Benefits and case studies using internal curing of concrete
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CHAPTER 9 – BENEFITS AND CASE STUDIES
USING INTERNAL CURING OF CONCRETE

9.1 INTRODUCTION

Proper curing of concrete is important to ensure that it achieves its intended performance and durability. Conventionally, this is achieved through external curing, applied after mixing, placing and finishing [1]. As demonstrated in the previous chapters of the present report, internal curing (IC) is potentially a very promising tool in providing additional moisture in concrete for a more effective hydration of the cement. This chapter summarizes the main benefits of internal curing and presents case studies in which those benefits could be observed in existing concrete structures.

Since the 1950's, internal curing had been inadvertently accomplished in lightweight concrete structures before its potential for reducing self-desiccation in high-performance concrete (HPC) was recognized later in the 1990's [2]. Low-density aggregates were primarily used to reduce the mass of concrete structures. In most applications, the aggregate was saturated prior to mixing to ensure adequate workability, as it was recognized that dry porous aggregate could absorb some of the mix water during concrete fabrication and placement [3,4,5]. Lightweight concrete with a density ranging from 1440 to 1840 kg/m^3 has been used in bridge decks, marine structures and other structures [6]. It was shown to achieve long-term durability from the excellent in-service performance observed in the field [7,8]. Improved cement hydration due to internal curing is one of the benefits of using lightweight concrete in structures among other benefits related to design and construction, such as: structural efficiency, seismic performance, constructability, repair, durability and economic considerations [7,9].

The following paragraphs provide a short summary of the benefits inherent to internal curing of concrete, which have been introduced and explained in the previous chapters of this report.

Increased moisture content – High-performance concrete with high-cement content and low water-cement ratio is vulnerable to self-desiccation and autogenous shrinkage, and can benefit from the added moisture provided by internal curing. High moisture content in concrete will reduce the coefficient of thermal expansion, which is important with respect to thermal cracking. The benefits of internal curing are increasingly important when pozzolans are incorporated in the concrete mixture, as the pozzolanic reaction is contingent upon the availability of moisture [5]. However, the amount of internal curing water introduced into the concrete by the IC agent normally should not be higher than that required to prevent self-desiccation. High moisture content may not be desirable in concrete structures subject to severe freeze-thaw cycles or to very high temperatures.

Enhanced concrete curing – Concrete made with saturated high-absorption aggregates carry their own internal curing water supply, which can provide a more effective and longer curing of concrete. Internally-cured concrete is less sensitive to poor external curing practices or unfavorable ambient conditions than conventional concrete. Especially in very low permeability concrete, conventional external curing may not be effective in preventing self-desiccation at the centre of thick concrete elements. The use of the internal curing technique, however, does not replace recommended curing practices, as it is important to keep the concrete surface continuously moist during the curing process in order to prevent surface cracking due to plastic or drying shrinkage [10].

Reduced concrete permeability – While improvement of long-term strength has been observed, the main contribution of internal curing is the reduction of permeability [9,11] resulting from an extended period of curing during which additional products of hydration are formed in the capillaries of the binder. Additional benefits from a reduced concrete permeability are the improved abrasion resistance and increased corrosion resistance of the steel reinforcement [7].

9.2 CASE STUDIES

A large number of case studies have been conducted, especially in the past 50 years on lightweight concrete structures [6], including bridges, buildings and offshore platforms. The majority of the case studies conducted on lightweight concrete structures focused on those benefits directly related to the reduced weight of the structure. Internal curing, which came as a possible secondary benefit, is not often documented. In addition, the state of dryness of lightweight aggregates used in these lightweight concrete structures varied considerably: from completely dry [12], to an intermediate state [13], and to completely soaked [14]. The main reasons for using dry or partially-dry aggregates in some of these structures were to reduce the risk of bleeding, or to maintain a relatively low moisture level in concrete when a dry environment was required.

Long-term observations of the benefits of internal curing in existing concrete structures are seldom reported, especially in normal weight aggregate (NWA) concrete structures, because of the novelty of the technique. Only those case studies providing some specific information on internal curing are briefly presented below in a chronological order. In the following case studies, internal curing was achieved by using LWA (4 projects), NWA (2 projects), and super-absorbent polymers (1 project).

