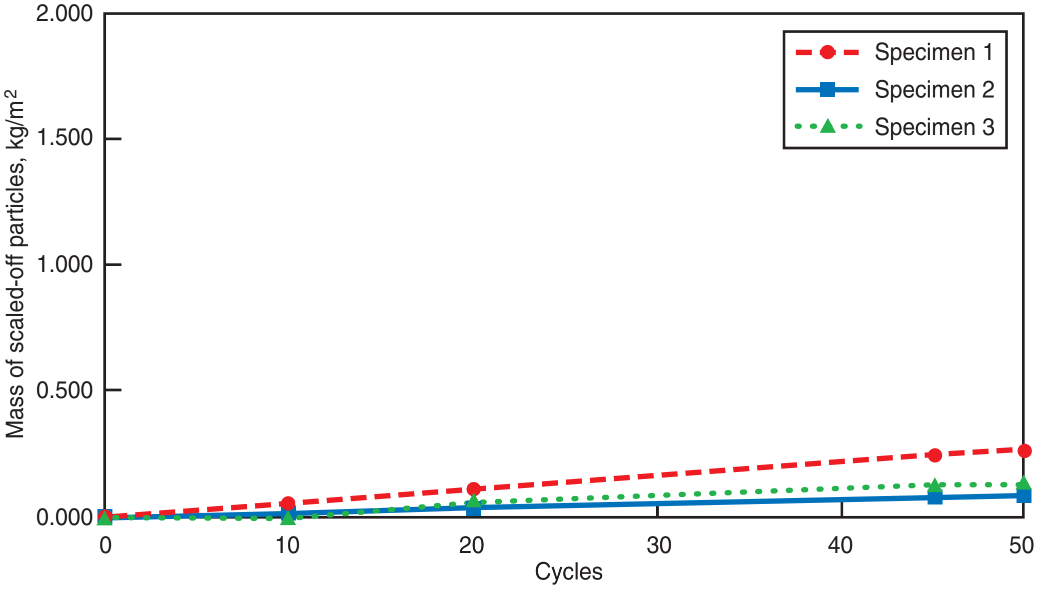

Figure C-16. ASTM C 1262 results – mix premix micro air.

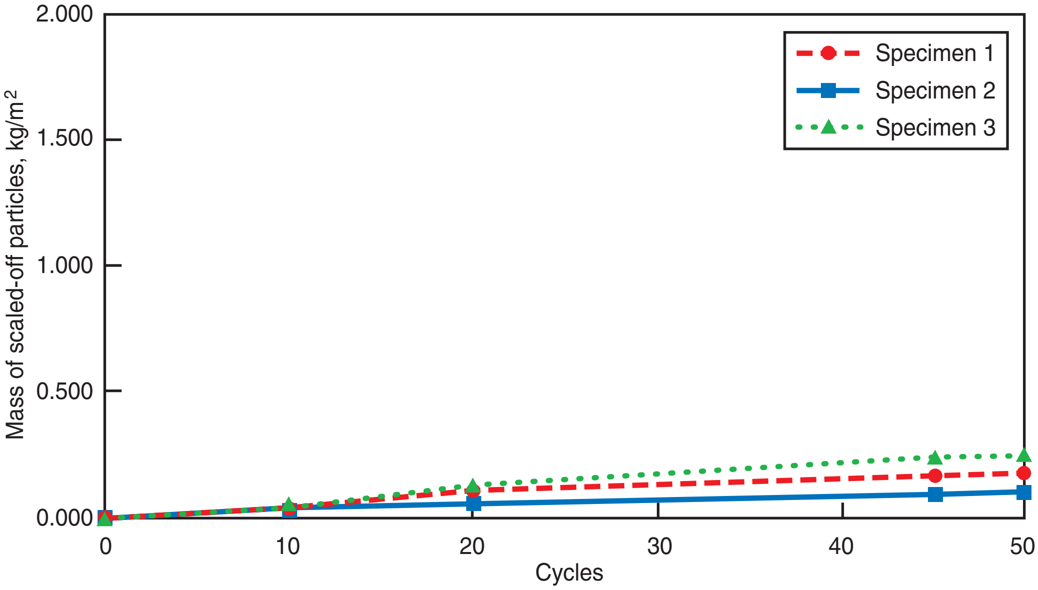

Figure C-17. ASTM C 1262 results – mix premix AireX–L.

