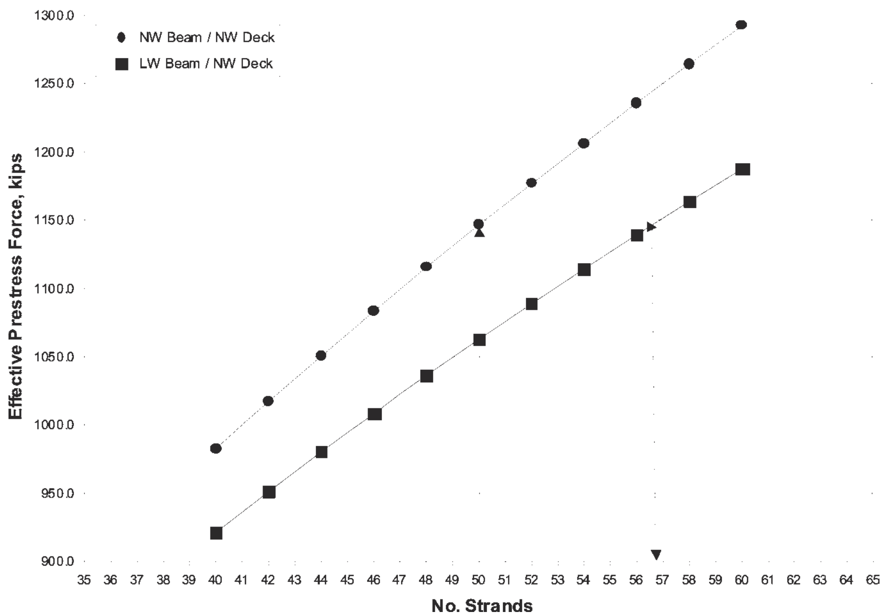

Figure 3: Comparison of Effective Prestress Force

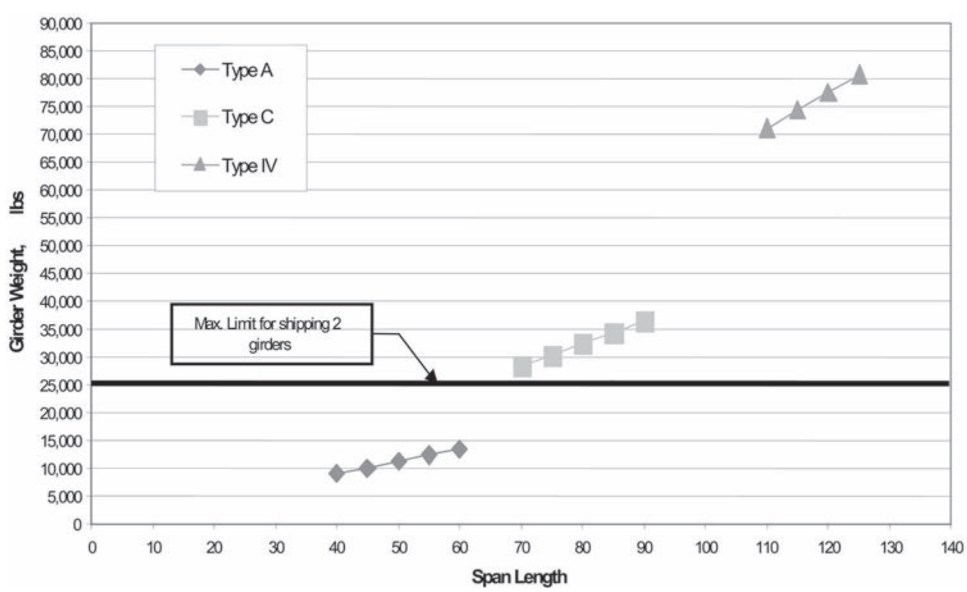

Figure 4: 6000 psi Precast Concrete Girder Shipping Comparison

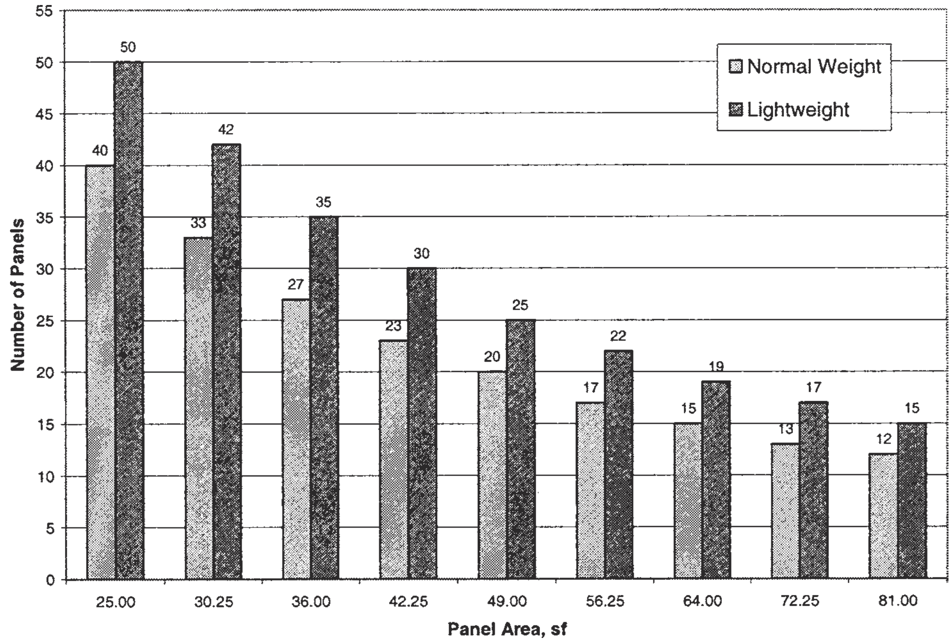

Figure 5: Precast Concrete Panel Shipping Comparison

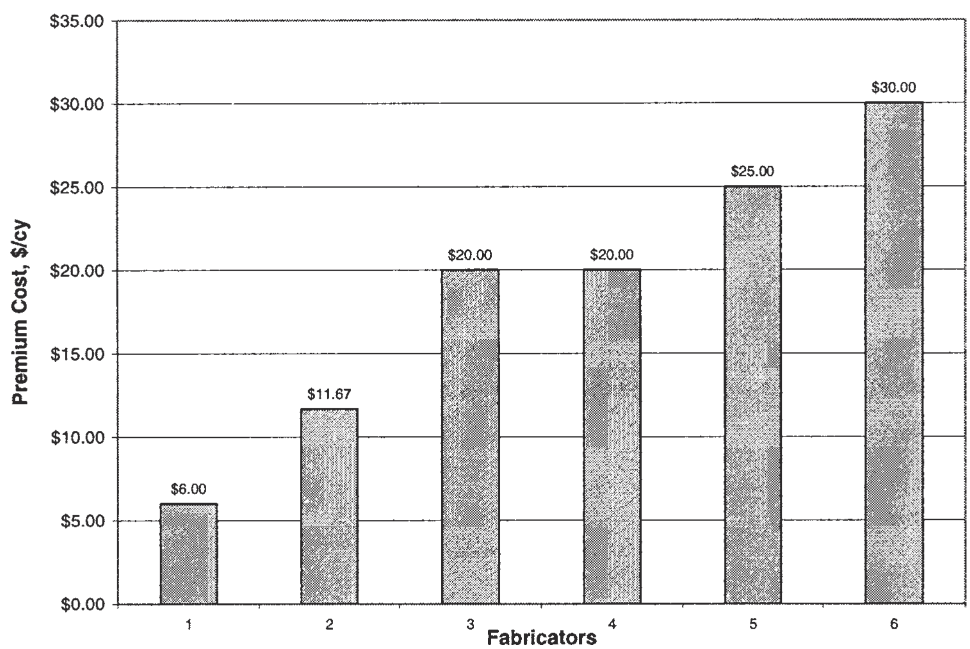

Figure 6: Premium Cost of Lightweight Concrete

Lightweight Concrete Makes a Dam Float

by C. L. Tasillo, B. D. Neeley, and A. A. Bombich

Synopsis: In initiating the final phase of modernizing the locks and dams on the Monongahela River, the U.S. Army Corps of Engineers, Pittsburgh District, used float-in and in-the-wet technology to build the new Braddock dam. This is the first use of such technology for an inland navigation project in the United States, and was employed to eliminate the cost and construction time associated with a conventional cofferdam for mass concrete construction. The new Braddock dam design was fabricated as two large, hollow-core segments. Unlike such applications used for offshore structures, the inland application was limited by navigational draft, and lock and bridge clearances. This restricted the overall dimensions and mass of the segments. The use of lightweight concrete in a significant portion of the two large dam segments was central to the success of the design. Good planning, an understanding of the concrete materials, and quality control were critical to project success.

Keywords: Braddock Dam; concrete density; float-in construction; freeze-thaw durability; lightweight aggregate; lightweight concrete; quality control

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INTRODUCTION