The U.S.S. Selma Concrete Ship, USA [15] – This 7500-ton reinforced expanded shale concrete tanker, launched in 1919, is a unique demonstration of durability of high-strength lightweight concrete in a marine environment. The waterline area of the concrete hull has been exposed to salt air and awash due wave action for many decades. In 1980, an examination of concrete cores taken at both the submerged and waterline areas showed no evidence of microcracking and very little corrosion of the steel reinforcement despite the thin concrete cover of 16 mm. Core test results revealed a compressive strength of 70 MPa and an elastic modulus of 25 GPa for the lightweight concrete. It was concluded that the unusual resistance to weathering and corrosion may be due to some or all of the following physical and chemical mechanisms: (i) high aggregate-mortar bond, (ii) reduced stress concentration, (iii) high ultimate strain capacity, (iv) well-dispersed void system, (v) long-term pozzolanic action, and (vi) low mortar permeability due to the high-cement content and possibly internal curing.
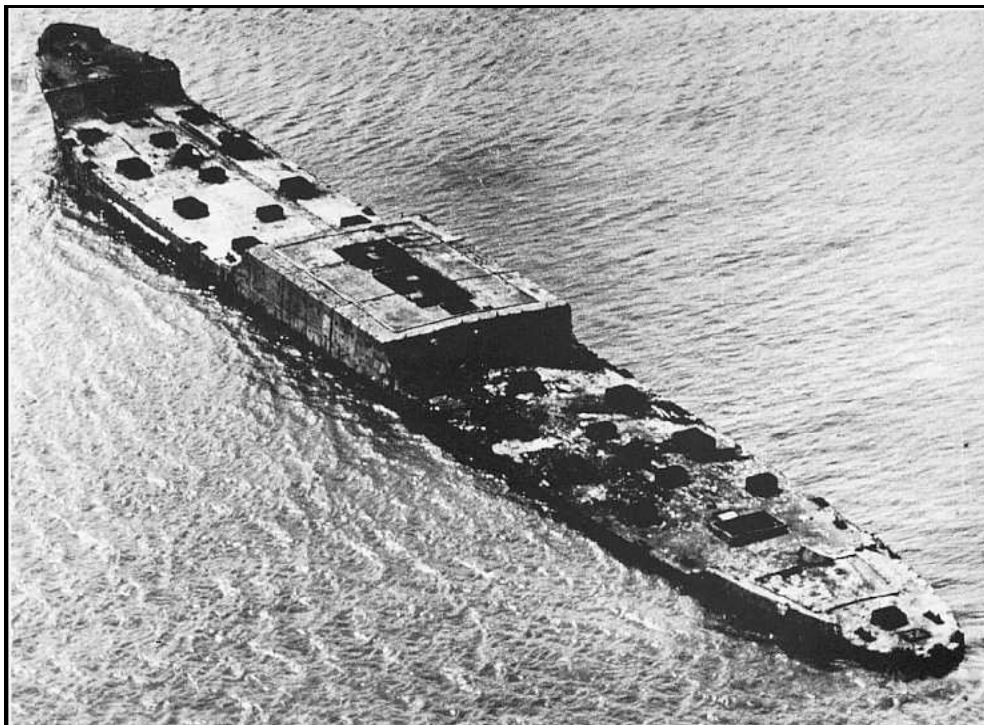

Fig. 1: U.S.S. Selma Ship launched in 1919 – Photograph taken in 1953 [15]
(Authorized reprint from American Concrete Institute)

Powell River Ships, Canada [16] – Ten concrete ships are currently being used as a floating breakwater at the Pacific Paper Powell River Plant in British Columbia, Canada. One of these ships was built in the 1920's and the other nine in the 1940's. The hulls of these ships were constructed with a double mat of reinforcing steel and lightweight concrete made with fine and coarse expanded lightweight shale aggregates. Cores taken from five of these ships in the 1990's were subjected to laboratory testing. Petrographic studies revealed limited microcracking, excellent aggregate/matrix contact zone, prolonged hydration of the cement, and insignificant damage due to freezing and thawing despite the fact that the concrete was not air-entrained. The paste volume was estimated at 30% to 35%, suggesting that the mix was cement-rich. They reported that the microscopic examination clearly showed evidence of continued hydration and development of the cement matrix due to internal curing. As a result, compressive strengths up to 60 MPa were measured on concrete cores, which were well beyond the minimum design strength of 35 MPa. The measured concrete density ranged from 1700 to 2080 kg/m^3. They concluded that the lightweight concrete used in the construction of these ships has performed exceptionally well in a harsh marine environment.

