DURABILITY OF LIGHTWEIGHT CONCRETE BRIDGES

Reid W. Castrodale, PhD, PE, Carolina Stalite Company, Salisbury, NC
Kenneth S. Harmon, PE, Carolina Stalite Company, Salisbury, NC

ABSTRACT

Many engineers are hesitant to use lightweight concrete in bridge construction because of concerns about the durability of lightweight concrete exposed to weather and traffic conditions experienced by bridges. They suspect that lightweight concrete, made with what appears to be a porous aggregate, could not provide durability that is comparable with concrete made with normalweight aggregate. However, considerable evidence from long-term field performance and laboratory tests indicates that lightweight concrete can provide the excellent durability that is needed for bridges.

This paper begins by briefly defining lightweight aggregate and lightweight concrete. Common objections to using lightweight concrete for bridges are then addressed. Unique characteristics of lightweight concrete that contribute to making its durability in bridges equal to or better than normalweight concrete are then discussed. Observations of long-term performance of in-service bridges and other major projects, as well as data from laboratory testing and research, are then used to demonstrate and explain the outstanding durability of many lightweight concrete bridges. The paper concludes with a brief discussion of issues that need to be addressed in project specifications to assure the satisfactory long-term performance of lightweight concrete bridges.

KEYWORDS: Lightweight Concrete, Bridges, Durability, Performance, Girders, Decks, Specifications

INTRODUCTION

Lightweight concrete has many applications for bridge construction, ranging from the use of lightweight concrete to reduce the weight of prefabricated elements for handling and transportation to the use of lightweight concrete for decks and prestressed concrete beams to reduce the weight of the structure for improved structural efficiency and seismic performance. There are also other significant advantages, especially for bridge decks, that should encourage the increased use of lightweight concrete for bridge components.

Lightweight concrete has been used for bridges in this country since the 1920s[1]. The good performance of most of these structures is a testament to the durability of lightweight concrete. However, many engineers are hesitant to use lightweight concrete in bridge construction because they are concerned about the durability of lightweight concrete exposed to the weather and traffic conditions experienced by bridges. They suspect that concrete made with what appears to be porous lightweight aggregate could not provide durability that is comparable with concrete made with normalweight aggregate. While durability is most critical for bridge decks, because of their direct exposure to weather, traffic and deicing chemicals, all elements of a bridge must be durable if it is to achieve, with only minimal maintenance, the 75 year or greater service life that is now expected of highway bridges[2].

An FHWA report[3] entitled “Criteria for Designing Lightweight Concrete Bridges,” which was published in 1985, responded to concerns expressed at that time about the durability, wear resistance and long-term freeze-thaw qualities of lightweight concrete by stating that “no evidence was found that these properties differ from those of normalweight concrete. In fact, there is evidence that these properties could be better for lightweight concrete, especially if the normalweight concrete is of poor quality.”

After a brief introduction to the concepts and materials of lightweight concrete, this paper addresses concerns about the durability of lightweight concrete for bridges by addressing some of the common misconceptions about lightweight concrete. Unique characteristics of lightweight concrete that contribute to making bridge elements constructed using lightweight concrete (LWC) as durable as or even more durable than normalweight concrete (NWC) are then discussed. Observations of long-term performance of in-service bridges and other major projects, as well as data from laboratory testing and research, are then used to demonstrate and explain the outstanding durability of many lightweight concrete bridges. The paper concludes with a brief discussion of issues that need to be addressed in project specifications to assure the satisfactory long-term performance of lightweight concrete bridges.

The great majority of the information presented in this paper comes from a review of the literature. In many cases, lengthy quotations from references have been included because the statements of the original authors were very well-stated and communicated the necessary information. For references cited in this paper, the URL for downloading the reference from the internet, if available, is also given in the list of references. The reader is encouraged to review the cited references for additional information.

While many references were used for this paper, several stand out as major resources that are especially helpful for engineers considering the use of lightweight concrete for bridges. These include the report mentioned above that was prepared by T.Y. Lin International for FHWA in 1985[3], which is still very applicable today; the report of ACI Committee 213 – Lightweight Aggregate and Concrete[4]; and a major document prepared in 2000 by Holm and Bremner for the US Army Corps of Engineers on using high strength lightweight concrete for durable marine structures.[5] Finally, a comprehensive document that addresses the full range of properties and applications for structural lightweight aggregate has just been published[6] by the Expanded Shale, Clay and Slate Institute (ESCSI), which is the trade association for manufacturers of rotary kiln produced structural lightweight aggregate. A large number of other informative and useful documents on lightweight concrete are also available for downloading from the ESCSI website: www.escsi.org.

This paper addresses only the durability aspects of lightweight concrete. For information on the structural properties, design specifications and advantages of using lightweight concrete for bridges, the reader is directed to two other papers by the authors.[7, 8]

While reviewing the literature in preparation writing for this paper, the authors were reminded of the wide use and great acceptance that lightweight concrete has had in the past. Engineers have been convinced of the structural benefits and properties of concrete, as well as its durability, for many years. An example is the following discussion of high strength structural lightweight concrete made by the internationally known engineer Ben Gerwick, Jr., in a lecture in 1984[9]:

> When confined, it has greater ductility, due to progressive crushing of the aggregate. There are far fewer microcracks between paste and aggregate resulting in better high cycle fatigue endurance. The lower modulus accommodates thermal and other deformation strains with less cracking. Finally, the protection of the reinforcing steel from corrosion under severe environmental exposure appears to be enhanced.
>
> Thus we have a superior material available, originally chosen for its lighter density, which now appears justified for use in sophisticated structures for many other reasons as well.

A similar encouragement to use lightweight concrete is found in the 1985 report prepared by T.Y. Lin International for FHWA[3]:

> Although there is no consensus of opinion concerning the suitability of lightweight concrete for bridge structures, nor concerning experiences with its performance, it should be noted that the material does have sufficient record of successful applications to make it a suitable construction material for buildings and ships, as well as for bridges.
>
> Sufficient information is available on all aspects of its performance for design and construction purposes.

In recent years, several national and state research projects have been initiated to gather additional information on the properties and behavior of lightweight concrete for bridge structures, which are expected to further strengthen the confidence in the material that was held by leading engineers over 20 years ago. The authors hope that this paper will help bridge engineers today to better understand the durability characteristics of lightweight concrete for bridges so that the material can be used more widely to improve the durability and reduce the cost of bridges throughout the United States.

WHAT IS LIGHTWEIGHT CONCRETE?

Definition of Lightweight Concrete

Lightweight concrete is a structural concrete in which some or all of the coarse and fine aggregate has been replaced with aggregate that is lighter than normalweight aggregate. Structural lightweight concrete in the US typically uses lightweight aggregates that are manufactured using a rotary kiln process. The density of lightweight concrete typically varies from about 100 to 125 pcf. See the ACI report[4] and an earlier paper by the authors[7] for more basic information on lightweight concrete.

The Expanded Shale, Clay and Slate Institute (ESCSI) reported[10] that a total of nearly 2,000,000 cubic yards of lightweight aggregate were used for ready mixed or precast/prestressed concrete in 2007. This quantity of aggregate would correspond to roughly 3,000,000 cubic yards of concrete. With this large quantity of lightweight concrete being used in a year, it is clear that many ready mixed concrete and precast/prestressed concrete producers must be successfully using lightweight concrete.

Types of Manufactured Lightweight Aggregate

Lightweight aggregates are manufactured using shale, clay and slate as the raw material. After crushing and grading, the raw material is fed into a rotary kiln, where it is heated to 1,800 to 2,300 deg. F. At these temperatures, the material expands as gases are released in the softened material. These gases form many small, mostly discontinuous, pores which remain as the material cools and hardens after leaving the rotary kiln. The result is a vitrified, inert material that is significantly lighter than the raw material, yet still retains much of its strength. Depending on the type of raw material and processing, the aggregate may or may not be crushed to obtain the desired particle shape and size for use as aggregate in concrete.

Expanded aggregates manufactured using different types and sources of raw materials and processed using different methods will have somewhat different properties. However, with proper attention to qualification of aggregates, quality control and mixture proportions, most structural grade lightweight aggregates have been successfully used for concrete bridge deck construction and several have been successfully used for prestressed concrete girder construction.

Lightweight Aggregate Properties

The relative density (previously referred to as the specific gravity) of rotary kiln expanded lightweight aggregates typically ranges from 1.3 to 1.6, while the relative density for normalweight aggregates typically ranges from 2.6 to 3.0.

For structural lightweight aggregates, the maximum dry loose density is 70 pcf for fine aggregates, 55 pcf for coarse aggregates and 65 pcf for the loose density for the combination of coarse and fine aggregates, as specified in ASTM C 330[11].

Because of their cellular structure, lightweight aggregates absorb more water than normalweight aggregates. Based on 24 hour tests, lightweight aggregates typically absorb from 5 to more than 25% by mass of dry aggregate[5]. Absorption of normalweight aggregates is typically less than 2%. With proper consideration of absorption in mixture proportioning, batching and control, lightweight concrete can be consistently produced with the required workability and mechanical properties.

Construction Properties of Lightweight Concrete

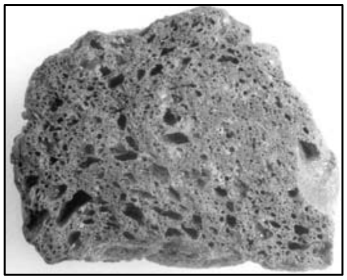
When properly proportioned, lightweight concrete can be delivered and placed with the same equipment as normalweight concrete. It can also be placed and screeded with less physical effort than that required for normalweight concrete. Excessive vibration should be avoided to prevent driving the heavier mortar fraction down from the surface where it is required for finishing. The same attention to curing should be taken for lightweight concrete as for normalweight concrete.

RESPONSES TO OBJECTIONS TO USING LIGHTWEIGHT CONCRETE FOR BRIDGES BASED ON DURABILITY CONCERNS

In this section, some of the less technical objections to the use of lightweight concrete are addressed. A more technical discussion of the unique characteristics of lightweight concrete that are related to its durability is given in the next section.