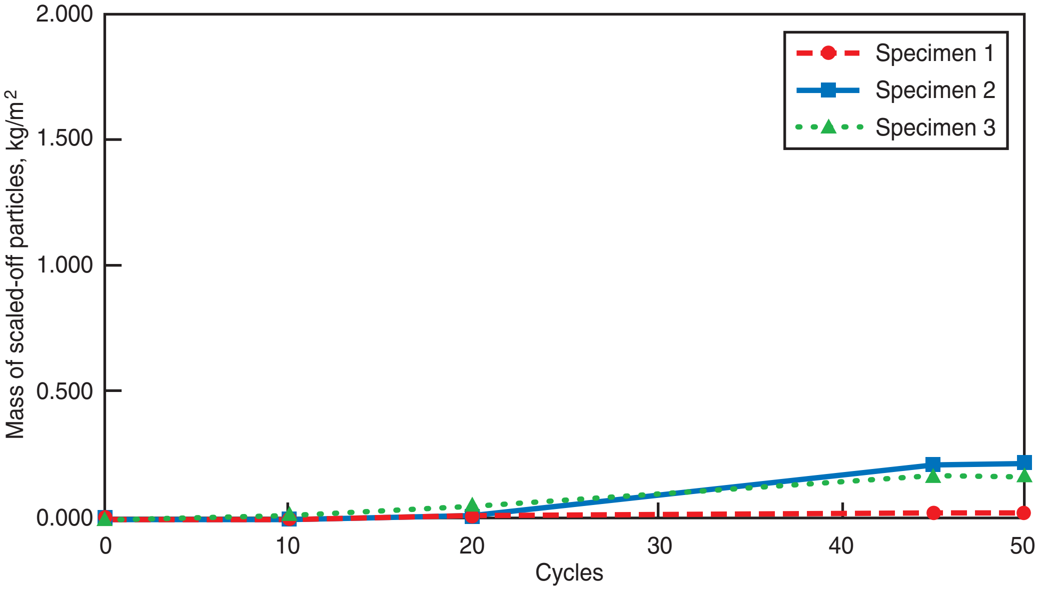

Figure C-18. ASTM C 1262 results – mix premix Airmix 200–P.

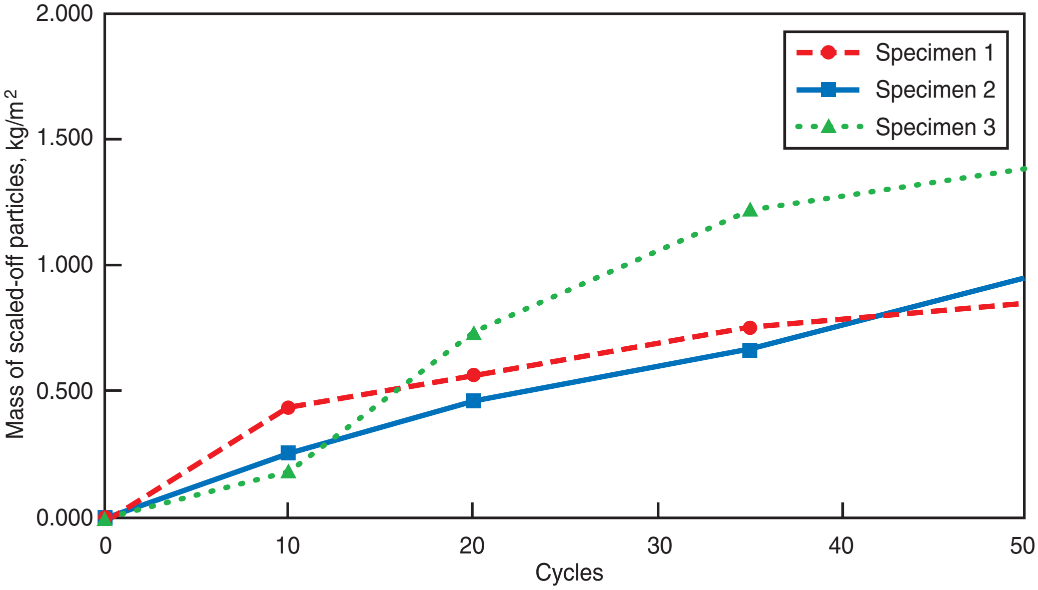

Figure C-19. ASTM C 1262 results – mix pugmill Ref.

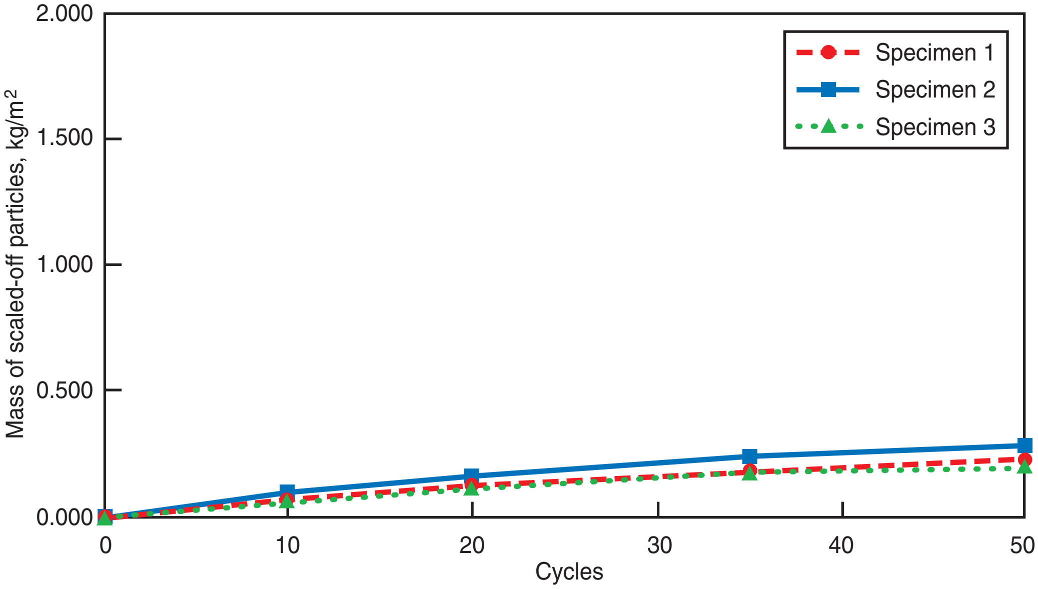

Figure C-20. ASTM C 1262 results – mix pugmill micro air.