The Iroise Cable-Stayed Bridge, France [17] – Built between 1991 and 1994, this 800-m long lightweight concrete bridge crosses the Elorn River in the city of Brest in Bretagne. With four lanes of traffic, the bridge is composed of a 400-m long central span and two 200-m long access spans, supported by two 120-m long high-strength concrete pylons. Lightweight concrete, with a density of 1800 kg/m^3, was used in the bridge deck with the goal to reduce its mass by 2200 metric tons. The coarse aggregate was an expanded shale with a bulk density of 700 kg/m^3 and a water absorption capacity of approximately 4% at 48 hours. The fine aggregate was a normal-density 0-2 mm siliceous sand. The lightweight concrete had a water-cement ratio of 0.43, a cement content of 400 kg/m^3, an average 28-day compressive strength of 45 MPa and an elastic modulus of 23 GPa. Internal curing with pre-soaked coarse lightweight aggregate (providing up to 18 kg/m^3 of IC water) and external curing were provided to the deck concrete. It was observed that this lightweight concrete mixture provided adequate workability and that all design requirements were met or exceeded.

Fig. 2: Iroise Bridge, City of Brest, France
(Photographer: Vincent Le Quéré; Source: www.structurae.de)

The Wellington Stadium, New Zealand [18] – With a seating capacity of 40000, this modern sports stadium (opened on Dec. 31, 1999) is New Zealand's first major structure built with lightweight aggregate concrete. Apart from the engineering challenge of weak ground, the site is exposed to wind-blown sea spray and is located just beside one of the country's most active and violent seismic fault lines. Pre-soaked expanded shale coarse aggregate, with a bulk density of 800 kg/m^3 and moisture content of 16-26%, was selected to produce 13000 m^3 of lightweight concrete for all the precast components in the main stadium bowl structure. The lightweight concrete had an air content of 5%, a density of 1845 kg/m^3, an average 28-day compressive strength of 44 MPa and an elastic modulus of 20 GPa. Lightweight concrete was selected for many design and construction advantages, including internal curing. They reported that the markedly superior durability performance of similar lightweight concrete structures around the world has been attributed to 3 unique properties of the lightweight aggregate: (i) *pozzolanic action*, from silicates growing across the paste-aggregate boundary, creating a dense and impermeable concrete in spite of the porous nature of the aggregate; (ii) *water absorption*, preventing accumulation of bleed water if the aggregate is used partially dry, and providing internal curing of concrete if the aggregate is used saturated; and (iii) *reduced stress concentration*, since lightweight aggregate and hardened cement paste have similar values of stiffness.

Fig. 3: Wellington Stadium during construction, New Zealand [18]
(Source: Fletcher Building Ltd)

HPC bridges in Ohio, USA [19] **–** The Ohio Department of Transportation has used high-performance concrete to build bridge decks for more than 12 years. Their typical HPC mix design has a water-cement ratio of 0.42, including ASTM Type 1 cement (255 kg/m^3), slag (100 kg/m^3), fine NWA (755 kg/m^3), coarse NWA (1045 kg/m^3), and 7% entrained air. A detailed survey of HPC bridge decks in Ohio revealed that the decks constructed with coarse NWA with an absorption capacity near 1.5% had a significantly lower propensity for cracking than similar bridge decks built with NWA of an absorption capacity near 0.5%. The survey indicated that, in both cases, the construction and external curing practices used in the surveyed bridge decks were comparable. It was concluded that this difference in absorption capacities of the NWA was key to the reduced cracking. A simple calculation can demonstrate that a 1% difference in absorption for 1045 kg/m^3 of coarse aggregate can provide a 10 kg/m^3 difference in internal curing water, which is not negligible.

Concrete pavements in Texas, USA [20] **–** In January 2005, about 190 000 m^3 of LWA-modified concrete was used in a paving project in Hutchins, Texas, which is likely the largest project in the world taking advantage of internal curing with prewetted LWA. Table 1 presents the mix designs of a typical pavement concrete and the LWA-modified concrete developed for the project by *TXI Ready Mix Concrete* from Dallas, Texas. Portions of both the regular fine and coarse aggregates were substituted on a volume basis by an intermediate-size expanded shale LWA, with a prewetted bulk density of 960 kg/m^3. In addition to providing internal curing water to the mix, this specific substitution strategy improved the overall aggregate grading, resulting in enhanced workability and consolidation. The concrete was required to provide flexural strengths over 4.5 MPa at 28 days; field tests indicated that the 7-day strengths reached 90 to 100% of the required 28-day flexural strength.

