ESCSI TECHNICAL INFORMATION SHEET
EXPANDED SHALE, CLAY AND SLATE INSTITUTE / Rotary Kiln Structural lightweight Aggregate

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Freeze-Thaw Durability of Structural Lightweight Concrete Made with ESCS Aggregates

Introduction

Concrete is one of the most widely used and durable construction materials in the world. It is used for building foundations, floor and roof slabs, columns, and beams. It is also used to construct bridge structures and decks and pavements for streets, roads, highways, and parking lots. Pavements and bridge decks present perhaps the biggest challenges to concrete's durability because of their potential exposure to cycles of freezing and thawing and the use of deicing chemicals. Through many years of research and experience, the concrete industry has developed ingredients and methods for producing concrete that is able to resist damage caused by freeze-thaw cycles and exposure to deicing agents. The most effective strategy for producing durable concrete for these exposure conditions is to create an efficient air void system within the cement paste. The American Concrete Institute (ACI) publishes many documents developed by its technical committees that give excellent guidance on producing and placing durable concrete. The principles of building durable concrete structures, pavements, and bridge decks are now standard practice throughout the construction industry. Less well known, however, is the fact that structural lightweight concrete can be just as durable and resistant to the effects of freezing and thawing cycles as normalweight concrete.

The same principles for creating resistance to freezing and thawing apply to structural lightweight concrete and normalweight concrete. Properly air-entrained concrete will be durable concrete, whether normalweight or lightweight, as we will see below.

Bridge Decks

Probably one of the most severe exposure conditions for concrete is in bridge decks in regions where deicing agents are used. Reports by various DOTs, like Meggers (2022), report the vulnerability of bridges to freeze-thaw conditions. If concrete freezes at the beginning of winter and stays frozen until the end of winter, only one (or very few) cycle(s) of freezing and thawing will have occurred, with little likelihood of damage until the passage of many years. However, severe damage may be caused in relatively mild climates where many freezing and thawing cycles occur each season, and large amounts of deicing agents are applied. Deicing chemicals melt ice and snow and produce water that increases concrete saturation and chloride concentration. The concrete then refreezes when the temperature drops, frequently resulting in daily cycles. Until recently, salt, often mixed with sand, was the most common deicing agent. It was broadcast onto the pavement or deck to melt ice and snow. If the salt was not promptly removed, corrosion of reinforcing steel was facilitated. Today in many regions, it is common for a liquid brine to be applied to the concrete before frozen precipitation occurs. This is an effective strategy for keeping the pavements clear of snow and ice, but often the brine itself damages the concrete because the chlorides are introduced even if the precipitation never occurs.

Once corrosion begins, the concrete cover over the reinforcement starts to spall. The problem is very severe in the northeastern region of the United States, making this a useful location for comparative studies of the relative performance of lightweight and normalweight concrete. These areas have had a long history of bare concrete bridge decks, whereas, in Canada, it is common to use a waterproof membrane on the concrete under the asphalt to prevent the ingress of chloride ions into the concrete.

Field Performance

As early as 1935, more than 34 lightweight concrete bridges had been built in North America, including nine in Canada (Ref. 1, Expanded Shale, Clay and Slate Institute, ESCSI 1960). The good performance of several early bridges, built before concrete was air-entrained, is surprising. The fact that water-reducing admixtures in the 1950s entrained some air and were used in placing lightweight concrete might, in part, account for the good long-term performance of bridge decks built in that era (Holm 1983). Another reason for their good performance is that pores within the lightweight aggregate can act as pressure relief chambers when the hydraulic pressure develops as the free water freezes. Crushed porous brick has also been shown to provide freeze-thaw protection in a similar manner when added to concrete that was subsequently exposed to freezing and thawing.

For the last several decades, it has been common practice to use entrained air in all lightweight concrete. When freezing and thawing are anticipated, 4 to 8 percent entrained-air contents are recommended in lightweight concrete with a nominal maximum aggregate size of 3/4” (19.0 mm), and 5 to 9 percent when the nominal maximum aggregate size is 3/8” (9.5 mm). It is essential that the air voids be well distributed throughout the cement paste matrix to achieve an effective air-void system that will protect the concrete from repeated cycles of saturated freezing and thawing. Generally, the longest distance from any point in the cement paste matrix to an entrained air void should be less than 0.2 mm.