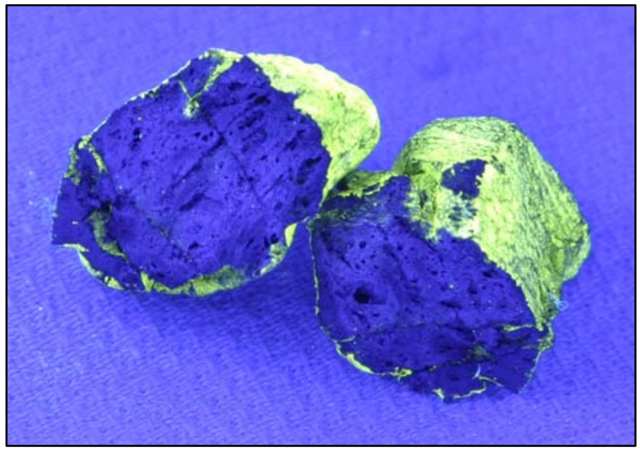
Lightweight aggregate looks like a sponge so it must be very permeable

This first objection is that lightweight aggregate, which appears porous, must act like a sponge. Therefore, it may seem reasonable to suppose that water can easily penetrate the apparently porous lightweight concrete, leading to deterioration from several causes.



This objection is quite understandable. Lightweight aggregate particles definitely have holes or pores in them, as shown in the photo. The exposed pores on the aggregate particles result in the lightweight aggregate having a higher absorption than normalweight aggregate.

However, the great majority of the pores in lightweight aggregate particles are not connected. Therefore, while moisture is absorbed into the pores that are exposed at the surface, it cannot move all the way through an aggregate particle. If the particles were actually porous, with the moisture passing deeply into or even through the particles, the absorption would be much higher than is typically experienced.



The actual condition of lightweight aggregate particles exposed to water for an extended period has been visually demonstrated by soaking a lightweight aggregate particle in a yellow fluorescent water-based dye for 180 days. The particle was then cracked open and exposed to a black light as shown in the photograph. The photo reveals that the water and dye had penetrated into the interior of the particle in only a few places where pathways existed for it to gain access. The great majority of the interior of the particle showed no evidence of the dye in the pores. Absorption at the time of test for this particle was 8% by mass.

This idea is confirmed by Vaysburd[12] who notes that "although lightweight aggregates are usually very porous, numerous investigations have demonstrated that lightweight aggregate concrete has a water permeability equal to or lower than that of normal-weight concrete."

Lightweight concrete bridges have some problems in the past

While there are reports of good performance of lightweight concrete bridge structures, many engineers are still hesitant to use lightweight concrete because they are concerned about its durability. In some cases, they may have heard about lightweight concrete bridges that have not performed well. However, the reported problems were often attributable to more than just issues with lightweight concrete, and many may not be related to lightweight concrete at all, but were caused by other factors. After investigating reports of poor performance of lightweight concrete bridges, the FHWA report[3] concluded that "most of the problems have to do with the specifications of the concrete, its placement in the field, and the familiarity with its behavior."

Furthermore, there have been advances in the understanding and use of lightweight concrete over the years, just as there have been for normalweight concrete. Issues encountered in some of the earlier applications of lightweight concrete for bridges and by some of the early researchers have been addressed and are no longer an issue, when lightweight concrete is properly proportioned, placed, finished and cured.

An example is that early laboratory tests of lightweight concrete reported inadequate resistance to freezing and thawing when tested using usual procedures.[13] It was then found that a drying period of at least 7 days prior to freezing-thawing testing was required for the concrete to perform adequately. This was a reasonable drying period before the concrete would experience freezing temperatures considering normal construction practices. Therefore, the standard procedure for freeze-thaw testing given in ASTM C 666[14] was modified for lightweight concrete by provisions given in ASTM C 330[11], which call for a drying period before testing. A recent research program also found poor freeze-thaw performance of lightweight concrete, but recognized that a period of drying before testing, as specified in ASTM C 330, would have improved the results.[15]

A second example is that early testing at the PCA labs found that some of the properties of lightweight concrete did not show long-term gains in strength.[16] However, the mixes tested were batched using dry lightweight aggregate. Since then, it has become standard practice to moisture condition lightweight aggregate by prewetting before batching to facilitate batching and pumping. This practice also provides additional moisture in the concrete (absorbed in the lightweight aggregate – see discussion of "internal curing" below) that does not enter into the mixing water but is available during hydration to extend the continued development of strength and other properties.

Lightweight aggregate appears to be soft, so it must wear excessively

Since lightweight aggregate particles appear porous, it seems reasonable to suspect that the particles must be soft and easily crushed. However, lightweight aggregate particles are composed of a hard vitrified material with a high silica content and a hardness similar to quartz.[4] Lightweight aggregates generally satisfy the usual requirements for maximum losses measured in the LA abrasion test.[17] See the later section on abrasion resistance for more information on this issue.

Lightweight aggregate floats in concrete

Lightweight aggregate is certainly less dense than other solid materials in concrete. Therefore, it may tend to concentrate at the top of a concrete placement if the concrete has excessive slump or lack of cohesiveness. However, with proper mix design and appropriate consolidation, lightweight concrete can be placed with no segregation. Lightweight aggregate has even been used without segregation in self-consolidating concrete (SCC).

Lightweight concrete will not be durable if it is ground or grooved

Because lightweight aggregate appears porous or soft, it may seem reasonable to suspect that the surface of a lightweight concrete deck should not be ground or grooved, which is now the typical practice for bridge decks in many states. The rationale is that grinding would expose the interior of lightweight aggregate particles, which would significantly increase the penetration of moisture and contaminants into the deck. Others have been concerned that lightweight concrete would be too weak to retain grooves cut in the surface of a deck or would wear excessively. Field experience has shown that these concerns are unfounded.

The Virginia Dare Bridge in North Carolina is 5.2 miles long and has a lightweight concrete deck for the entire length of the bridge. The specifications required that the entire surface of the deck be diamond ground during construction. The good condition of the bridge deck after several years in service was described in an earlier paper by one of the authors.[18] One of the NCDOT resident engineers on the project gave the following response to a question about the use of lightweight concrete on the deck of this bridge:

> We grooved the Chowan River Bridge [another bridge in the area which used lightweight concrete for a portion of its deck]. I have seen no problems with wearing surface there. We diamond ground the entire deck surface on Manteo Bypass [another name for the Virginia Dare Bridge] for rideability reasons. We were a little worried about the lightweight being so exposed, but found favorable research elsewhere across the country.
>
> So far, (5 years), I don't think we have seen any problems with the ground lightweight. Pop outs from entrapped water being frozen in the deck surface seem plausible in theory, and I was worried it could happen, but we have not seen anything to support it.[19]

The Route 33 Bridge over the Mattaponi River in Virginia was recently constructed with a lightweight concrete deck for much of its length. The bridge deck was ground where needed for smoothness and then the entire surface of the deck was transversely grooved. This bridge has been in service since 2006.[18]

Lightweight concrete is difficult to finish

It has been reported that contractors will occasionally approach a DOT to try to change a lightweight concrete deck to normalweight concrete because of concerns about finishing. However, ACI Committee 213[4] reports that "There is little or no difference in the techniques required for placing lightweight concrete from those used in properly placing normalweight concrete." The report goes on to say that "A well-proportioned lightweight concrete mixture can generally be placed, screeded, and floated with less effort than that required for normalweight concrete."

The NCDOT resident engineer mentioned above also commented on the finishing of the lightweight concrete deck:

> Lightweight does present a few new wrinkles, but I do not find it to be a negative for the product. Aggregates have to be handled with more care, and air testing is a little more cumbersome, but I don't think we should shy away from designing bridges with lightweight decks for those reasons. They work themselves out in about two or three pours. Normal weight has just as many nuances.[19]

Contractors and suppliers are not familiar with lightweight aggregate and concrete

Since many bridge engineers are not familiar with lightweight concrete, they assume that most ready mix suppliers and contractors are also not familiar with lightweight concrete.

As mentioned earlier, a significant volume of lightweight concrete is used each year in the ready mix and precast/prestressed concrete industries. Most of it goes into building products at the current time, but there is also significant experience with lightweight concrete bridge decks in some parts of the country. Therefore, in most major metropolitan areas where lightweight concrete is commonly used for floor slabs in mid- and high-rise buildings, concrete suppliers should be very familiar with the use of lightweight concrete. Lightweight aggregate manufacturers provide technical support for other concrete suppliers and contractors who may not be familiar with using lightweight aggregate.

DURABILITY OF CONCRETE FOR BRIDGES

Before beginning the more technical discussion of how lightweight concrete can be durable when exposed to the severe conditions experienced by bridges, the concept of durability needs to be explored further.

Bridge elements are subject to severe exposure conditions in many locations. Conditions are especially severe where freezing and thawing occurs and the decks are subjected to applications of corrosive deicing chemicals. It has also been observed that bridge decks are prone to cracking at early ages, in many cases even before traffic has been placed on the bridge. Traffic can also cause wear on the surface of a bridge deck. Environmental conditions combined with potential deficiencies in the quality and impermeability of concrete and the effects of traffic can lead to premature deterioration of a concrete bridge deck and other bridge elements.

Assuming that the concrete and structure meet all of the necessary material and structural requirements, a durable concrete must therefore resist the intrusion of water, chlorides and other materials that can lead to corrosion, or other processes that can lead to the deterioration of the structure. The concrete should therefore have these main characteristics:

- It must be "impermeable" to prevent intrusion of water and other agents by diffusion, etc., which contributes to the onset of corrosion or other deterioration.
- It must be "crack free" to prevent direct entry of water, etc. which contributes to the onset of corrosion or other deterioration. This includes both cracking visible on the concrete surface and internal microcracking.
- It must have the proper internal structure to prevent freeze-thaw damage, which may be related to the other two factors, since without internal water, freeze-thaw damage cannot occur.
- It must resist wear from traffic or water.