The Braddock Dam Project is one facet of the Monongahela River Project, which involves three inland navigation facilities. The Monongahela River Project was authorized by the Water Resource Development Act of 1992, which gave approval to replace the dam at Braddock Pennsylvania (River Mile 11.2), replace the twin locks at Charleroi Pennsylvania (R.M. 41.5), and remove the locks and dam at Elizabeth Pennsylvania (R.M. 23.8). The existing dam at Braddock was built in 1902, and consists of a fixed crest weir structure founded on a timber pile foundation. The replacement dam at Braddock is a gated dam founded on a drilled shaft foundation. The new dam will raise the navigation pool by 1.5 m (5 ft). The increased depth of the Braddock pool, combined with dredging of the existing Elizabeth pool, will allow the Elizabeth facilities to be removed. The Elizabeth dam was built in the same era, and is of similar design and conditions as the Braddock dam. The increased elevation of the Braddock pool will not adversely affect flooding potential since flow over the dam will be controlled by the gated structure. The Monongahela River navigation system is illustrated in Figure 1, and shows the changes proposed as part of the Lower Monongahela Project.

The U.S. Army Corps of Engineers (USACE), Pittsburgh District, in collaboration with the Inland Waterways Association, agreed to build the new Braddock dam using float-in and in-the-wet technologies. These methods were seen as a new approach to future navigation facility construction. The elimination of the cofferdam, necessary to facilitate conventional construction in-the-dry, lends to potential cost saving and a shorter construction schedule. Therefore, the Braddock Dam was built using a drilled-shaft foundation placed underwater, combined with two dam segments that were floated into place. The segments were constructed downstream at a casting basin on the Ohio River. The casting basin was designed as a two-stage basin. The first stage allowed each segment to be constructed, or cast, in-the-dry. The basin was flooded, and the segment was floated into the deeper portion of the basin. The basin water