THE DURABILITY OF SEGMENTAL RETAINING WALL (SRW) UNITS

FIGURE 1
EFFECTS OF DRAINAGE AND SALT EXPOSURE FROM PARKING LOT ABOVE SRW (REF. 6., FIGURE 14)

FIGURE 2
MN I35 BRIDGE PIER DAMAGE (2012)

FIGURE 3
BURNSVILLE, MN BUS TERMINAL, CONCRETE DEGRADATION (2012)

INTRODUCTION

This is the second article in a ten article series developed under a grant from the NCMA Education and Research Foundation. In the first article on SRW's (available on www.ncma.org) we showed how the industry had come a long way from zero-slump products made on hand operated machines producing 200 units in a 10-hour day to multi-unit plants manufacturing thousands of units a day on modern manufacturing equipment. When the SRW (landscape products) began in the mid 1980's, architectural requests for products put new demands on producers to manufacture multiple colored products, products with different face textures and products for a wide range of applications. Industry continued to capitalize on manufacturing technology developments to respond to the architectural market demands to create new appealing SRW products.

Success and growth in the landscape, commercial and transportation markets brought big production demands to the industry but also introduced a relatively new consideration for SRW's, freeze-thaw durability, to an otherwise proven product (see figure 1). The aggressive actions of expanding water during freeze-cycles and chemical attack has provided a challenge to all concrete products. To address the exposure needs of retaining wall units, the Federal Highway Administration (FHWA) and industry stepped up research, introduced new additives, improved mix designs, instituted new quality control programs and worked collectively to provide the needed durability. Thanks to years of research and development, wet-cast concrete has improved its performance in freeze-thaw conditions but still has not totally solved the issue. SRWs have made significant progress over the last 20 years to improve freeze-thaw resistance to meet the strict requirements set forth by transportation departments. The products manufactured today perform much better than the products manufactured just 10 to 15 years ago.

In this article we will look at the history of making durable concrete products and how the SRW industry is providing products that will perform well in severe environments.

HISTORICAL DEVELOPMENT

In a report (ref. 13) published by the Federal Highway Administration (FHWA), it was estimated that in 2004 the value of concrete production for highway construction and maintenance was more than 9 billion dollars. However 34 percent of the United States' major roads were still in poor to mediocre condition. While the most persistent problem for concrete in cold climate regions is the concrete deterioration caused by freezing and thawing; preventative solutions are not universally accepted.

Air-entrainment has been used to improve freeze-thaw resistance of wet-cast concrete products since the 1930's. Research in the 1940s to the 1960s sought to establish air requirements for frost-resistant concrete, and many specifications in use today include minimum air-entrainment performance requirements. However, after 80 years of study, more research is still underway to produce durable wet-cast concrete products to provide more acceptable performance under freeze-thaw conditions and chemical reactions to de-icing chemicals.

Zero slump concrete products have been used since the early 1900s for foundation walls, interior and exterior building walls. In most of these applications the walls were not subject to saturated conditions and exposed to the extreme freezing and thawing conditions. Performance of zero-slump structures has been excellent, leaving some manufacturers surprised that their SRW products exhibited durability problems following their initial introduction to the market. SRWs represented the application of a previously proven product into a different environmental exposure that sometimes included saturated conditions and/or harsh de-icing chemicals.

In 1997 the Minnesota Department of Transportation issued a memorandum, based on comments from the local communities, that SRW products should not be used for retaining wall structures along roads and highways due to freeze-thaw durability concerns in the presence of deicing salts. This memorandum came out about 10 years after the introduction of SRWs and millions of square feet of SRWs had been installed. The questionable performance referenced by Minnesota Department of Transportation represented only a small percentage of the total installed product used for DOT applications.

In a historical perspective, the timing of this action was relevant because freeze-thaw durability is a function of exposure time in addition to other variables such as the number of freeze-thaw cycles, the degree of saturation, and the concentration and exposure to deicing chemicals. The majority of walls have performed perfectly with no observed distress. Other walls performed well for many years before experiencing any kind of degradation. In the last 10 years the performance of SRW units has improved significantly due to better mix designs, additional compaction during manufacturing, improved quality control, and strict testing requirements. Problems viewed in the field today may not reflect performance characteristics of current production, but rather that of units produced more than 10 years ago before the improvements were understood and put into place.