Table 1: Mixture proportions of reference and LWA-modified concretes [20]

Material	Reference mixture (kg/m^3)	LWA-modified mixture (kg/m^3)
Water	144	144
Cement (ASTM Type I/II)	268	268
Fly ash (ASTM Class C)	67	67
Fine aggregate (0-5 mm)	772	652
Intermediate LWA (2-10 mm)	0	178
Coarse aggregate (5–25 mm)	1092	914

This LWA-modified concrete, and some variations, have been used in many other pavement construction projects in Texas during the past two years, in which about 230 000 m^3 of LWA-modified concrete has been placed. Many contractors observed that cracking has been extremely minimal, in contrast to other projects using conventional paving concrete mixtures. Many field tests indicated that the average 28-day compressive strength was improved by 20% when compared to similar mixtures without LWA. Laboratory tests on LWA-modified concrete cylinders also reported that the compressive strengths of air-cured cylinders were similar to wet-cured cylinders at all ages, suggesting that the pre-saturated LWA provided sufficient moisture for internal curing of the concrete.

FIFA World Cup Pavilion, Germany [21] – This pavilion was built for the 2006 FIFA World Cup in Kaiserslautern, which was one of the host cities. It was designed as a filigree, thin-walled structure with very slender columns and no conventional reinforcement. In order to meet the rigorous design requirements (including reduced autogenous shrinkage, high durability, enhanced ductility, self-compaction, and high-quality surface), self-compacting fibre-reinforced high-performance concrete with internal curing was selected. Super-absorbent polymers (SAP) were used to entrain internal curing water in the concrete mixture containing normal-density aggregates. The concrete had a free water/cement ratio of 0.24 and included CEM I 42.5 R HS Cement (800 kg/m^3) and micro silica (120 kg/m^3) as binders, a blend of quartz powers and basalt sands for a total amount of 1050 kg/m^3, 6-mm steel fibers (145 kg/m^3) and SAP (0.4% by mass of cement) with an average particle size of 200 μm. The content of SAP was adjusted to provide 45 kg/m^3 of internal curing water in the concrete. The laboratory tests conducted on the concrete revealed that the rheological properties of the fresh concrete were not adversely affected by the use of SAP when compared to a reference mixture made without SAP. The early-age autogenous shrinkage was greatly reduced by internal curing (from -605 to -72 με at 7 days), however, total shrinkage (incl. drying shrinkage) was only found to decrease slightly at older age (from -1050 to -950 με at 28 days). This finding indicates that the quantity of internal curing water was sufficient enough to prevent self-desiccation. It was also reported that the 28-day strengths in compression (150 MPa), direct tension (8 MPa) and bending (12 MPa) of the SAP-cured concrete were approximately 20% lower than those of the reference concrete made without SAP. These reductions in strengths may be explained by the SAP-entrained porosity, which can be regarded as additional macro pores.
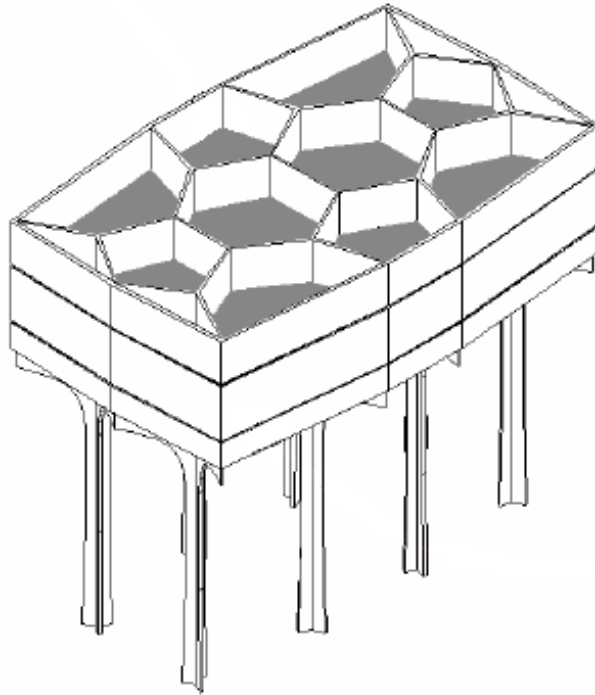
Fig. 4: FIFA World Cup Pavilion, City of Kaiserslautern, Germany [21]

9.3 SELECTION OF IC AGENT FOR USE IN CONCRETE STRUCTURES

Design engineers need to select an internal curing agent that will maximize the performance of the concrete with regard to certain desired characteristics at the fresh and/or hardened state, while providing no significant decline in other relevant properties. This section provides advice on the proper selection of an IC agent to optimize the performance of concrete structures.