elevation was then lowered to meet the adjacent river elevation. A sheet pile and waler exit gate was pulled, and the segments were moved through the exit gate using a series of winches. Once the nose of the segment was in the river channel, the segment was connected to a towboat for transport. The first segment was launched prior to the completion of the second segment. During launch of the first segment, the second segment was temporarily flooded to assure that the unfinished structure did not prematurely float. The layout of the two-stage casting basin is illustrated in Figure 2.

From the casting basin, the segments were floated 44.3 km (27.5 miles) upstream to an outfitting facility near the Braddock project. At this facility, the base of the piers for the control gates were extended and additional work was performed to prepare the segments for set down. The piers could not be extended at the casting facility due to restrictions on the 3-m (10-foot) navigational draft and bridge clearances. The segments were ultimately set down and engaged on the drilled shaft foundation. The transport of the Segment 1 is shown in Figure 3.

Unlike such applications used offshore, the inland application was limited by navigational draft, and lock and bridge clearances. This restricted the overall dimensions and mass of the segments. The use of lightweight concrete in a significant portion of the two large dam segments was central to the success of the design. This paper presents some of the background information supporting the use of in-the-wet construction techniques, including some obstacles that had to be overcome to execute the design. Quality control measures used during construction of the large dam segments, and lessons learned in this first-of-a-kind project are discussed. Emphasis is provided on lightweight concrete precast panels and cast-in-place portions used to fabricate the dam segments.