CAUSES OF FREEZE-THAW DURABILITY ISSUES

The following sections discuss research that has been performed on zero-slump concrete products and areas where improvements could be achieved. In a brief summary of freeze-thaw durability we know:

- Water enters the pore spaces of the unit
- Upon freezing the water expands up to 9%
- The pressure from the ice causes fracturing of the internal structure of the product causing cracking and spalling of the concrete
- Freeze-thaw damage is generally seen to the top exposed surfaces where water and moisture can collect and stand.

Research into wet-cast concrete showed that improved performance can be achieved through:

- lowering the permeability of the concrete (keep the moisture out of the product)
- Increasing the tensile resistance (strength) of the concrete to resist the internal expanding pressures
- Provide air entrainment (microscopic air voids) to allow movement of water if freezing should occur.

These techniques have worked well for traditional freeze-thaw actions with water, but the highway departments apply also aggressive deicing chemicals to reduce the freezing temperature of water and prevent freezing on the roadways. This now introduces a chemical attack on concrete; for example, magnesium chloride provides a much greater attack on concrete than calcium chloride.

We know what causes freeze-thaw degradation: ice and chemicals. We know what can reduce degradation: increased strength, and reduced permeability. The sections below discuss the research in detail to see what the experts in the industry discovered.

FIGURE 4
FREEZE-THAW DAMAGE ON SRW UNIT IN THE FIELD (REF. 6., FIGURE 49)

RESEARCH INTO FREEZE-THAW DURABILITY

In concrete we see a few areas of concern with freeze-thaw durability that are common to both wet-cast and dry-cast units: cracking, scaling, and spalling of the concrete and chemical attack from deicing chemical. When water freezes it expands about 9%, producing pressures in the pores of the concrete. If the concrete does not have sufficient tensile strength the cavity will dilate and rupture. The accumulated effect of successive freeze-thaw cycles may cause eventual cracking, scaling, and crumbling of the concrete. (ref. 6)

In the FHWA-funded report (Durability of Segmental Retaining Wall Blocks: Final Report (ref. 6)), there was a paragraph that stated the obvious for freeze-thaw durability:

> *"Through this discussion, it is quite evident that the mechanisms of frost damage and salt scaling are not completely understood for conventional concrete, and this understanding is even less when considering SRW blocks and other dry-cast products. Lack of understanding with regard to SRW block durability can be attributed to several factors, including the relative newness of the SRW market (compared to conventional concrete), the unique nature of SRW block microstructure, and the general lack of scientific publications on the topic. Based on this review, the need for comprehensive research on the frost resistance of SRW blocks is quite evident, and the efforts detailed in the rest of this report aim at addressing these needs."*

FIGURE 5
SNOW ACCUMULATION ON WALL (REF. 8, FIGURE 4.12)

Chan (ref. 6) stated the obvious, more research is needed and documentation of performance is required to find the solutions that work consistently.

FIGURE 6
MEDIUM QUANTITY OF DEICING SAND/SALT IN SNOW ACCUMULATION (REF. 8, FIGURE 4.69)

CONDITIONS FOR FREEZE-THAW DEGRADATION

CRITICAL SATURATION

Research has shown that for water expansion to cause detrimental effects, the pores need to be about 91.7% filled (ref. 6). This is termed 'critical saturation'. In areas of freeze-thaw damage we see degradation at the top and front edges of the units, the area where water will concentrate and freeze, or in areas where faces are exposed to repeated spray from plowing operations.

This observation is important since in areas of high freeze-thaw cycles (the lower Mid-west areas of the U.S.) there is not a sufficient moisture supply (snow pack) to keep the units saturated during the F-T cycles and we thus see very little damage. In the northern states where a snow pack is more readily present, there is more moisture available and more damage has been noted.