It seems that the majority of the recent efforts toward achieving durable structures have been directed toward the first and third points listed above. However, if the concrete is cracked for whatever reasons, the impermeable concrete between the cracks may not protect the reinforcement from corrosion. Similarly, a crack free deck that has permeable concrete will not have good long-term performance since the water can gain access to the interior of the concrete directly through the concrete. Therefore, concrete must have all of the characteristics listed above to achieve the desired durability.

The proper delivery, placement, finishing and curing of concrete, as well as aspects of the structural layout and design, play a very significant role in the achievement of durability goals for any concrete structure. However, these issues will not be discussed further here since the focus of this paper is on durability aspects.

UNIQUE CHARACTERISTICS OF LIGHTWEIGHT CONCRETE THAT CONTRIBUTE TO ENHANCED DURABILITY

The unique characteristics of lightweight concrete that contribute to enhanced durability are explored in this section. The contributions to durability of the different characteristics are simple to understand. However, the characteristics have complex interactions with other characteristics. Furthermore, some characteristics affect several durability parameters, and some parameters will be affected by several of the characteristics. This makes the separate discussion of each of the unique characteristics somewhat difficult, but it will be attempted in this section. The various parameters that are typically measured to demonstrate durability will be discussed in the next section, where evidence from field performance and test results will be presented.

For some aspects of durability, such as wear and abrasion resistance, lightweight concrete does not provide a unique benefit. Therefore, these issues are discussed with other durability parameters in the next section.

Contact Zone

The contact zone is the layer of cement paste surrounding each aggregate particle. In a very useful discussion of this topic, Holm and Ries define the term as representing “two distinctly different phenomena: (1) the mechanical adhesion of the cementitious matrix to the surface of the aggregate, and (2) the variation of physical and chemical characteristics of the transition layer of the cementitious matrix close to the aggregate particle.”[20] Deterioration of concrete can be attributed to a breakdown of the cementitious matrix or the aggregate, which is usually assumed, or may be caused by the “breakdown in the contact zone causing a separation of the still-intact phases.”[20] Therefore, the characteristics of the contact zone (also called the transition zone) have a profound impact on the durability and structural performance of the concrete.

Concrete has the potential to be impermeable to liquids and gases. However, this ideal is frequently not achieved in practice because it requires full hydration of the portland cement and an absence of microcracks around the aggregate which “form in the concrete during the hardening process as well as later due to shrinkage, thermal, and applied stresses.”[21] It has been observed that the contact zone surrounding lightweight aggregate is superior to the contact zone around normalweight aggregate,[20] a result of the improved bond between the cement paste and lightweight aggregate and other factors that will be discussed in the following.

An outstanding discussion of this topic was written by Vaysburd[12]. A significant portion of his comments are repeated here. He begins by describing the contact zone for normalweight aggregate:

> Dense aggregate does not actively participate in the formation of the concrete structure. Water migrates to the aggregate surface as the mix consolidates and during the setting process. Films of water form around the dense aggregate particles. Bleed water becomes entrapped under the horizontal grain surface of the aggregate. Water films, bleeding, and inefficient packing of the cement paste around the aggregate surface boundary can lead to the formation of voids around the aggregate that are not effectively filled during the hydration process; this leads to a zone more porous than the bulk matrix. … The cement matrix at the interface has a high porosity and a weak bond to the aggregate.[12]

He then comments on the significance that the contact zone surrounding normalweight aggregate has regarding durability:

> In the beginning, the voids and microcracks in the zone of weakness in normalweight concrete may not have much effect on the penetration of aggressive agents via water into the concrete. Later on, however, drying and temperature changes, freezing and thawing, and the local stress effects may exceed the tensile strain capacity of the concrete and cracks will occur. The microcracks originating at the zone of weakness tend to propagate in length and width due to stresses on the concrete structure; they then connect with existing microcracks in a crack network. … Since the flow of water in porous materials follows the path of least resistance, the discontinuous network of microcracks plays a significant role in concrete permeability and durability.[12]

In an earlier paper, Vaysburd concludes that these microcracks around the coarse aggregate cause the permeability of concrete to exceed the permeability of cement paste by two orders of magnitude.[22]

Vaysburd then describes the contact zone for lightweight aggregate:

> In contrast, lightweight aggregate takes a very active role in the formation of the structure in lightweight concrete. … The aggregate surface is rough, and, together with the physical penetration of the cement paste into the aggregate, it offers an excellent bond to the cement matrix. … In structural lightweight concrete, the contact zone between the cement matrix and porous particles is difficult to identify. The microstructure is characterized by an absence of microcracks and porous pockets.[12]

He then concludes:

> In lightweight concrete, the region between the aggregate and the surrounding mortar matrix can be considered a true *transition zone* …. In

> normalweight concrete, the interfacial region between the aggregate and the mortar matrix is a *zone of weakness* …. It can be argued that such relatively thin regions in composite materials – the transition zone in LWC and the zone of weakness in NWC – can be practically ignored. However, these thin regions to a large degree determine the mechanical and durability properties of concrete.[12]

In his earlier paper, Vaysburd notes:

> Main routes for infiltration of water in normal weight concrete are the cement matrix itself and the interface between the aggregate and the matrix. In lightweight concrete, due to the strong bond and high quality of the material in the contact zone, the only route is through the bulk matrix. This is why structural lightweight concrete exhibits higher impermeability than normal weight concretes of the same grade.[22]

Neville made similar observations regarding the interface zone surrounding normal-weight aggregate:

> Why is the interface zone different from the bulk of the hardened cement paste? The microstructure of the interface zone is greatly influenced by the situation that exists at the end of placing and compaction of concrete. At that stage, the particles of cement are unable to become closely packed against the relatively large particles of aggregate. This "wall effect" means that there is less cement present to hydrate and fill the original voids in the fresh mix. In consequence, the hardened cement paste in the interface zone has a much higher porosity than the hardened cement paste further away from the particles of the aggregate. It is known that the higher the porosity the lower the strength.[23]

Neville concludes that findings of a high water-cement ratio and higher porosity near the surface of normalweight coarse aggregate particles support this concept. Since the reduced interface properties are also present around normalweight fine aggregate particles, he estimates that the total volume of paste in normalweight concrete that has reduced properties is between one-third and one-half of the volume of the hardened paste.[23]

Later in the paper, Neville[23] discusses the particularly good bond between the hardened cement paste and lightweight aggregate. He indicates several reasons for this, including the rough surface texture of the aggregate and the penetration of the cement paste into the pores of the aggregate. The interchange of moisture between the fresh paste and aggregate reduces the "wall effect" he mentioned in his discussion of normalweight concrete. He also mentions internal curing, which enhances the properties of the transition zone around the lightweight aggregate particles, and elastic compatibility, both of which are discussed further below. He notes that this good bond results in the "absence of the development of early bond microcracking." An indication of the lack of microcracking in lightweight concrete is its linear-elastic behavior in compression to stresses as high as 90% of the ultimate strength of the concrete. For normalweight concrete, microcracks develop under even modest loads, resulting in the familiar non-linear stress-strain relationship in compression in which the concrete continues to soften under increasing compressive stress.

As he concludes his paper, Neville comments on requirements for concrete exposed to environmental conditions that are similar to those required for bridges:

> … when it is desirable to produce concrete with a strong monolithic action (for example, when temperature cycling is expected), means of reducing the difference between the moduli of elasticity of the aggregate and the hardened cement paste should be sought; in other words, lowering the former and raising the latter are desirable.[23]

While bridge elements do not go through the magnitude of temperature cycles that some fuel production facilities may experience, they are still subject to major repetitions of thermal stresses, as well as stress cycles caused by vehicular loads. Therefore, Neville's suggestion appears to be an appropriate consideration for bridge elements. Implementing his recommendation would lead to lower modulus aggregates (like lightweight aggregates) and a high quality paste.

Holm, et al.[24] reported that electron microscopic examinations of concrete from several bridge decks "consistently revealed that the lightweight aggregates were extremely well bonded to the cement past matrix." The bridge decks had been in service for a number of years in a range of locations and exposure conditions. The authors go on to observe:

> As in the case of the concrete ship, the exact boundary between the two porous phases is difficult to identify, whereas the transition between dense aggregates and porous hydrated cement paste is abrupt. Moisture exchange can take place between the partially saturated lightweight aggregate and the still plastic mortar phase and thereby reduce the tendency of fresh lightweight concrete to develop thin films of water at the interface between the aggregate and cement paste.[24]

These authors also present evidence that a chemical bond exists between the lightweight aggregate and cement paste. This is possible because the surface of the lightweight aggregate particles has pozzolanic properties that allow a beneficial chemical reaction with the paste. They cite a study that found the contact zone for lightweight concrete has greater "cohesion, density and strength" than the contact zone for normalweight concrete and another study that found reduced permeability for lightweight concrete and attributed it to "the formation of a coating layer of dense cement paste" surrounding the lightweight aggregate particles.[24] An evaluation by Sturm, et al. of old concrete ships exposed to a harsh marine environment also noted beneficial pozzolanic reactions in expanded aggregates.[25]

Holm, et al. also feel that the lightweight aggregate absorbs bleed water during the early stages of hydration.[24] This would prevent the formation of water lenses at the aggregate-paste interface, which often weakens the bond of normalweight aggregate particles. This idea is developed further by Holm and Bremner,[5] where they assert that the hygral equilibrium achieved between the paste and lightweight aggregate particles (both of which are porous) leads to a significant reduction in bleed water lenses which typically form around normalweight aggregate particles (which are not porous).

The quality of the contact zone directly affects the bond between the aggregate and paste. Vaysburd[22] reported the results of tensile tests used to demonstrate the bond strength of a lightweight aggregate, a normalweight granite aggregate, and cement mortar without coarse aggregate. The results are very interesting. Figure 1 shows a bar graph of bond strength test results for lightweight aggregate (LWA), normalweight aggregate (NWA) and cement mortar (None) at 3 and 28 days.