Both dam segments were set down on the drilled shaft foundation in 2002. The segments were locked on to the drilled shaft pin connections, and the first lift of tremie infill concrete has been completed. Completion of the segment infilling will occur in-the-dry when the individual gate bays are dewatered.

PRELIMINARY STUDIES

Investigation of Different Lightweight Aggregates

Background -- Before committing to lightweight concrete mixtures in the project specifications, the Pittsburgh District wanted to verify that lightweight concrete mixtures could be produced meeting the required unhardened and hardened properties for the Braddock Dam segments. To execute this investigation, the Pittsburgh District contracted with the Corps' Geotechnical and Structures Laboratory, Concrete and Materials Branch located at the Engineering and Research Development Center, Waterways Experiment Station in Vicksburg, MS.

Test Plan --The test plan called for proportioning lightweight concrete mixtures that met the unhardened and hardened properties shown in Table 1. The initial lightweight concrete mixture was proportioned using a 19-mm (3/4-in.) nominal maximum size expanded shale lightweight coarse aggregate. Subsequent to completion of this mixture, two additional and similar mixtures were proportioned using expanded slate and expanded clay lightweight aggregate, respectively. The fine aggregate used in all mixtures was natural alluvial sand. The portland cement met the requirements of ASTM C 150, "Standard Specification for Portland Cement", Type II (1). Pozzolan was not used. Air-entraining and water-reducing admixtures were used as needed. Six mixtures were proportioned; four using the expanded shale lightweight aggregate, and one each with the expanded slate and expanded clay. The proportions for the six mixtures are shown in Table 2, and the test results are shown in Table 3 and Table 4.

Compressive Strength -- As indicated in Table 1, the specified compressive strength was 34.5 MPa (5,000 psi) at 28-days. To provide a statistical tolerance for batch-to-batch variations and ensure that a minimal number of batches would fail to meet the specified strength, the required compressive strength was 42.8 MPa (6,200 psi) at 28-days age. Of the six mixtures, only the expanded shale mixture having the lowest w/c of 0.37 (Mixture H3-4) met the compressive strength requirement of 42.8 MPa (6,200 psi) at 28-days age. However, it is likely that a mixture meeting this requirement could have been proportioned using the expanded slate coarse aggregate with a lower w/c, since the mixture using the expanded slate coarse aggregate at a w/c of 0.45 (Mixture S1-4) produced compressive strengths similar to those of the expanded shale coarse aggregate at a w/c of 0.40 (Mixture H2-4). The data trends also indicate that a mixture using the expanded clay aggregate could have met the 28-days age compressive strength requirement at a lower w/c similar to that used in Mixture H3-4. The 28-day compressive strength test results are shown in Table 3.

Flexural Strength -- All six mixtures easily met the minimum flexural strength requirement of 2.95 MPa (425 psi) at 28-days age. In fact, all mixtures except H1-2 met this strength requirement at 7-days age. The 28-day flexural strength test results are shown in Table 3.

Unit Weight -- The maximum saturated unit weight requirement was 2,000 kg/m^3 (125 lb/ft^3). All six mixtures easily met this requirement. The unit weight and absorption test results for the six mixtures are shown in Table 4.

Approval of Contractor Selected Materials

Background -- Subsequent to the completion of the preliminary lightweight aggregate investigation described above, the Pittsburgh District included lightweight concrete as an integral part of the precast shell for the two Braddock Dam segments. After the construction contract was awarded, the Contractor selected an expanded shale lightweight coarse aggregate for use in the lightweight concrete portion of the dam segments, which was from the same source as was used in the preliminary investigation.