This can usually be achieved by using an air-entraining admixture meeting the requirements of ASTM C260. In special situations where exposure conditions are severe or where unusual placing techniques are involved, the actual air-void spacing should be measured in simulated job site conditions to confirm that an adequate air void system will be achieved. This can be done using the procedures described in ASTM C457. If not properly protected from freezing at an early age, concrete made with lightweight aggregates with a high degree of saturation may be vulnerable to early freezing damage. As with normalweight concrete, lightweight concrete should be protected from freezing conditions until it has been cured (time and temperature) in accordance with procedures in ACI 306, *Guide to Cold Weather Concreting*. This is necessary to allow adequate strength to develop before exposure.

Based on the study of lightweight concrete bridge decks completed in 1960 (ESCSI 1960) and other published reports in the United States (FHWA 1985), England, and Japan, the performance of lightweight concrete bridge decks is at least as good as normal density concrete decks (Brown III, Larsen & Holm 1995).

Laboratory Studies

In addition to studies of lightweight concrete bridge decks throughout the world, laboratory investigations have been conducted on structural lightweight concrete to gain a better understanding of the good field performance of the material.

An early study (State Highway Commission of Kansas 1953) reported the superior performance of 4½ x 6 x 22½ in. beams in freeze-thaw conditions, i.e., 275 cycles, each including 22 hours at -20° F and 2 hours at 70° to 80° F. The reported expansion was 0.013 percent compared to the specified allowable expansion of 0.07 percent without any significant loss.

ESCSI also conducted two studies in 1968 and 1974 at the University of Toledo (Ohio). The 1968 study evaluated concrete made with eight different expanded shale, clay, and slate (ESCS) coarse aggregates and either lightweight or normalweight sand. The moisture content of the ESCS aggregates varied from 67% to 100% of the 24-hour absorption of the aggregates. As placement of concrete by pumping became more prevalent after the 1968 study, a second study was conducted in 1974 in which seven ESCS aggregates were pre-wetted to one of three conditions: 67% of the 24-hour absorption, the maximum absorption attainable under normal atmospheric soaking conditions, or the maximum absorption attainable utilizing thermal or vacuum saturation. In the 1974 study, only normalweight sand was used.

The concrete specimens were tested in the 1968 and 1974 studies in accordance with ASTM C666 procedures, except that they were air-dried for a variable amount of time following an initial 14-day wet curing period. The air-drying times were 14 days, 28 days, and 56 days in both studies, and an additional set of specimens was air-dried for 98 days in the 1974 study. The results of both studies indicated an average durability factor of 95.5 for lightweight concrete made with normalweight sand. For concrete using both coarse and fine ESCS aggregates, the average durability factor was 92.9. The degree of saturation had only a modest effect on the durability factor, as did the longer drying times. Detailed information concerning these testing programs, including individual durability factors calculated for each variable tested, can be found in ESCSI (1970) and ESCSI (1979).

More recent studies by Kansas DOT continued to investigate the influence of ESCS aggregates on the freeze-thaw behavior of concrete structures including bridge decks and pavements (Grotheer & Peterman 2009; Perkins & Peterman 2010). Further, experimental studies by KS-DOT utilized air void analyzer (AVA) method (AASHTO TP 75-08) and super air meter (SAM) (modified ASTM C231 Type B Pressure Meter) to measure the benefits of closely spaced air voids in ESCS aggregates for improving the freeze-thaw durability of concrete (Jenkins, Meggers & Schmiedeke 2022). Further, studies by Nebraska DOT have shown application of ESCS aggregates to improve the transport properties of concrete. This improvement reduces the chloride diffusion and permeability as significant indicators of freeze-thaw resistance (Abdigaliyev, Kim, & Hu 2020). The internal curing is an example of such improvements using ESCS aggregates as shown by numerous DOT reports, including Indiana and Colorado (Barrett et al., 2015; Jones et al., 2014). The ESCSI Report 4363 provides a comprehensive report on laboratory evaluation of ESCS lightweight concrete transport properties and their influence on durability and service life of concrete elements, including bridge decks, parking garages, and marine structures (Tehrani 2020).