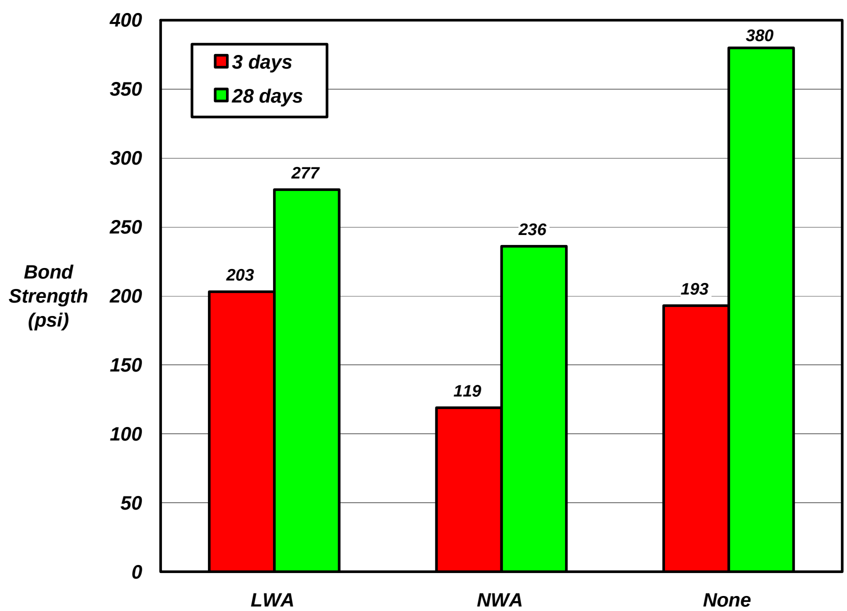


Figure 1 Bond Strength between Aggregate and Cement Mortar (data from Ref. 22)

The figure shows that at 3 days, the bond strength of the lightweight aggregate was significantly greater than the bond strength for the normalweight aggregate. At 28 days, the bond strength of the lightweight aggregate was still noticeably better than the bond strength of the normalweight aggregate. This increased bond strength would be expected to improve the tensile strength of the concrete and its resistance to microcracking due to internal stresses.

It is clear from the literature that a superior bond exists between lightweight aggregate and paste, which reduces microcracking and porosity in the contact zone between the paste and aggregate. The reduced microcracking and porosity means that there are fewer pathways available for moisture, oxygen, chlorides and other contaminants to penetrate the concrete and cause deterioration.

Internal Curing

Since lightweight aggregate has greater absorption than normalweight aggregates, for which absorption is typically very low, it is typically premoistened before batching so that water is not absorbed out of the mixture, leading to slump loss and difficulties with pumping, finishing and strength loss. Once the concrete is placed and hydration begins, the water absorbed in the premoistened lightweight aggregate is released over time into the concrete to allow continuing hydration of cement and other pozzolanic reactions. This effect is called "internal curing." The absorbed water is not available to react immediately with the cement during mixing, so it is not considered when determining the water-cementitious materials ratio (w/cm).[26]

The concept of internal curing using lightweight aggregate has been recognized since 1957.[26] However, only recently has it begun to receive widespread attention and study. In 2007, an entire session at an ACI Convention was devoted to internal curing using lightweight aggregate and other means.

The continuing availability of internal curing moisture provided by premoistened lightweight aggregate is especially beneficial for high performance concrete that is intended to be nearly impermeable to external moisture. However, external moisture also includes curing water, which means that it is very difficult if not impossible for externally applied curing water to penetrate the concrete far enough to be beneficial in the continued hydration of the cement. Concrete with low w/cm ratios will often not have adequate internal moisture for the cement to fully hydrate or for pozzolanic reaction to continue. Vaysburd states that for a concrete with a w/cm ratio well below 0.4, all available water will be consumed when about 90 percent of the cement is hydrated.[12] When the moisture is consumed, self-desiccation occurs within the concrete and the beneficial reactions will cease. For a typical sand lightweight concrete mixture with premoistened lightweight aggregate, every 1 percent by mass of absorbed moisture represents about 1 gal/cy of internally available curing water.

The release of absorbed water from lightweight aggregate into concrete is illustrated by Figure 2 from Holm et al.[26] The moisture content of the lightweight aggregate at batching was 24% by mass, so it is clear that about half of the absorbed moisture is released into the concrete within a day after placement. The moisture continues to be released into the concrete with time, accelerating somewhat once air drying begins. The lightweight aggregate continues to release moisture into the concrete for over a month, after which it appears that equilibrium is achieved and the moisture content remains fairly constant. In this case, the release of moisture in the aggregate from an initial moisture content of 24% to an equilibrium moisture content of about 2% corresponds to about 22 gallons of additional curing water per cubic yard of concrete, which should be adequate to allow complete hydration of the cement and the continuing reaction of any pozzolans.

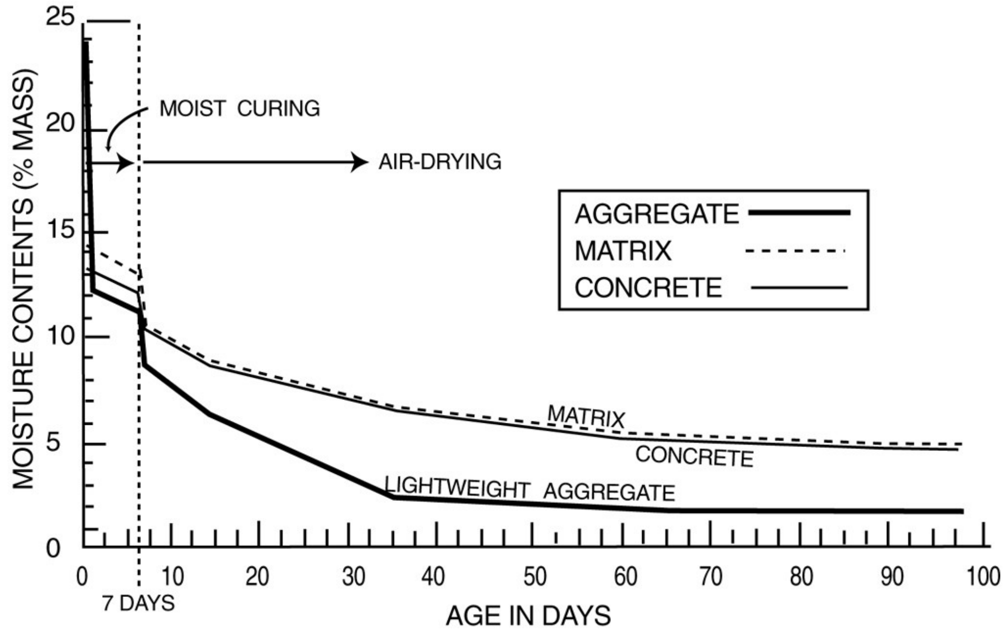


Figure 2 Moisture content versus time in lightweight concrete[26]

Properties of normalweight concrete can be improved by replacing a portion of the normalweight aggregate with premoistened lightweight aggregate to provide internal curing. The use of lightweight fine aggregate has been found to be especially effective for this type of application, although coarse aggregate can also be used. Research has conclusively shown that high strength normalweight concrete mixtures containing an adequate volume of high moisture content lightweight aggregate have a reduced sensitivity to poor curing conditions.[26]

In addition to the enhanced curing of the concrete, a number of other more measurable and practical benefits also result from internal curing. Several are noted in the following.

Neville notes that internal curing enhances the bond between lightweight aggregate and the cement paste because the additional moisture is being released from the aggregate to the contact zone.[23] As discussed in the previous section, improving the quality of the contact zone directly affects durability (by reducing permeability) and strength.

Internal curing can improve the tolerance of concrete to improper curing of concrete. An early study by Bloem, cited by Holm et al.,[26] comparing the strength of concrete cylinders and cores taken from concrete elements concluded that “Measured strength for lightweight concrete cylinders was not reduced by simulated field curing methods employed. This would tend to support the suggestion that the high absorption of lightweight aggregate may have the beneficial effect of supplying curing water internally.” Research by Campbell and Tobin, also cited by Holm et al.,[26] comparing strength of field and laboratory concrete concluded that the internal curing effect of lightweight aggregate apparently produced concrete that was more forgiving because it was “less sensitive to poor field curing conditions.”

Long-term strength gain has been observed when lightweight aggregates are moistened prior to batching compared to a similar normalweight concrete. A study reported by Holm[27] demonstrated a long-term increase in compressive strength with lightweight concrete compared to normalweight concrete for comparable mixtures. The results of the study are shown in Figure 3, in which the lightweight concrete is labeled “Solite” and the normalweight concrete is labeled “stone.” When some of the portland cement was replaced with fly ash, the compressive strength continued to increase throughout the period for the lightweight concrete, but it reached an early plateau with the normalweight concrete, showing little strength gain over the mixture without fly ash. This figure demonstrates that the absorbed moisture provided by lightweight aggregate is especially important when pozzolans are in the mix. This is because the pozzolanic reaction will only continue while water is available.[26]