Approval Testing -- The project contract required that the lightweight coarse aggregate meet the requirements of ASTM C 330, “Standard Specification for Structural Grade Lightweight Aggregates” (2). In addition, the lightweight aggregate was required to meet aggregate soundness requirements when tested by CRD-C 114, “Test Method for Soundness of Aggregate by Freezing and Thawing of Concrete Specimens” (3). The Pittsburgh District once again contracted with the Corps’ Geotechnical and Structures Laboratory, Concrete and Materials Branch to execute the approval-testing investigation. The results of the investigation are shown in Table 5. The data indicates that the expanded shale lightweight aggregate met all requirements of ASTM C 330 (2), including freezing and thawing (F/T) requirements. However, the aggregate failed the CRD-C 114 (3) aggregate soundness test, which is also a F/T test. A discussion of this failure follows.

ASTM C 666 Testing -- Five lightweight concrete specimens were fabricated and tested according to the procedures of ASTM C 666, “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing”, Procedure A (4), as a part of the ASTM C 330 (2) verification. The curing regime for the test specimens prior to initiation of the F/T cycles was modified according to the requirements of ASTM C 330 (2); i.e., after the initial 14-days of moist curing, the specimens were allowed to dry for 14 days in air prior to initiation of the F/T cycles. The results of F/T cycles on these saturated specimens were consistent and satisfactory, with an average durability factor of 97. The range on these 5 specimens was 94 to 98.

CRD-C 114 Testing -- The results of the CRD-C 114 (3) aggregate soundness tests were very different. On a set of 9 specimens, the average durability factor was 35 with a range of 84 to 3. This action was surprising to us because it contradicted good F/T resistance noted on aggregate from the same source tested in the ASTM C 330 (2) investigation described above. The mixture proportions of the two concrete mixtures were similar. The primary differences in the two concrete mixtures were the portland cement content and the w/c. The mixture tested in the ASTM C 330 (2) investigation had a higher portland cement content (335 kg/m^3 (564 lb/yd^3) versus 314 kg/m^3 (530 lb/yd^3)), and a lower w/c (0.46 versus 0.49). It was not believed that the magnitude of the differences in the mixture proportions should have been sufficient to render the extreme differences in the results of the F/T tests. In an effort to discern a cause for the divergent results, additional F/T tests were run, suspect samples were examined petrographically, and a through examination of the function of the F/T apparatus was undertaken. In some cases, a cracked and/or poorly performing specimen could be linked to what appeared to be a dilated lightweight aggregate particle or particles. In other cases, no obvious reason for the low durability factor could be visually determined. In the end, no conclusive explanation for the erratic and sometimes excessively poor F/T results was found. Two plausible explanations for the subsequently poor F/T results related to the speed of cycling and degrees of aggregate saturation are given below for consideration.

Analysis of Unsatisfactory Freezing-and-Thawing Performance of Laboratory Specimens

A thorough examination of the temperatures and overall function of the F/T apparatus revealed no obvious divergences from the requirements of ASTM C 666 (4). One issue of possible importance, however, is the cycling rate for the F/T cycles. ASTM C 666 (4) allows a quite broad cycling rate, ranging from 2 hours per cycle up to 5 hours per cycle. The F/T apparatus used at the Corps' laboratory cycles at the maximum rate allowed by ASTM C 666 (4); i.e., 2 hours per complete cycle, resulting in 12 complete cycles per day, while most F/T apparatus used in private industry cycle at a much slower rate. The fast cycling rate produces a high and fast-moving thermal gradient through the concrete on both the freezing and the thawing cycle. A round-robin series of tests on these machines was initiated in 1949 and completed in 1953 by McCoy (5). The results of this series of tests indicated that the tests results were somewhat sensitive to the rate of thawing. Another conclusion of the study indicated that the standard deviation of the results increased as the durability factors decreased, with the standard deviation of the results becoming so high as to render durability factors below approximately 50 as statistically incomparable. These tests were carried out on normal density concretes, yet it is reasonable to expect that the implications also apply to lightweight concretes. Furthermore, it is possible that lightweight concretes, because of their significantly lower thermal conductivity and diffusivity, could be even more sensitive to the fast-moving F/T gradients than are normal-weight concretes. Based upon this experience, it is recommended that a slower rate for F/T cycles is more appropriate for use in evaluating the performance of lightweight aggregates.