DEICING CHEMICAL

Deicing chemicals have caused the largest amount of damage to pavements and wet-cast concrete structures. Chemicals used for pavement deicing include sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. Deterioration of concrete by deicers is related to complex processes associated with physical and chemical alteration in cement paste and aggregates. It is affected by factors such as the cation composition of the deicer, type of aggregate used in the concrete, and the reactivity of those aggregates (ref. 9). Deicing salts also allow a deeper penetration of moisture into the concrete matrix and greater water saturation into the unit (ref. 6) thus increasing the potential of achieving critical saturation.

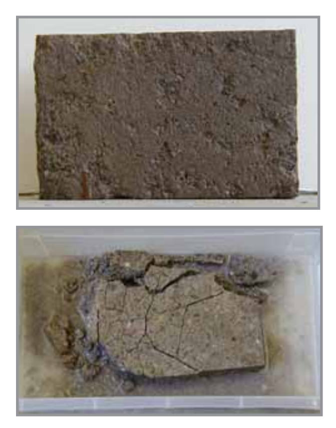


FIGURE 7
SRW SAMPLES SPECIMENS AFTER ASTM C1262 TESTING IN WATER FOR 100 CYCLES (TOP) AND IN SALINE SOLUTION FOR 60 CYCLES (BOTTOM) (REF. 6 FIGURES 221 AND 222)

RESEARCH

When freeze-thaw degradation was first reported in SRW units, the National Concrete Masonry Association (NCMA) began a research program to identify the causes of degradation and provide recommendations to the industry on manufacturing durable units. In 2000, the Minnesota Department of Transportation and NCMA initiated a survey of SRW walls to determine the extent of freeze-thaw degradation (ref. 8). Beyond Minnesota, SRWs are used on a national basis and, as such, the FHWA initiated a pooled fund research study on the durability of Segmental Retaining Wall Blocks (ref. 6).

Embacher surveyed 104 SRWs in Minneapolis and reported only 7% had poor or very poor performance. The conclusions reported that apparently poor durability problems, where they exist, are directly related to the lack of durability of the wall units, thereby, indicating that these problems are largely due to the improper mix designs and/or the use of nondurable aggregates. Recommendations were made to investigate and improve durability of the materials and mixtures used in their masonry block units.

Research by Chan et. al. indicated the freeze-thaw damage from salt solutions was worse than damage from freeze-thaw in water. Freeze-thaw damage to units tested in water was typically reported as surface scaling where while a saline solution test media typically caused internal cracking and complete degradation of the units (see figure 7).

Chan also reported that minimum paste content in the mix was a critical factor to freeze-thaw durability. Although the research did not recommend a specific requirement, the mixes that were demonstrated through testing to have excellent freeze-thaw durability (relative to DOT freeze-thaw specifications) had at least 16 to 18 percent paste content as determined using ASTM C457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.

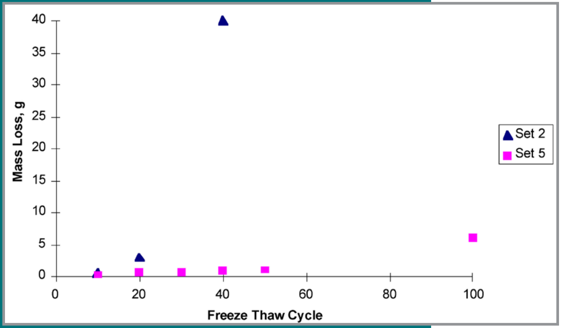


FIGURE 8
MASS LOSS FOR 2 SAMPLES TESTED AT DIFFERENT AGES. (REF. 10 MACDONALD ET AL. FIGURE 3)

MacDonald (ref. 10) investigated SRW unit freeze-thaw durability by looking at the microstructure of units that passed and failed the MnDOT requirements (ASTM C1262 with 3% saline and less than 1% weight loss after 40 cycles). He concluded that the compressive strength, absorption, and density are relatively poor indicators of resistance to freezing and thawing, but was unable to postulate a clear theory as to why this should be the case. What NCMA has found is that even though the compressive strength, absorption and density are not reliable freeze thaw resistance indicators between different mixes, improvement on those properties in a single mix (assuming good quality aggregates are used) actually increases the freeze thaw resistance of the final product. In the graph below, MacDonald had two sets of units from the same production lot (same mix design, production run and manufacturer). Set 2 was tested

28 days following manufacture and failed the C1262 testing in saline at 40 cycles. Set 5, however, was tested 56 days after manufacture and passed.