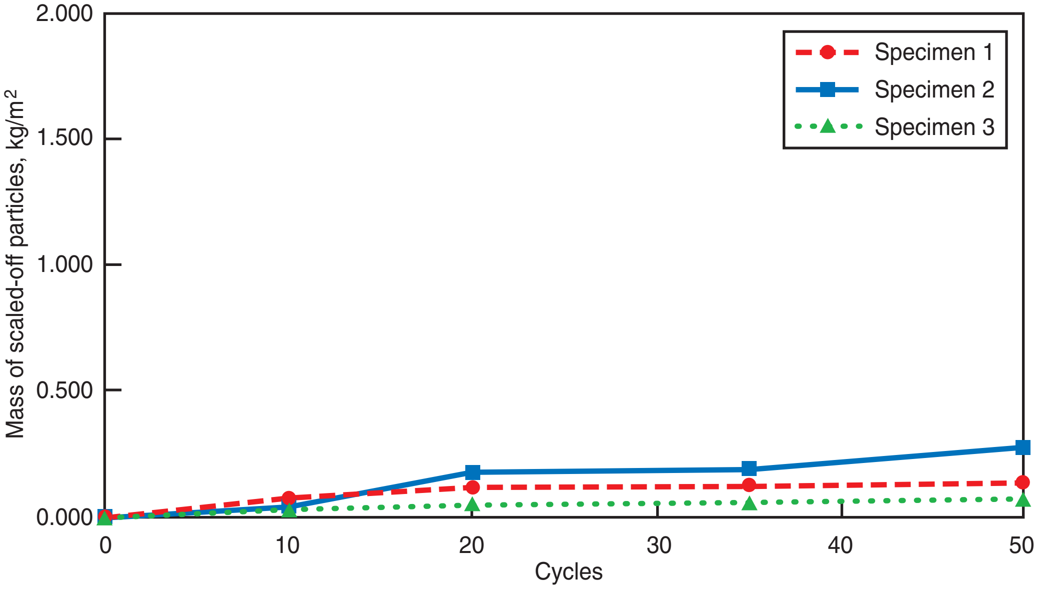

Figure C-21. ASTM C 1262 results – mix pugmill AireX–L.

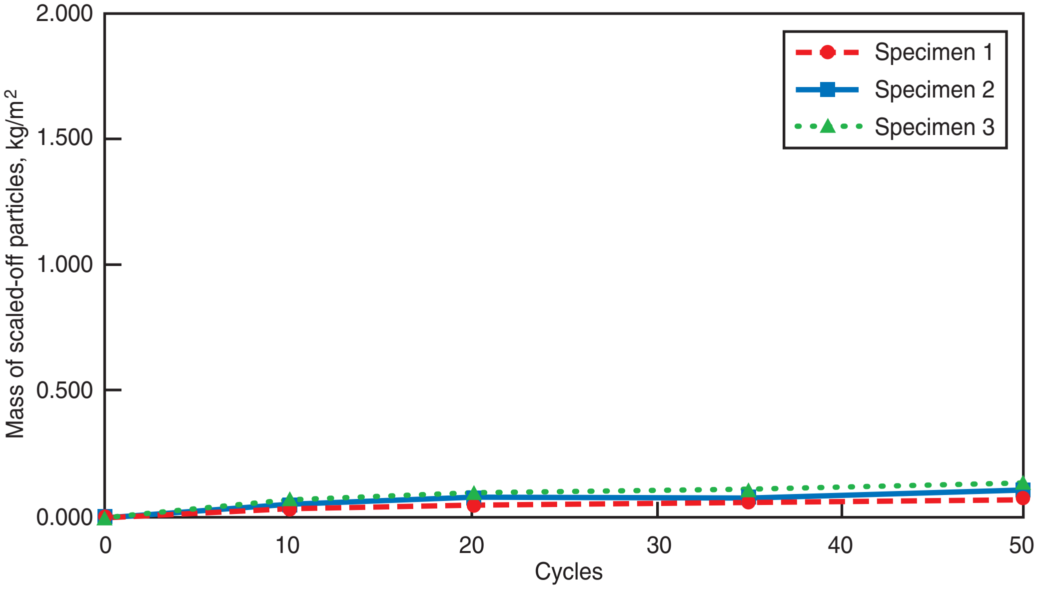

Figure C-22. ASTM C 1262 results – mix pugmill Airmix 200–P.

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An organization of cement companies to improve and extend the uses of portland cement and concrete through market development, engineering, research, education, and public affairs work.