Treat Island

Natural Resources Canada, through its Canadian Centre for Mineral and Energy Technology (CANMET), built a marine exposure site on Treat Island near Eastport, Maine, more than 75 years ago. Since its inception, prisms made from a wide range of concrete types have been placed on the site, which has very severe exposure conditions, with the highest tides in the world and approximately 100 freeze-thaw cycles per year.

Since 1978, CANMET and the U.S. Army Corps of Engineers have installed more than 250 concrete prisms at the site, of which 63 are semi-lightweight (concrete made with lightweight coarse aggregate and normalweight sand). The prisms have dimensions of 12 in. by 12 in. by 36 in. (305 mm by 305 mm by 914 mm). They are located on a wharf at a mid-tide level so that they are subjected to twice-daily tidal cycles that have resulted in about 100 cycles of freezing and thawing per year. All the lightweight concrete specimens are air entrained.

Malhotra and Bremner (1996) examined the condition of concrete specimens after years of exposure at the Treat Island site. The evaluation included visual examination and rating and ultrasonic pulse velocity testing. Also, a complete photographic record was made. The report concluded that after at least 17 years of exposure, both the normalweight and semi-lightweight concretes incorporating fly ash or slag or silica fume or a combination of these materials were in good to excellent condition, provided water-to- cementitious materials ratio was kept below 0.50 and the Portland cement content was kept at a certain minimum level. There was no significant difference in the performance of concrete made with ASTM Types I, II, and V cement. The paper states that “with normal-weight concrete, there appears to be a potential for the mortar over the aggregates to come off in a sporadic fashion indicating a plane of weakness at the aggregate-cement paste interface. With semi-lightweight concrete, this is not noted; deterioration occurs by a uniform loss of the surface layer” (Malhotra and Bremner 1996). The paper goes on to report that “at this stage, all specimens having cementitious contents of 360 kg/m^3 (607 lb/yd^3) or greater show excellent performance.” An analysis of the data contained in the report indicated at least equal performance of semi-lightweight concrete with normalweight concrete when compared at similar ages and with similar binders (Holm and Bremner 2000).

Thomas & Bremner (2012), Thomas et al. (2012), and Thomas & Scott (2010) renewed experimental investigations on collected samples from Treat Island in 2009 and 2010, after 25 years of exposure. Results found all specimens to be “in excellent condition with no evidence of surface scaling, mass loss or cracking.” Concrete samples also exhibited “a very high resistance to chloride-ion penetration”, indicating excellent transport properties. As a result, retrieved steel reinforcement, embedded at 3/8-in. (10 mm) cover were found in pristine condition after 13 years of exposure to marine environment of the Treat Island.

Bridges

Ozyildirim (2008) in a report for the FHWA reported the performance of several bridges by Virginia DOT resisting freeze-thaw cycles. The VDOT utilized lightweight concrete containing ESCS aggregates to construct the bridge deck of Cowpasture River bridge in Route 269 (formerly 60). Freeze-and-thaw resistance was measured according to ASTM C666 using water containing 2% NaCl. The weight loss of ESCS lightweight concrete was reported to be 3.8% after 300 cycles, which was substantially lower than the 7% acceptable limit. Similarly, VDOT applied ESCS aggregates to construct high-performance lightweight concrete bridge structure on Route 106 over Chickahominy River and Route 33 over Mattaponi and Pamunkey Rivers. The freeze-thaw resistance was reported for bridge beams and decks and confirmed satisfactory weight losses after 300 cycles.

The ESCSI 4700 (ESCSI 2001b) provides a brief introduction of several bridges utilizing ESCS aggregate concrete in various climate zones, like Benicia-Martinez Bridge in California, Brooklyn Bridge in New York, and Boknasundet Bridge in Norway. These bridges present a century of concrete durability in freeze-thaw and other severe conditions and continue to serve their purpose. The ESCSI 4700.4 (ESCSI 2001a) provides additional details about each structure.

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