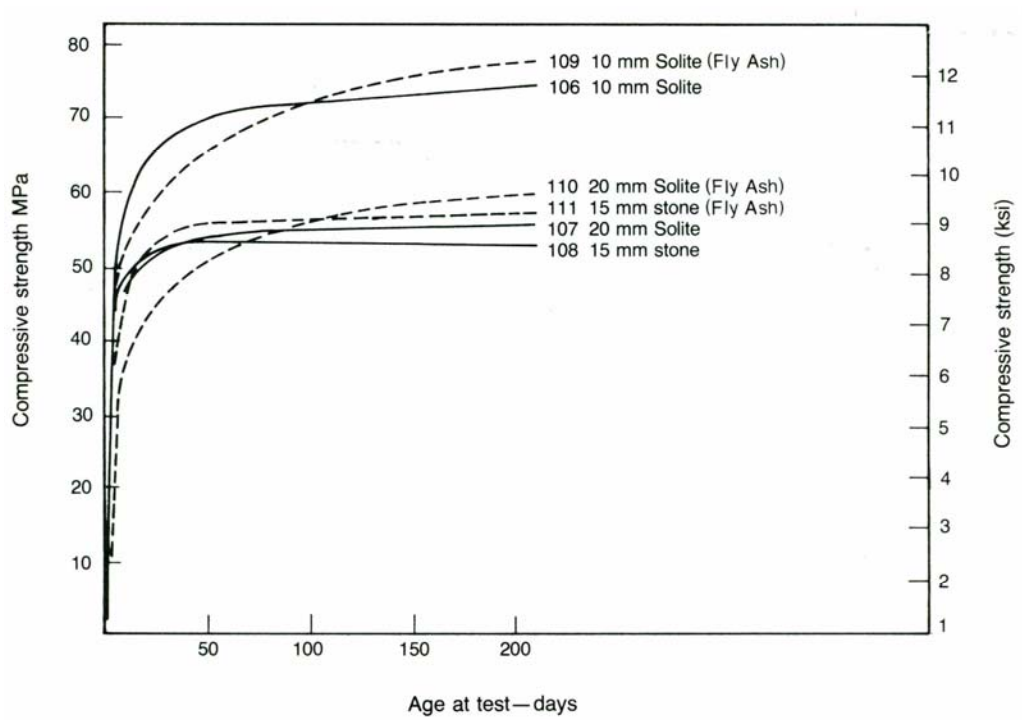


Figure 3 Compressive strength versus time for lightweight and normalweight concretes using 4” x 8” cylinders[27]

Internal curing also reduces shrinkage. It tends to minimize plastic shrinkage when a concrete surface is exposed to unfavorable conditions that lead to rapid drying.[26] It is also effective in significantly reducing or even eliminating autogenous shrinkage that occurs as a result of self-desiccation.[28]

Much of the early research on lightweight concrete, such as the work at PCA by Shideler,[16] was conducted using mixtures that were batched with dry lightweight aggregates, which was the accepted practice at the time. Therefore, the results of these early studies do not reflect the benefits from internal curing that are described above.

Elastic Compatibility

In normalweight concrete, the aggregate particles are up to 5 times stiffer than the hardened cement paste surrounding them.[29] This unequal stiffness of the different components in the concrete matrix results in stress concentrations from internal and external actions which can cause microcracking around normalweight aggregate particles. However, in lightweight concrete, the modulus of elasticity of lightweight aggregate particles is much closer to the modulus of elasticity of the hardened cement paste because of the porous nature of the lightweight aggregate. This allows the concrete to behave more monolithically.[23] The more uniform stiffness of the lightweight concrete matrix, which is referred to as "elastic compatibility," reduces or eliminates stress concentrations around the aggregate particles and the microcracking that accompanies them. With reduced microcracking, the durability of the concrete is improved by reducing the permeability of the concrete.

Figure 4 is an illustration of the concept of elastic compatibility that was developed by Bremner and Holm.[29] The figure shows that a typical 4,000 psi air-entrained sand lightweight concrete is an essentially homogeneous material because the stiffness of the components of the matrix are equal. Based on the figure, as the strength of lightweight concrete increases, the stiffness of the cementitious matrix increases and a mismatch in stiffness between the aggregate and the mortar begins to develop. However, the mismatch is much less than the mismatch that exists between the cementitious matrix and normalweight aggregates.

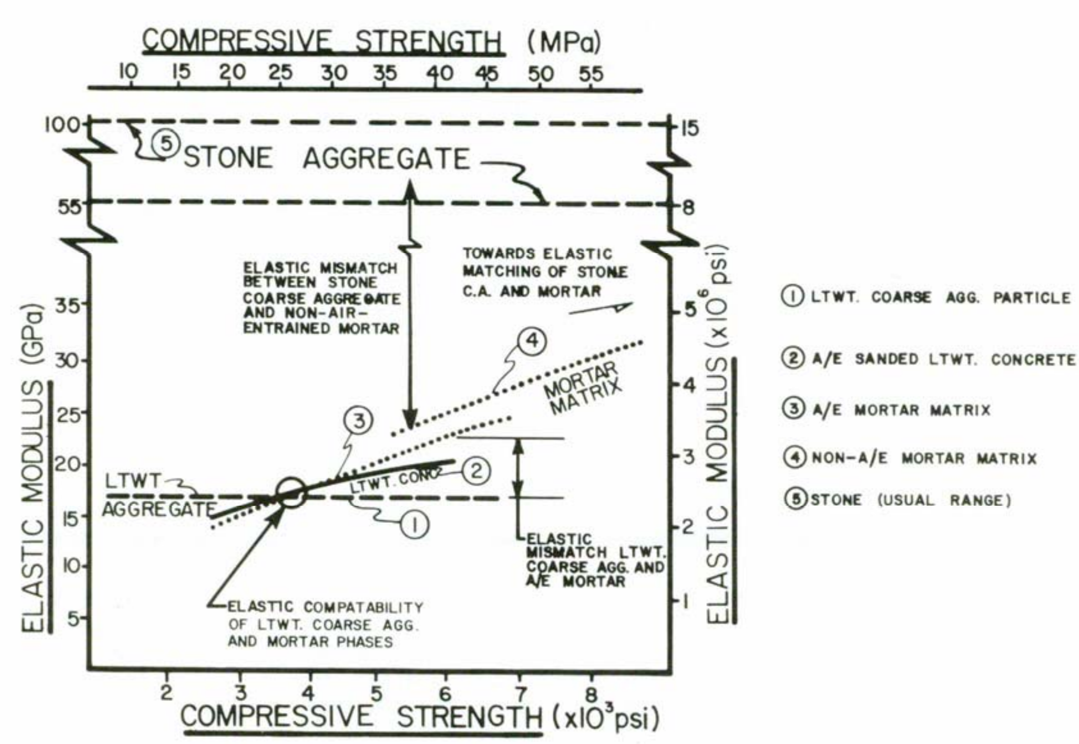


Figure 4 Elastic Characteristics of lightweight and normalweight concrete[26]

Elastic compatibility in lightweight concrete affects a number of properties of concrete. These will be considered in the following. In some cases, it is hard to distinguish between the improvements to behavior resulting from the improved contact zone or bond discussed above, and elastic compatibility. Both effects contribute to reduced microcracking around the aggregate particles. It appears that the good bond and excellent strength and lack of porosities and microcracking in the contact zone provide the foundation for the good durability of lightweight concrete. Then elastic compatibility contributes to maintaining good durability by reducing or eliminating the stress concentrations around the aggregate particles that can cause microcracking as the concrete is subject to stresses and strains from various sources.

Vaysburd states that "The elastic match in lightweight aggregate concrete and the elastic mismatch in normal-weight concrete are extremely important for tensile strain capacity (resistance to cracking) and therefore durability."[12] His point is that lightweight concrete with its elastic compatibility has greater resistance to cracking, which improves durability.

Elastic compatibility or incompatibility has a strong influence on the behavior of concrete in compression. A stress-strain curve for concrete in compression becomes non-linear as microcracks form and grow, typically around the aggregate particles, which weakens the structure of the concrete. For lightweight concrete, stress-strain curves typically remain linear to stresses approaching 90% of the failure strength of the concrete,[23] revealing that microcracks between the lightweight aggregate and the cementitious matrix do not form until a high level of stress. In comparison, the familiar curvilinear stress-strain curve for normalweight concrete with lower compressive strengths reveals an early onset of microcracking around the aggregate particles because of the elastic mismatch between the normalweight aggregate and the cementitious matrix.

Elastic compatibility, or the lack thereof, also influences the permeability and therefore durability of concrete. This is demonstrated by Bremner, et al.[21] with an investigation of the gas permeability of hollow concrete cylinders under different levels of stress and gas pressure. The intent was to study the effect that compressive stress has on permeability (and therefore durability) in concrete, since bridges and other structures are often subjected to varying stress levels during the life of the structure while also being exposed to water and other contaminants. Both lightweight and normalweight concrete cylinders were tested. The investigation revealed a relationship between gas permeability the extent of microcracking within the concrete. The gas permeability was found to remain nearly constant for lower levels of stress. It was also found that the permeability of lightweight concrete was noticeably less than normalweight concrete. The reduced permeability was taken as an indication of reduced microcracking in the lightweight concrete at lower stress levels than in normalweight concrete. When the applied stress exceeded a threshold value, the permeability began to increase rapidly as the stress continued to increase. This increasing permeability reflected the growth of microcracks and increasing connectivity between microcracks that allowed the gas to pass more readily through the concrete. The report states that "rapid increases in permeability occurred at approximately 54 to 62% of the ultimate strength for normal weight concrete and 72 to 83% of the ultimate strength for structural lightweight concrete."[21]

Test results are plotted to show the changing permeability with increasing compressive stress in Figure 5 for lightweight and normalweight concretes at two levels of internal pressure in the hollow cylinder: 30 and 60 psi. These results show that the lightweight concrete had less permeability and therefore less microcracking at all levels of stress, and that the lightweight concrete retained a lower permeability to a higher level of stress before the rapid increase in permeability (and microcracking) occurred. The researchers concluded that "The close match between the stiffness of the expanded lightweight aggregate and the cement paste matrix [elastic compatibility] minimizes internal stress concentration and explains the delayed onset of microcracking as compared to normal weight concrete."[21]