The F/T resistance of lightweight aggregate, or aggregate soundness, is critical in the performance of any concrete made with the aggregate under consideration. Indeed, this is true of any aggregate, whether it be lightweight aggregate or normal-density aggregate. It is known that the degree of saturation of aggregate particles at the initiation of F/T cycles is an important factor in the aggregate's overall resistance to degradation from F/T cycles. If the aggregate particles are minimally saturated, there is a likelihood that little damage will occur during repeated F/T cycles because there will be sufficient unfilled pore space in the aggregate particles to accommodate the volume change of freezable water. Therefore, insufficient tensile strain will develop in the particles to initiate cracking. This important factor is equally true whether the aggregate in question is lightweight aggregate or normal-weight aggregate. However, due to the much higher absorptive capacity of lightweight aggregates, further complicated by the change in rate of absorption as the aggregate particles approach maximum saturation levels attainable under atmospheric conditions, the actual moisture content of lightweight particles at the time of batching and mixing the test concrete can be much less certain than when normal-weight aggregates are being used.

Determining the soundness of aggregate in concrete subjected to cycles of saturated F/T is the stated purpose of the CRD-C 114 (3) test procedure. The method seeks to accomplish this goal by specifying in the mixture proportions a water-cement ratio that is sufficiently low (0.49) to provide adequate F/T resistance, together with an entrained air content that is sufficiently high (5.5 to 6.5%) to provide adequate F/T resistance. The reasoning then goes that if the paste fraction of the mixture is adequate to resist repeated cycles of saturated F/T, yet unsatisfactory performance occurs, the unsatisfactory performance must be related to the test aggregate. For the test procedure to work as designed, one of the fundamental requirements is to ensure that the test aggregate is thoroughly saturated. Following the guidance of the test method, this is accomplished by soaking overnight. Since the test procedure was written for normal-weight aggregate, this amount of time would be considered sufficient to achieve near full saturation in most cases.

While 12 to 18 hours of soaking is probably not enough time to achieve near full atmospheric saturation in lightweight aggregate, the point is still made that to adhere to the spirit of the CRD-C 114 (3) test procedure, one must make every effort to reach a high degree of saturation in the test aggregate. This was done on the lightweight aggregate used in the CRD-C 114 (3) tests. In addition to overnight soaking, the aggregate had already been subjected to numerous days of continuous sprinkling. It is possible that the degree of saturation was higher in the lightweight aggregate used in the concrete for the CRD-C 114 (3) test than was the case in the earlier specimens tested for conformity to ASTM C 330 (2). Paragraph 4.12 of ACI 213R, "Guide for Structural Lightweight Aggregate Concrete" (6) supports this conclusion by stating "The use of water-saturated aggregates (approaching the 24 hr water absorption) at the time of mixing generally reduces F/T resistance of lightweight concrete. Under some conditions, air entrainment will improve the durability of concrete made with these saturated aggregates. However, experience has shown that as such concretes are allowed to dry, durability improves considerably."

Holm, Ooi, and Bremner (7) reported that lightweight concrete made with highly saturated lightweight aggregates performed poorly in laboratory F/T tests when the test specimens were moist cured continuously from time of fabrication until initiation of the F/T tests. The poor durability factors were similar to those described above in this study. However, additional test specimens cast from the same concrete yielded high durability factors when the specimens were allowed to air-dry for as few as 5 days prior to initiation of the F/T cycles. The implications are that during a relatively brief period of drying in air, the moisture content of the lightweight aggregate particles decreases sufficiently that the particles are much less susceptible to dilation during the F/T cycles.