McDonald concluded that the reason for the better test performance of units cured longer can be attributed to the improved pore size distribution of the bulk paste phase in the concrete over time. The volume of freezable water was determined to be less in the older and more completely hydrated samples and the capillary pore structure is segmented, thereby producing a higher degree of freeze-thaw resistance. A better- compacted unit provides for fewer interconnected voids, a smaller void structure, lower permeability and, therefore, less water to freeze.

FIGURE 9
FREEZE THAW TESTING CHAMBER (NCMA PHOTO)

RESEARCH SUMMARY

Based on general evaluations of SRWs in various cold-weather regions in the U.S. and based on detailed evaluations of SRWs in Minnesota and Wisconsin, Chan reported most SRWs have performed well, with little signs of frost damage or salt distress.

Embacher commented on the correct mix design and the use of more durable aggregates. Chan commented on a minimum paste content to achieve good durability. McDonald (ref. 10) found that freeze-thaw durability of concrete retaining wall block cannot be predicted based on the air void structure, compressive strength, density or absorption. However they did indicate better freeze-thaw durability could be achieved with a better degree of hydration (and therefore curing).

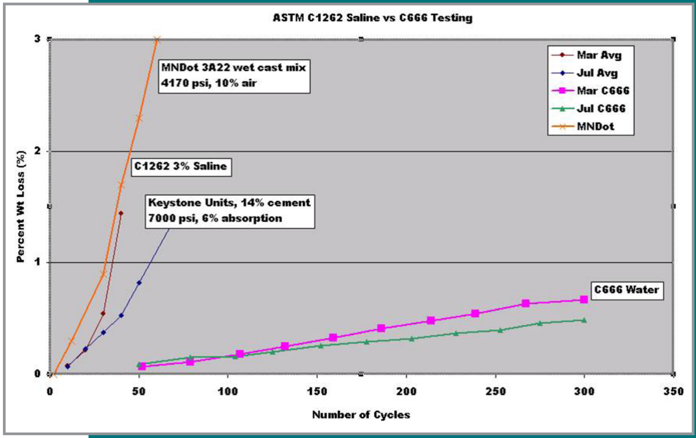


FIGURE 10
ASTM C666 AND C1262 SALINE TESTING COMPARISON

TESTING STANDARDS

It is obvious from the previous section that there is no reliable indicator of good freeze-thaw durability. Mix design, cement content, density, absorption, and cement hydration have been indicated as important factors, but no clear recipe for success could be stated. In the absence of a reliable indicator, it became apparent that a standard method for testing the actual freeze-thaw resistance of units was needed.

When the first problems were reported with durability there was no standard test method for durability testing for SRW units. ASTM C666 was the standard test for wet-cast concrete but was determined to not be appropriate for zero slump products based on the specific specimen sizes required, the rapid freezing and thawing rates employed, and/or the imposed saturation conditions of some of the different methods included in that standard. After similarly evaluating and discounting the efficacy of other existing methods, the NCMA supported the development and standardization of ASTM C1262, Standard Test Method for Evaluating the Freeze-Thaw Durability of Dry-Cast Segmental Retaining Wall Units and Related Concrete Units, first approved in 1998. When ASTM C1372, Standard Specification for Dry-Cast Segmental Retaining Wall Units, was printed, it suggested that in areas of repeated freezing and thawing under saturated conditions, freeze-thaw durability shall be demonstrated by test or proven field. When testing is required, then the units should have less than 1% weight loss for 100 freeze-thaw cycles in water. For transportation work, many states with freeze-thaw conditions specify that SRW units be tested using ASTM C1262 with a 3% saline solution when those units may come into repeated contact with of deicing chemicals. Many states have adopted ASTM C1262 and require less than 1% weight loss after 40 cycles in a saline solution. However, criteria adoption is inconsistent between states with some having both more and less stringent requirements.