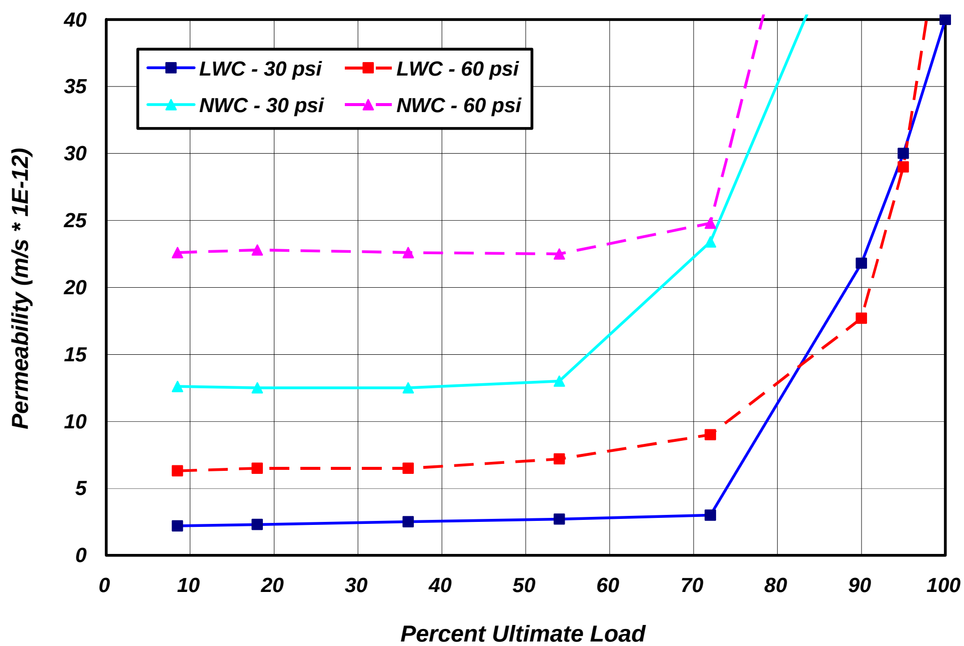


Figure 5 Permeability versus Compressive Stress for Concrete (based on Ref. 21)

Lower Modulus of Elasticity of Lightweight Concrete

It is universally accepted that lightweight concrete has a lower modulus of elasticity than a comparable normalweight concrete because of the reduced stiffness of the lightweight aggregate. Generally, the modulus of elasticity of lightweight concrete is 50 to 75% of the expected modulus of normal weight concrete with the same strength.[3,4] While the reduced stiffness of lightweight concrete typically requires designers to address increased deflections, prestress losses and cambers for girders (see Refs. 7 and 8), the reduced stiffness can be beneficial for bridge decks and other bridge elements. For decks and other bridge elements, forces resulting from restrained deformations, such as shrinkage or thermal changes, will be reduced with a lower modulus. This is especially important for bridge decks which are restrained by girders and are subject to significant deformations from variations in temperature at early ages (due to hydration) and later ages (due to daily and seasonal effects), as well as shrinkage.

Krauss and Rogalla, authors of the NCHRP report titled "Transverse Cracking in Newly Constructed Bridge Decks,"[30] stated that “the project’s analytical studies showed that the concrete modulus of elasticity, adjusted for creep, affects both thermal and shrinkage stresses more than any other physical concrete property …". The authors continued: "Using low-elasticity aggregates should therefore reduce thermal and shrinkage stresses, and the risk or severity of transverse cracking." In response to these findings, the report recommends that concrete with a low cracking tendency should be used for bridge decks. To accomplish this objective, the authors present a list of recommendations, the first two of which are that concrete for bridge decks should have a low early modulus of elasticity and low early compressive strength. However, lightweight concrete can be used to satisfy the main requirement (low modulus of elasticity) without having to sacrifice strength, since the elastic modulus of lightweight concrete is less than that of normalweight concrete for the same strength.

Holm[27] also suggests that lightweight concrete has a high ultimate strain, which is related to the lower modulus of elasticity. A higher ultimate strain is an important factor in reducing cracking. Ozyildirim and Gomez indicate that it is desirable to have a low modulus in a bridge deck to improve the strain capacity and crack control.[15] Gerwick states that the lower modulus of lightweight concrete “accommodates thermal and other deformation strains with less cracking.”[9]

Lightweight fine aggregate provides effect similar to entrained air

When lightweight fine aggregate is used in concrete, which has not been as common in recent years as it was in the early years of using lightweight concrete, it appears that the improved durability of the lightweight concrete may be attributed to “a well dispersed void system provided by the fine lightweight aggregate fraction that may serve an absorption function in weathering resistance as well as reducing salt concentration levels in the mortar phase.”[27] In the same paper, a study by Fagerlund is cited which found that lightweight fine aggregate particles that were smaller than 0.025 mm (0.01 in.) had a spacing factor very similar to entrained air.[27] The lightweight fine aggregate particles apparently contribute to the freezing and thawing resistance that has been observed in some lightweight concrete structures.

While this beneficial effect of lightweight fine aggregate has not been widely acknowledged or utilized, it does appear that the pores in the lightweight fine aggregate may function in the same way as entrained air in protecting the paste from the effects of freezing and thawing.

Void space to allow for formation of potentially disruptive materials

Some potentially deleterious reaction products have been found in voids in lightweight aggregate particles.[24] The formation of these materials within the aggregate pores was beneficial, since the aggregate had provided space for the precipitate to form without causing an undesirable expansion within the concrete paste. While this is not a primary consideration in the use of lightweight concrete, it adds to the cumulative benefits of using the material.

FIELD AND LABORATORY EXPERIENCE REGARDING DURABILITY OF LIGHTWEIGHT CONCRETE

In this section, information will be presented documenting the good durability of lightweight concrete when tested in the laboratory or observed in the field. The following aspects of durability will be discussed:

- Freezing-thawing resistance
- Permeability
- Alkali-Silica Reactivity (ASR) and Sulfate Attack
- Carbonation
- Fire Resistance
- Fatigue Resistance
- Coefficient of Thermal Expansion
- Abrasion resistance
- Skid resistance

Freezing-Thawing Resistance

The durability of lightweight concrete when exposed to freezing and thawing has generally been good. Holm summarizes the conclusion of a major study on freeze-thaw durability of lightweight concrete in the following:

> The results of these major programs that include hundreds of laboratory tests may be simplistically summarized by noting that air-entrained lightweight concretes proportioned with a high quality binder provide satisfactory durability results when tested under usual laboratory freeze-thaw programs.[27]

A recent study of lightweight concrete for bridge decks and girders at Purdue University concluded that “In general, the results indicate that the resistance of LWC to freezing and thawing is far superior to that of concrete made with the normal weight aggregate used in this research.”[31]

A comprehensive study of all major types of aggregate available to the New York Thruway was conducted by Walsh in 1959-1962.[32] The program evaluated the performance of test slabs that were subjected to over 200 cycles of freezing and thawing and over 100 applications of deicing chemicals over the course of several years. At the end of the study, the researcher noted that the lightweight concrete decks had superior performance.

Based on a review of laboratory tests and in-service performance of several structures in Virginia, Ozyildirim concluded that “properly air-entrained LWC made with high quality lightweight aggregates provides satisfactory resistance to freezing and thawing in structures. They also show satisfactory results in the harsh freeze-thaw test when limited air drying is provided prior to testing. The field performance with LWC has been satisfactory."[33] This is demonstrated by the test results shown in Table 1 for the VA Route 33 bridges over the Mattaponi and Pamunkey Rivers in Virginia, where high performance concrete was used for both the lightweight and normalweight decks. The test results for the lightweight concrete batches shown in the table satisfy all of the acceptance limits and are better than the results for the normalweight concrete batches.

Table 1 Air content and freeze-thaw test results for high performance deck concrete used for VA Route 33 bridges[33]

Batch	Air (fresh conc) (%)	Weight Loss (%)	Durability Factor	Surface Rating
Pamunkey NW B1	6.0	17	96	3.1
Pamunkey NW B2	7.0	26.7	70	1.8
Pamunkey NW B3	5.7	8.6	91	1.4
Mattaponi LW B1	7.0	6.6	102	1.5
Mattaponi LW B2	5.2	2.8	103	0.9
Pamunkey LW	5.7	6.1	107	1.0

NW=Normal weight, LW=Lightweight
Acceptance limits at 300 cycles: Weight Loss $\leq$7, Durability Factor $\geq$60, and Surface Rating $\leq$3.

The William Preston Lane, Jr., Memorial Bridge consists of two parallel structures that cross the upper reaches of the Chesapeake Bay in Maryland.[34] The first structure, constructed in 1952, has 3.25 miles of lightweight concrete decks on the steel girder, truss and suspension spans of the superstructure.[24] The lightweight concrete was not air-entrained and had an air dry density of 105 pcf, using lightweight aggregate for all the aggregate in the concrete.[35] Normalweight concrete, which was also not air-entrained, was used for the 0.78 miles of concrete deck on the approach spans that were supported on prestressed concrete girders.

After 21 years of service, the entire bridge was subjected to extensive physical testing, which included core drilling, petrographic analysis and ultrasonic testing. After removing the 2 inch asphalt wearing surface that had been applied at the time of original construction, the investigators found that the lightweight concrete had "almost negligible deterioration."[36] An examination of the cores showed secure adhesion between the paste and aggregate and little microcracking.[24] However, the normalweight concrete decks had deteriorated, with poor adhesion between the paste and gravel aggregate and significant cracking.[24] The observed deterioration of the deck concrete was attributed to the effects of freezing and thawing. The difference in condition between the two types of deck was significant enough that ultrasonic testing was only conducted on the normalweight concrete decks on the approach spans.[36] Because of the good performance of the lightweight concrete decks, the normalweight concrete decks were replaced with lightweight concrete, a new wearing surface was installed, and the bridge was put back in service. After only 9 years in service, the new lightweight concrete decks were found to have high chloride concentrations, but no signs of steel corrosion or deterioration.

Therefore, it was suggested that the lightweight concrete may have a high tolerance for chloride.[12]

Some early studies reported unsatisfactory freeze-thaw performance of lightweight concrete.[13,37] In these tests, the lightweight concrete was tested according to ASTM C 666, which generally requires that specimens be stored in saturated lime water until testing. A subsequent comprehensive study by ESCSI showed that allowing lightweight concrete to dry for 14 days before subjecting it to freeze-thaw testing provided results similar to longer drying periods.[35] A 14 day drying period was then adopted by ASTM C 330[11] as a modification for lightweight concrete to the standard testing method in ASTM C 666.[14] Holm et al. report results from a series of freezing and thawing tests of concrete made with a lightweight aggregate with 24% absorbed water.[26] The tests demonstrated that the concrete had excellent resistance to freezing and thawing cycles if the specimens were air dried for as little as 5 days after an initial moist cure period of 7 days (see Figure 6).