This transfer of moisture out of the lightweight aggregate particles likely occurs due to two separate phenomenons. First, moisture is lost from the concrete to the atmosphere. This occurs easily at the outset of the drying period as surface moisture evaporates. Additional moisture underneath, but near to the surface, easily migrates to the surface where it too evaporates. As moisture evaporates from the surface of the concrete, a moisture gradient develops from the surface of the concrete inward. As water held in the capillary system of the paste slowly transfers to the surface for eventual evaporation, water internal to the lightweight particles will gradually be drawn out to replace some of the water that has been lost from the capillary system. However, the rate of evaporation gradually decreases as internal moisture deeper in the concrete (that is theoretically available for evaporation) finds longer travel distances to reach the surface. Powers and Brownyard (8) observed that the permeability of cement paste was controlled by its capillary porosity, and concluded that capillary pores consisted of a network of interconnected channels through the gel. Powers, Copeland, and Mann (9) showed that as concrete matures, hydration products replace both the original volume of the cementitious material and some of the pore space originally filled with water. Continuing growth of the hydration products eventually results in the lessening of capillary continuity in the paste, further hindering migration of internal moisture to the surface. Consequently, given that most structural lightweight concrete is made with water-cementitious ratios of 0.50 or lower (0.37 to 0.48 in this study), loss of capillary continuity can occur in as few as 3 (for 0.40 water-cement ratio) to 14 days (for 0.50 water-cement ratio) in a typical structural lightweight concrete. Once capillary continuity has been lost, the rate of transfer of moisture to the surface, and the resulting evaporation to the atmosphere is significantly hindered. Therefore, while evaporation of water to the atmosphere certainly acts to lower the moisture content of lightweight aggregate particles in concrete, the rate of loss of moisture diminishes significantly after only a few days in most cases.

However, a second phenomenon continues to draw water from the lightweight aggregate particles over a much longer period of time. Especially prominent in concretes having low water-cementitious ratios, water is slowly drawn from the aggregate particles to fuel hydration of the cementitious material. This phenomenon, known as internal curing, was first discussed by Klieger (10) in 1957, and has been well documented by many others since. Once the readily available water held in the capillary system has been depleted by hydration, the next readily available source of water (assuming external moist curing has been discontinued) is that absorbed by the lightweight aggregate particles. As the concrete matures, the moisture content of the aggregate particles will gradually decrease as the water once held inside the aggregate particles is slowly drawn out and used in hydration.

In summary, whether due to drying, or internal curing, or both, with the passage of time the moisture content of lightweight aggregate particles decreases. Unique characteristics of the concrete mixture and the environment to which it is exposed will influence the rate that change occurs. This largely explains why mature, lightweight aggregate concretes have shown very good performance over extended periods of time in structures exposed to the natural environment. But how does this relate to laboratory testing, and more precisely, the diverging results presented in this paper. One likely theory is that there is some critical moisture content, perhaps a percentage of the total absorptive capacity, above which a given lightweight aggregate particle becomes prone to dilation when exposed to repeated cycles of F/T. Of course, dilation of aggregate particles leads to premature failure of the concrete. Once the moisture content of the aggregate particles has fallen below the critical level, F/T durability probably increases dramatically. While we do not know what this critical moisture level is, or even if the critical level is consistent across the spectrum of lightweight aggregate sources, it would appear that, in most cases, the 14 days of air drying required by ASTM C 330 (2) sufficiently lowers the moisture content of the aggregate particles to make a difference in the laboratory performance of lightweight concrete specimens tested in F/T. However, the degree of aggregate saturation prior to mixing the concrete, and characteristics of the mixture proportions could also impact length of drying/curing time necessary to result in satisfactory performance.

Either of the two scenarios discussed above, rapid cycling or differing degrees of aggregate saturation, offer possible explanations to the poor performance in the CRD-C 114 (3) test. Differing degrees of saturation offers a likely explanation for the divergent durability factors between the tests for ASTM C 330 (2) conformance and CRD-C 114 (3) aggregate soundness. However, neither of the two possibilities can be proven without additional testing. In any case, having a high degree of aggregate saturation coupled with rapid cycling appears to create a level of severity in a F/T test that many lightweight aggregates could have difficulty passing, although, as the ASTM C 330 (2) results show, rapid cycling by itself doesn't necessarily guarantee poor results. In the end, a decision was made to accept the lightweight expanded shale aggregate based upon a long history of good field performance data and the satisfactory performance of the ASTM C 666 (4) (as modified by ASTM C 330 (2)) results. It was believed that the project mixture proportions were better