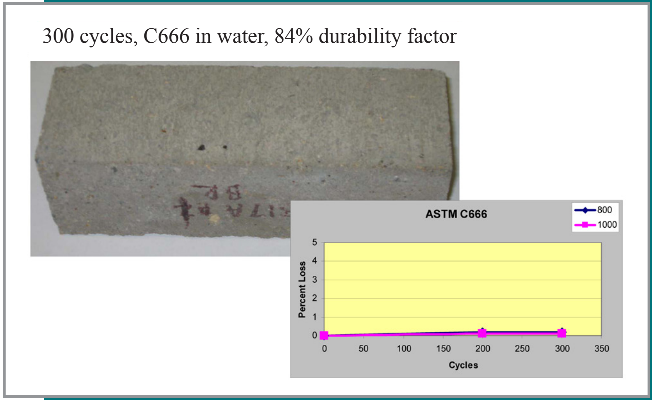
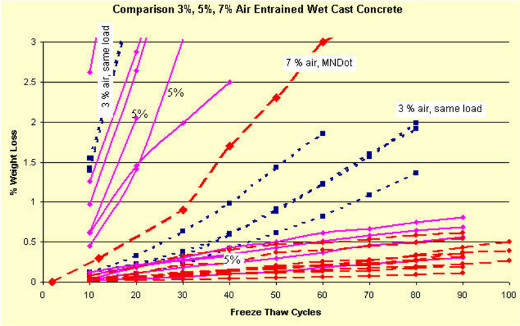

300 cycles, C666 in water, 84% durability factor

FIGURE 11
ZERO SLUMP CONCRETE SAMPLES TESTED IN ASTM C666

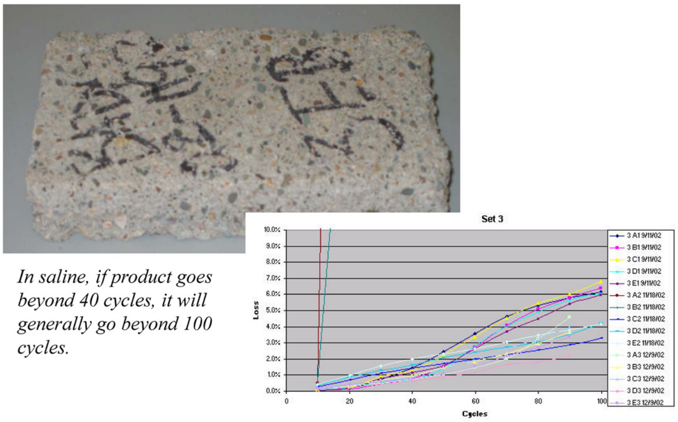
COMPARISON OF ASTM C666 AND ASTM C1262

Minnesota DOT (MnDOT) expressed concerns on the durability of zero-slump products based on a small percentage of degrading walls



Field sampling from ready-mix trucks, using field air contents, shows wet-cast with less than 7% air is questionable passing the saline test. [AASHTO requirements 6% entrained air +/- 1.5%]

FIGURE 12
WET CAST SAMPLES RANDOM TESTED WITH ASTM C1262 SALINE



In saline, if product goes beyond 40 cycles, it will generally go beyond 100 cycles.

FIGURE 13
TESTING BEYOND ONE PERCENT LOSS

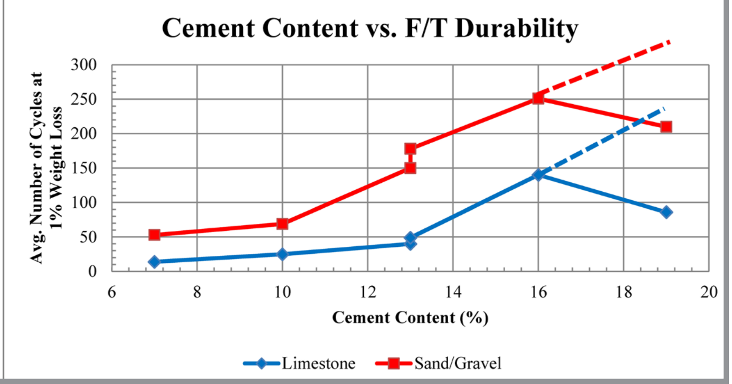


FIGURE 14
NCMA RESEARCH – FREEZE THAW MASS LOSS AT DIFFERENT CEMENT CONTENT

due to deicing chemical attack. The criteria they proposed was ASTM C1262 in a three percent saline solution with less than one percent weight loss at 90 cycles. Manufacturers trying to meet this specification found it very difficult to achieve. Braun Intertec (a Mid-west testing firm) and a MN manufacturer looked at testing in ASTM C666 and ASTM C1262 to see if there was a comparison.