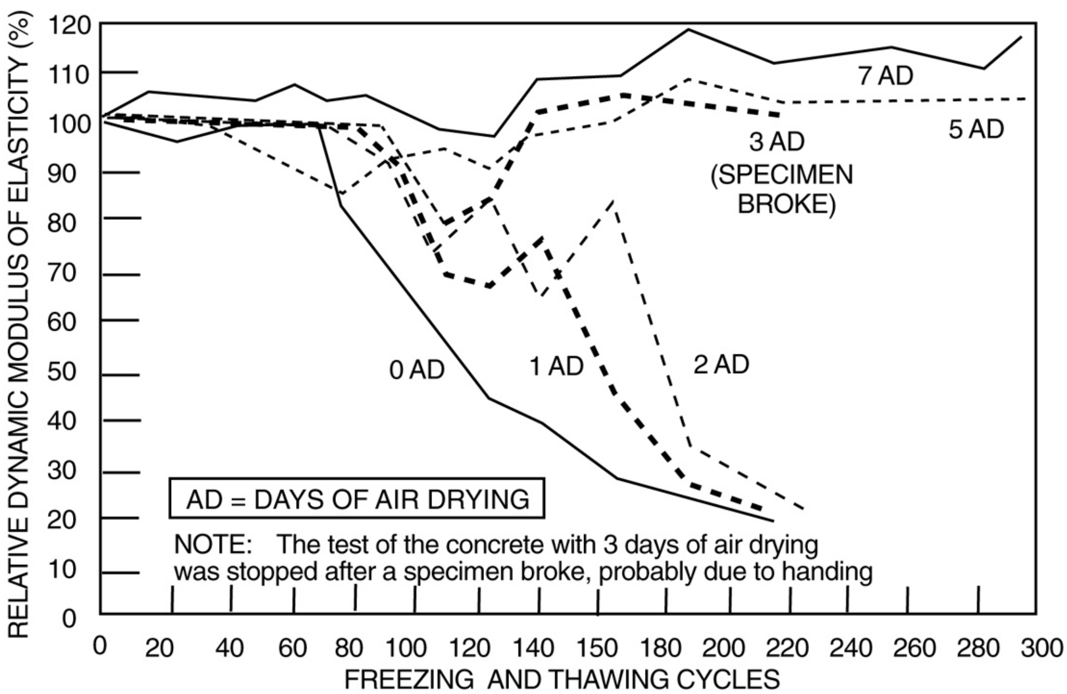


Figure 6 Relative dynamic modulus of elasticity for LWC exposed to freezing and thawing cycles[26]

Permeability

Permeability of concrete has an important influence on the durability of concrete. Lightweight concrete has been shown to have satisfactory permeability as consequence of the unique characteristics described in the preceding section. Results of several approaches to evaluating permeability are given in the following.

ACI Committee 213 reports that several test programs comparing the permeability of lightweight and normalweight concrete measuring different quantities and using different concrete properties of have all found that the permeability of lightweight concrete was equal to or less than the permeability of normalweight concrete.[4] The same report also cites a study by Onoda Cement Company which found that penetration of water and sea water under pressure was less for lightweight concrete than the normalweight concrete with similar properties.

A direct comparison of the field performance of lightweight and normalweight concrete was made at the Silver Creek Bridge over I-80 in Summit County, Utah.[38] The bridge was constructed in 1968. In 1991, after 23 years in service, cores were taken from the lightweight concrete deck and the normalweight concrete approach slab adjoining the bridge deck. The core samples were evaluated for chloride concentrations at different distances from the surface of the concrete. The results, which are presented in Table 2, show that the surface of the lightweight concrete had higher chloride levels than the normalweight concrete. However, the table also shows that at depths near where the reinforcement was located, which would be the critical location for determining potential for corrosion, the lightweight concrete deck had a much lower concentration of chloride than the normalweight concrete approach slab, indicating that the lightweight concrete deck should have a decreased potential for deterioration caused by corrosion.

Table 2 Chloride Content Test Results – Silver Creek Overpass after 23 Years in Service[38]

Depth	***Lightweight Concrete Bridge Deck***	***Normalweight Concrete Approach Slab***
0" to ½"	*36.7 lbs / CY*	*20.5 lbs / CY*
½" to 1"	*18.0 lbs / CY*	*18.0 lbs / CY*
1" to 1½"	*7.7 lbs / CY*	*15.7 lbs / CY*
1½" to 2"	*0.5 lbs / CY*	

Another comparison can be made using data for the San Francisco-Oakland Bay Bridge.[3] When constructed in 1936, a sand lightweight concrete was used for the upper roadway deck. In 1963 the deck received an overlay to cover embedded lane markers. In 1977, the overlay was replaced and the bottom of the deck was sealed with rubber paint. This deck is still giving satisfactory service today.

In 1979, cores were taken from the upper roadway deck to determine its chloride content.[3] The tests revealed a high chloride content in the first inch of the slab. However, with increasing depths into the slab, the chloride content decreased to less than 1 lbs/CY, the generally accepted corrosion threshold. The underside of the slab showed higher chloride levels than the top. However, no damage was found. In 1984, cores were taken from the normalweight concrete decks on the East Bay approach spans to the bridge. Tests of these cores indicated chloride concentrations above 1 lbs/CY had reached 4 inches into the concrete. In some cases, the chloride content was as high as 10 lbs/CY. Some spalling was found on the approach spans that required repair.

The Virginia Dare Bridge, also know as the Manteo Bypass, carries traffic on the US Route 64-264 Bypass across Croatan Sound in coastal North Carolina. Because of the highly corrosive coastal environment, NCDOT wanted a bridge that would provide a 100 year service life without repairs caused by damage from corrosion of reinforcement in concrete. The permeability of the concrete was modeled analytically using different combinations of concrete parameters and mitigation techniques from which the most promising combinations were identified.[39] No distinction was made between lightweight and normalweight in the durability analysis or prescriptive specifications. The final design used a lightweight concrete composite deck on removable forms for the entire 5.2-mile long structure. The bid quantity for lightweight concrete deck was over 1.865 million square feet, which is equivalent to 43 acres.

Specifications requirements and test results for the high performance lightweight concrete deck for the VA Rte 33 Bridge over the Pamunkey River are shown in Table 3.[18] Test results were obtained from the concrete supplier during the construction of the project. The relatively consistent behavior of the lightweight concrete test results over a 6 month period demonstrates that the concrete supplier could produce lightweight concrete with consistent properties that satisfied the project requirements.

Table 3 Concrete Properties for the VA Rte 33 Bridge over the Pamunkey River[18]

Compressive Strength at 28 days (psi)		
Specification requirement:	5,000	
Average value:	5,998	59 samples over a 6 month period
Maximum value:	7,573	
Minimum value:	3,267	8 samples were < 5,000 psi
Standard deviation:	934	
Permeability at 28 days (coulombs)		
Specification requirement:	2,500	
Average value:	989	17 samples over a 6 month period
Maximum value:	1,467	
Minimum value:	593	
Standard deviation:	245	
Fresh Concrete Density (pcf)		
Specification requirement:	120	including weight of reinforcement
Range of values:	111.8 to 117.5	

Thomas reported the results of a research project that studied the resistance of lightweight concrete to penetration of chloride ions.[40] The conclusions of the study found that the use of lightweight aggregate in concrete significantly reduced the electrical conductivity and chloride permeability of the concrete. The benefit of using the lightweight aggregate continued to increase with time, apparently indicating the continuing reaction of the supplementary cementitious materials as a result of internal curing moisture being supplied by the premoistened lightweight aggregate. It was reported that "the chloride diffusion coefficient for LWA concrete after 3 years was between one third to one half of that of normal density concrete of the same age and w/cm."[40] The test results were then used as input parameters for a service-life prediction model. The analysis indicated that the use of lightweight concrete could be expected to significantly extend the service-life of concrete structures by delaying the onset of corrosion and deterioration, although more tests are needed before firm conclusions could be made.

Abrasion Resistance

Field experience has shown that the wear characteristics of lightweight concrete are similar to normalweight concrete.[4]

Specifications for aggregates for bridge construction typically require that an aggregate satisfies the LA Abrasion Test (ASTM C 131).[41] Laboratory abrasion test losses for lightweight aggregates are often higher than for normalweight aggregates, but they still typically satisfy the maximum weight loss permitted by ASTM C 33[42] for normalweight aggregates.[17]

Lightweight concrete batched with expanded clay coarse aggregate and quartz sand was used for all elements of a drop-in span for the Sebastian Inlet Bridge in Florida which was completed in 1964.[38] The design density of the lightweight deck concrete was 115 pcf. Normalweight concrete with a fossiliferous limestone coarse aggregate and quartz sand was used for the remainder of the structure. Florida DOT investigated the properties of the normalweight and lightweight concrete deck on the bridge in 1997 and again in 2006.[43] Results for depth of wear measurements on the two-lane deck are shown in Table 4. For this bridge, the wear of the lightweight concrete deck was less than the wear of the adjacent normalweight concrete deck.