For optimum performance, an internal curing agent should possess: (i) high water absorption capacity, and (ii) high sorption/desorption rates. If the selected IC agent is a lightweight aggregate, its size distribution and stiffness should be similar to those of the substituted normal-density aggregate. If the lightweight aggregate replacement ratio is rather small, these last two features are not relevant. The quantity of internal curing water required to prevent self-desiccation of concrete can be easily calculated as suggested in Chapter 3. Before construction, especially if the contractor has limited experience with the use of IC agents in concrete structures, trial batches of concrete should be made as suggested: (i) choice of IC agent to supply the desired quantity of internal curing water; (ii) design and optimization of the concrete mixture without IC agent; (iii) design and optimization of the concrete mixture with IC agent substitution; (iv) saturation of IC agent to absorb the required amount of internal curing water (note that some IC agents, with a fast water absorption, do not need to be pre-soaked); (v) batching, placing and finishing of concrete; and (vi) external curing of concrete.

A great concern for design engineers and contactors is whether the concrete will achieve the specified compressive strength and all durability requirements in the structure in service. It has been shown in the present report that the technique of internal curing can reduce autogenous shrinkage considerably and improve many durability-related properties. As far as strength and stiffness are concerned, some case studies and laboratory investigations have shown that the compressive strength and modulus of elasticity of concrete may slightly be reduced by internal curing. This was explained in the previous chapters by the increased water-entrained porosity, affecting the density of concrete.

Recent work by Cusson and Hoogeveen [22] demonstrated that internal curing can reduce autogenous shrinkage considerably without affecting strength and stiffness. This was achieved by reducing the amount of mix water in the concrete by an amount equal to that used for internal curing. The reference concrete selected for the demonstration had a 0.34 water-cement ratio, a cement-sand-coarse aggregate ratio of 1:2:2, and a cement content of 450 kg/m^3. Three similar concretes were made with 3 different amounts of LWA sand: 6%, 12% and 20% of the total sand content, for which normal sand was partly replaced with presoaked LWA sand for internal curing. Table 2 presents the properties measured at 7 days for the four concretes. It can be seen that an increase in the amount of LWA sand used for internal curing resulted in a considerable reduction in the maximum autogenous shrinkage. Restrained shrinkage testing showed that the reference concrete would fail at the age of 1.5 days, while the concrete with a 20% sand replacement ratio would not fail, as the tensile stress/strength ratio always remained lower than 50% under full restraint. Table 2 also shows that an increase in the amount of LWA sand (i.e. an increase in internal curing water) did not result in a decrease of the strength and stiffness properties at seven days. By keeping the total amount of water (i.e. mix water and IC water) constant in the four concrete formulations, this was equivalent to reducing the mix-water/cement ratio as the amount of internal curing water was increased. As a result, shrinkage was reduced by internal curing and the strength and stiffness properties were not affected.

Table 2: Properties obtained for a 0.34 w/c high-performance concrete [22]

LWA sand ratio (%)	7-day splitting tensile strength (MPa)	7-day compressive strength (MPa)	7-day modulus of elasticity (GPa)	Max. autogenous shrinkage ($\mu\varepsilon$)
0% (ref.)	4.1	50	31.6	252
6%	4.8	50	31.2	210
12%	4.5	54	32.0	112
20%	4.2	57	31.4	46

9.4 FINAL REMARKS

As shown in the case studies presented in this chapter, there are many opportunities to improve different key properties of high-performance concrete through the judicious use of internal curing in addition to conventional external curing. The use of LWA, either for reducing the weight of the structure or providing internal curing to concrete, indicated that LWA concrete structures can achieve satisfactory durability properties in severe environments. The use of LWA or SAP in normal-weight concrete structures was also shown as very promising internal curing agents for improving the durability of high-performance concrete structures. It is expected that future applications will increasingly move towards the use of internal curing, especially in normal-density concrete structures, as internal curing becomes better known through good practice and evidence of good performance records.

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