The test samples selected were a MnDOT 3A22 wet cast mix (4000 psi [27 MPa] curb and gutter mix) and a zero slump 4000 psi (27 MPa) SRW block [at the time of testing, the mix design was not the current DOT mix design, the mix was proportioned with approximately 14% cement content]. In the graph below, the wet-cast mix exceeded a one percent weight loss in 25 cycles in saline (failed), whereas the zero slump mix exceeded 50 cycles in saline. The wet cast mix also had a severe mass loss in the saline solution, as was typical for zero slump mixes. Testing the zero slump product in the standard AASHTO test method (ASTM C666), the samples exceeded 300 cycles with 0.5 and 0.7 weight loss, or about an 84 percent durability factor. (In ASTM C666, a durability factor of less than 60% is considered failure).

This was interesting seeing the criteria for zero slump products was more strict than for wet cast concrete. Figure 11 is an image of the zero slump concrete after 300 cycles in ASTM C666.

ASTM C666 is a rapid freeze thaw method and is considered by industry to be a very severe test for concrete. [As a note of interest, this topic was brought up to MnDOT as their test method was more severe than the AASHTO standard. Minnesota has a very cold environment with lots of deicing chemicals and thus requires very durable materials. The response from MnDOT "**nothing fails in C666 here, we like C1262 in saline because everything fails**" (David Retner, MnDOT personal conversation).

One more series of testing was done on wet cast samples (MnDOT 3A22 mix design) taken from a truck at delivery, cured and tested.

Testing showed the three percent and five percent air samples failed to meet the one percent loss at 90 cycles, where the seven percent samples were meeting design specifications. In simple terms, a DOT mix with less than six percent air content may not meet the MnDOT design specifications for SRW wall units. SRW units meeting the MnDOT specification have to perform as well as a DOT mix with 6+ percent air content.

One last comment to be made in the comparison study and that is on the long-term performance of the products. The SRW product with 14% cement content would not meet the one percent loss in a saline solution, or failed the MnDOT specifications. However, in extending the testing beyond the one percent mark the product maintained integrity to over 100 cycles, losing three to five percent mass.

In closing this section, Figure 1 at the start of the article would represent a 2500 psi to 3000 psi (17.2 to 20.7 MPa) zero slump SRW manufactured before the standard specifications were in place. Knowing what we have learned since, it did what would have been expected, whether an SRW or a 3000 psi (20.7 MPa) wet cast mix with little or no air entrainment. MnDOT had it right, in a saline solution everything fails.

RECOMMENDATIONS

With standardized test methods in place (ASTM C1262) and criteria for both commercial and DOT applications for acceptable products (ASTM C1372 and various DOT requirements) in place, NCMA focused on performing research to assist manufacturers in producing durable products that would repeatedly comply with those requirements. As expected, research concluded SRWs required more cement, required durable aggregates, and needed more compaction resulting in accompanying industry recommendations:

(1) Susceptible aggregates adversely affect the freeze-thaw resistance of manufactured products. Recommendation – use DOT-approved aggregate sources or demonstrate adequate performance of units using freeze-thaw testing.

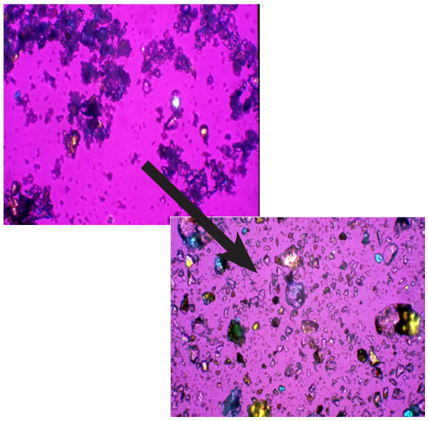
(2) Increased amounts of cement paste improve freeze-thaw resistance. Recommendation – increase cement content in mix design as needed to achieve specified performance.