Alkali-Aggregate Reactivity and Sulfate Attack

Lightweight concrete has been found to be generally unaffected by alkali-aggregate reactivity or sulfate attack.[6] It is thought that the reduced permeability of lightweight concrete is part of the reason for this performance, since without the presence of water, the detrimental reactions cannot proceed. It has also been suggested that the firing of manufactured lightweight aggregate to high temperatures activates the surface of the aggregate so that it can "act as a source of silica to react with the alkalis from the cement at an early age to counteract any potential long-term disruptive expansion."[6] The pores within lightweight aggregate particles are also though to provide space into which detrimental reaction products can form without damaging the concrete. This may be the reason that combining lightweight aggregate with reactive aggregates tends to reduce the detrimental expansion of concrete.[6]

Table 4 Maximum Tread Wear Depth of Deck Surface on Sebastian Inlet Bridge[43]

Location	Outside Wheel Path		Inside Wheel Path	
	4/1/1997	10/25/2006	4/1/1997	10/25/2006
NWC1	0.050	0.065	0.030	0.045
NWC2	0.110	0.123	0.150	0.143
NWC3	0.100	0.131	0.140	0.152
NWC4	0.120	0.124	0.040	0.041
Average	*0.095*	*0.111*	*0.090*	*0.095*
LWC1	0.060	0.076	0.100	0.100
LWC2	0.040	0.061	0.085	0.094
LWC3	0.095	0.106	0.030	0.043
LWC4	0.090	0.104	0.060	0.076
Average	*0.071*	*0.087*	*0.069*	*0.078*
Dimensions are inches; NWC: normalweight concrete; LWC: lightweight concrete				

The US Navy has selected high quality lightweight concrete with at least 25% replacement of portland cement by fly ash as the preferred mixture for providing durable concrete for a floating modular hybrid pier (MHP) concept. This concrete is expected to be "highly impermeable to CL ions, highly resistant to alkali silica reaction (ASR) and affordable."[44] In a related US Navy document, one of the reasons given for using lightweight concrete on the MHP project was that "Manufactured lightweight aggregates are not susceptible to detrimental alkali-silica reaction. There is no known instance of in-service distress due to alkali reaction with lightweight aggregates." In the same list of reasons for using lightweight concrete, the report indicates that lightweight concrete is "less susceptible to sulfate attack than NWC, because LWC is generally less permeable to ingress of sulfate ions."[45]

ACI Committee 213 reports that there are no documented problems with ASR and lightweight aggregates, but recommends that normalweight aggregates used in combination with lightweight aggregates in lightweight concrete should be demonstrated not to be reactive before use.[4]

Carbonation

Carbonation is an important factor that relates to the protection of steel reinforcement from corrosion that is provided by concrete. The alkalinity (high pH) of typical concrete prevents corrosion processes from occurring. When atmospheric carbon dioxide penetrates concrete and combines with the calcium hydroxide that forms as portland cement hydrates, calcium carbonate is produced, which reduces the pH of the concrete. This is the process of carbonation, which starts at the surface and may progress into the concrete. If the pH of concrete at the level of the reinforcement is reduced sufficiently, the concrete can no longer protect the steel reinforcement from corrosion.

Prevention of carbonation is most often related to w/cm or strength, but is most closely related to the permeability of the concrete. The ESCSI Reference Manual indicates that there are two main properties of concrete that resist carbonation: "High-quality, low permeability concrete will inhibit the diffusion of carbon dioxide, and concrete with high moisture content will reduce the diffusion rate to that of a gas through water rather than that of a gas through air."[6] Lightweight concrete contributes to both of these properties.

An excellent discussion of carbonation of lightweight concrete can be found in Holm and Bremner, including measurements of depth of carbonation for existing bridges and ships.[5] In that reference, it is estimated that high quality lightweight concrete with a cover greater than 40 mm (1.58 in.) will protect reinforcement from corrosion for 100 years, based on field observations of marine structures.

Skid Resistance

As concrete decks are exposed to traffic and environmental conditions, the concrete will wear, exposing the coarse aggregate. When lightweight concrete decks wear, the internal pores of the lightweight aggregate particles are exposed. The exposed pores provide excellent skid resistance which continues to be refreshed as wear continues, rather than experiencing the polishing and reduction in skid resistance that occurs with some normalweight aggregates.[3]

Coefficient of Thermal Expansion

In general, lightweight concrete has a slightly lower coefficient of thermal expansion than normalweight concrete. The resulting smaller expansion and contraction of the bridge elements reduces several structural effects such as expansion joint movements and internal stresses, which develop when thermal expansion is restrained by other structural elements as is common in bridge decks.[3,4]

Fire Resistance

While fire resistance is not generally considered to be a durability consideration for bridges, it seems that bridges have been exposed to fires more often in recent years. It is universally accepted that lightweight concrete has improved resistance to fire. This characteristic of lightweight concrete is used to great advantage in building construction where the thickness of a lightweight concrete floor slab can be reduced while maintaining the required fire rating (see Figure 7).[4]

Some natural aggregates become chemically unstable at temperatures of around 870 deg. F (500 deg. C).[45] Lightweight concrete, however, is more stable in a fire because the lightweight aggregate has already been exposed to high temperatures during its manufacturing process. Therefore, lightweight concrete tends to retain more of its strength at high temperatures when compared to normalweight concrete.

Lightweight concrete also has lower thermal conductivity, so the interior of a concrete element will take longer to reach an elevated temperature. This fact, combined with the lower coefficient of thermal expansion, will reduce the expansion of a lightweight concrete element subjected to fire, which can be an additional source of damage during a fire event. Because of the lower thermal conductivity, lightweight concrete will also keep mild and prestressed reinforcement at lower temperatures compared to normalweight concrete for the same duration of fire. This will help protect the properties of the steel during a fire event.

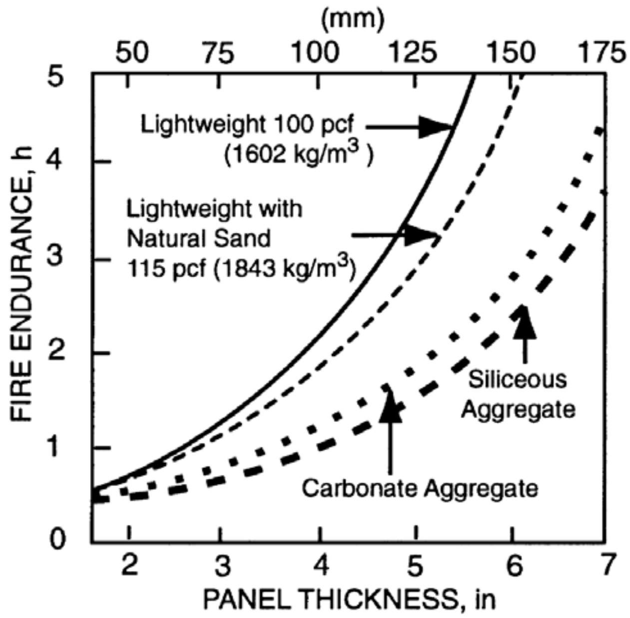


Figure 7 Fire endurance (heat transmission) of concrete slabs as a function of thickness for naturally dried specimens[4]

Fatigue Resistance

In general, the fatigue properties of lightweight concrete are not significantly different from normalweight concrete.[4] However, Gerwick states that high strength lightweight concrete has "far fewer microcracks between paste and aggregate resulting in better high cycle fatigue endurance," which is an issue for the massive offshore structures that he designed.[9] Hoff also found that "under fatigue loading, high-strength lightweight concrete performs as well as high-strength normalweight concrete and, in many instances, provides longer fatigue life."[46]

The US 19 Bridge over the Suwanee River at Fanning Springs was the first constructed in Florida with lightweight concrete. Since the bridge was using a new material and had long spans for its day, the Florida DOT tested the bridge in 1968, shortly after construction was completed, to evaluate its behavior. In 1992, after the bridge had been in service for 28 years, FDOT retested the bridge, attempting to duplicate the initial tests. The results of the two tests were then compared to determine the effects of fatigue or any other time-dependent effects that may have cause a change in behavior. After comparing the test data, the researchers concluded that "Deflection and strain data, when taken as a whole, indicate no increase in flexibility over time. When measurement uncertainty is included, most of the individual measurements may be considered as essentially the same."[10] Therefore, the testing showed that this bridge had experienced no degradation in behavior from fatigue or other effects.

SPECIFYING LIGHTWEIGHT CONCRETE

Construction specifications vary from state to state. Few states have fully implemented lightweight concrete in their standard specifications; some states have special provisions for use on bridges with lightweight concrete; many states do not have any standard specifications addressing lightweight concrete. Lightweight aggregate and any proposed lightweight concrete mixture need to meet appropriate material specifications, such as ASTM C 330,[11] to establish that the concrete has the necessary material and durability properties to be successfully used in a bridge project. Where specifications do not exist or are limited in scope, lightweight aggregate manufacturers can assist in preparing project specifications.

Generally, the only structural properties that need to be specified are density and compressive strength. Other structural properties may also be specified as required for the design, such as modulus of elasticity or splitting tensile strength. It is best to specify only material properties that are required for the design; over-specifying concrete properties will drive up the cost of the project. The designer should consult a lightweight aggregate supplier to ensure that any quantities specified other than density and compressive strength can be achieved economically using reasonable mixtures with available materials.

The density of the lightweight concrete can be specified using several different conditions (fresh, equilibrium and oven-dry). Therefore, to avoid confusion, the specifications and other contract documents must clearly indicate the designer's intent regarding the density. If the fresh density is not specified, the concrete supplier should be required to provide a fresh density that corresponds to the equilibrium density. The fresh density is required because it must be used as a basis for job site acceptance of the concrete.

Since the specified concrete density, whether fresh or equilibrium, only represents the weight of unreinforced concrete, the contract documents should state the assumed allowance for reinforcement used for computing dead loads. For heavily reinforced members, the designer should compute the actual weight of reinforcement because the usual assumption of 5 pcf may not be adequate.

Other issues must also be considered when selecting and specifying lightweight concrete for a project. A recent paper discusses the range of issues that need to be considered when preparing project specifications for lightweight concrete and gives examples of recent projects in which lightweight high performance concrete has been specified.[47]

CONCLUDING REMARKS

This paper has presented a comprehensive discussion of the durability of lightweight concrete for bridge elements. Common misconceptions have been addressed and technical information has been provided to support the position that lightweight concrete can be a durable material for building bridges. With the current emphasis on more efficient designs, more rapid construction, and longer service life for bridges, designers should consider using lightweight concrete for bridge construction.

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