(3) Improved levels of compaction during manufacturing improved freeze-thaw resistance. Recommendation – increase cycle time and, if needed, increase mix water content. Optimize aggregate gradation. Institute quality control measures to ensure manufacturing repeatability.

NCMA research demonstrated improved performance of units with higher cement contents and with more durable aggregates. (See Fig. 14 NCMA research) [The results decrease after a cement content of 16% which is caused when the increased finer fraction is lost during testing. When the testing was extended passed the 200 cycles the units actually showed better F-T resistance than samples with less cement content - behavior shown in the dashed lines. It is also necessary to mention that high cement contents may cause other production challenges such as the material may stick to the molds, reducing compaction that have to be considered. The behavior shown in the graph above indicates the test may not capture the long term behavior of products with high cement content].

MacDonald (ref. 10) commented on hydration and curing of the paste indicated better durability. In the production cycle, the producer has the option of increasing cement contents and/or improving the dispersion of that cement throughout the mix using admixtures. In a normal SRW product the images below show 40% of the cement remains unhydrated, perhaps as a result of the low levels of mix water used to manufacture zero-slump products. Newer generation admixtures provide for better dispersion of the cement and, therefore, better hydration.

Use of high-performance dispersants enhance cement utilization



- Cement grains tend to clump in water
- Cement clumps undergo inefficient hydration
- Low w/c ratios, shorter curing time add to the problem
- In SRWs, >40% of cement remains unhydrated

FIGURE 15
ADMIXTURE IMPACT ON SRW CEMENT REACTION (IMAGE COURTESY OF GRACE CONSTRUCTION PRODUCTS)

SUMMARY

In the mid 1990s SRWs were exhibiting freeze-thaw durability problems. Municipalities and DOTs expressed concerns to the industry as SRWs were a cost effective solution for earth retaining walls but may not be performing as well as expected. Industry initiated research to determine the parameters that were causing the durability concerns and the FHWA coordinated with DOTs to initiate a pooled fund research program into the durability of SRWs. Industry stepped forward and developed a test method for SRWs durability in freezing and thawing conditions that would provide a performance bench for durable products. Many DOTs accepted industry recommendations and specified use of the test method (ASTM C1262) with a 3% saline solution with accompanying performance requirements using that method.

Early manufacturing, done in the absence of adequate specifications or standardized test methods, relied on specifications and performance experiences associated with standard masonry units complying by ASTM C90, Standard Specification for Loadbearing Concrete Masonry Units (1900 psi [13.1 MPa] concrete mix). When freeze-thaw testing began, it was found a typical commercially available average SRW units would not meet the 1% mass loss requirements at 100 cycles of testing freeze-thaw in water (see Figure 1 and Figure 4). A new ASTM standard was developed, ASTM C1372, which better addressed the needs for SRW units and addressed durability requirements in areas of repeated freezing and thawing under saturated conditions.

Today, in areas of repeated freezing and thawing under saturated conditions, the SRWs should meet or exceed the requirements of ASTM C1372 (less than 1% weight loss after 100 cycles in water). In the northern states with severe freezing and thawing and exposure to deicing chemicals, SRWs approved for DOT use should have less than 1% weight loss after 40 cycles of testing using ASTM C1262 and a 3% saline solution or comply with the requirements of the applicable state.

INDUSTRY RESPONSE TO CONSUMER CONCERNS

Industry again has come a long way in the last 10 years to produce durable SRW products. After 80 years wet-cast concrete durability research is on-going. After 20 years continued research is still on-going with zero-slump concrete for durability in exterior freezing and thawing conditions with harsh deicing chemical exposure. We may not know everything about durability of zero-slump concrete, but we know much more now than we did in the 1990s. Manufacturers have adopted better QA/QC programs to monitor production and perform testing to confirm the units produced will provide the performance expected.

The units today are meeting the durability requirements of the commercial and transportation markets and as shown in the comparison discussion, may be exceeding the requirements set for wet cast DOT mix designs. Comments from the FHWA and DOT's indicate fewer complaints on SRW durability confirming better performance. Industry responded quickly to a problem that is a serious and costly concern for concrete products, freeze-thaw and chemical degradation.

COMMON SENSE SUGGESTIONS

The sections above presented the research, presented industry recommendations for manufacturing durable products and presented requirements for transportation markets. That was a very technical presentation and concluded we know more but not everything about durability. Below are some common sense solutions to avoid problems with freeze-thaw:

1. Avoid using SRW products for steps or walkways where de-icing salts will be used. Use SRWs as the base material with a concrete or stone slab step cover.
2. Where parking lot runoff may flow over the wall, provide a collection basin and either pipe the water around the wall or provide an extended shoot where the saline water does not flow down the wall.
3. Where de-icing chemical may land on a SRW retaining wall, consider a more durable capping unit. Durability concerns occur where there are saturated conditions in repeated freezing and thawing conditions.
4. In areas were SRW's are exposed to repeated exposure from snow removal equipment, consider sealants or water repelling chemicals periodically applied to the walls (saline, siloxane compounds).

CLOSING

SRWs are a very attractive and cost effective solution to earth retaining wall structures. Freeze-thaw and deicing chemicals are an enemy to all concrete products, but with consideration of the concerns, durable products can be and are manufactured. With some common sense suggestions, don't put concrete in an area of known durability concerns or protect the surface to get the life expected.

REFERENCES

1. ASTM C90-11b, Standard Specification for Loadbearing Concrete Masonry Units, ASTM International, 2011.
2. ASTM C457-98, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete, ASTM International, 2011.
3. ASTM C666-03(2008), Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, 2011..
4. ASTM C1262-10, Standard Test Method for Evaluating the Freeze-Thaw Durability of Manufactured Concrete Masonry Units and Related Concrete Units, ASTM International, 2011.
5. ASTM C1372-11, Standard Specification for Dry-Cast Segmental Retaining Wall Units ASTM International, 2011.
6. Chan, Cesar, K. Hover, K. Folliard, R. Hance, D Trejo, Durability of Segmental Retaining Wall Blocks: Final Report, FHWA HRT-07-021, 2007.
7. Concrete Technology, Durability, Portland Cement Association, 2012. (http://www.cement.org/tech/cct_dur_freeze-thaw.asp).
8. Embacher, R. A., Snyder, M. B. and Shultz, A. E., "Condition and Durability of Segmental Concrete Block Retaining Walls Along Roadways in Minnesota." Final Report to Minnesota Department of Transportation. University of Minnesota Department of Civil Engineering, Minneapolis, MN, 2001.
9. Lee, Hyomin, Robert D. Cody, Anita M. Cody, Paul Spry, Effects of Various Deicing Chemicals on Pavement Concrete Deterioration, Mid-Continent Transportation Symposium Proceedings, 2000 Proceedings.
10. MacDonald, K and M. Lukkarila, Freezing and Thawing Resistance of Dry Compacted Segmental Retaining Wall Units, International Cement Microscopy Association Meeting, Montreal, CAN, 2000.
11. SEM (Service d'Expertise en Matériaux Inc.), Literature Survey, SEM Project 200110, submitted to National Concrete Masonry Association, August 2001.
12. SEM (Service d'Expertise en Matériaux Inc.), Preliminary Report, Task 3—Frost Durability Index, SEM Project 200110, submitted to National Concrete Masonry Association, May 2004.
13. Tanesi, Jussara and Richard Meininger, Freeze-Thaw Resistance of Concrete with Marginal Air Content, FHWA-HRT-06-117.

SRW HISTORY ARTICLE SERIES

This article is the second article in a series of ten articles on the history of segmental retaining walls developed under a grant from the NCMA Education and Research Foundation. The first article, Production History of Segmental Retaining Wall (SRW) Systems, and all future articles in the series will be posted on the NCMA website (www.ncma.org).

SRW HISTORY ARTICLE SERIES

PRODUCTION HISTORY OF SEGMENTAL RETAINING WALL (SRW) SYSTEMS