Durable Concrete for Bridges

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Concrete is a durable material for bridges that can last a long time with minimal maintenance if designed and used correctly for a particular application. Concerns for safety, limited resources, and the desire to reduce lane closures or delays have prompted attention to the durability of concrete bridges worldwide. With new concrete technologies, structures can be built to last a long time. Whereas, bridges were designed previously for a service life of 50 years, this has now been extended to 75 years and more. In other countries, 100 years of service life are planned and structures are designed and built accordingly.

The durability of concrete largely depends on its ability to resist the infiltration of aggressive solutions. Concretes that are protected from the environment and that stay dry can last centuries. There are many good examples of longevity in Roman structures, such as the Pantheon, which was built around 126 A.D. and still remains intact. Today, structural applications use a combination of concrete and reinforcement for efficient load-carrying capacity, and this introduces new challenges in terms of durability. In this composite system of modern times, corrosion of the reinforcement in concrete exposed to water and aggressive solutions has become the most widely experienced distress in concrete structures.

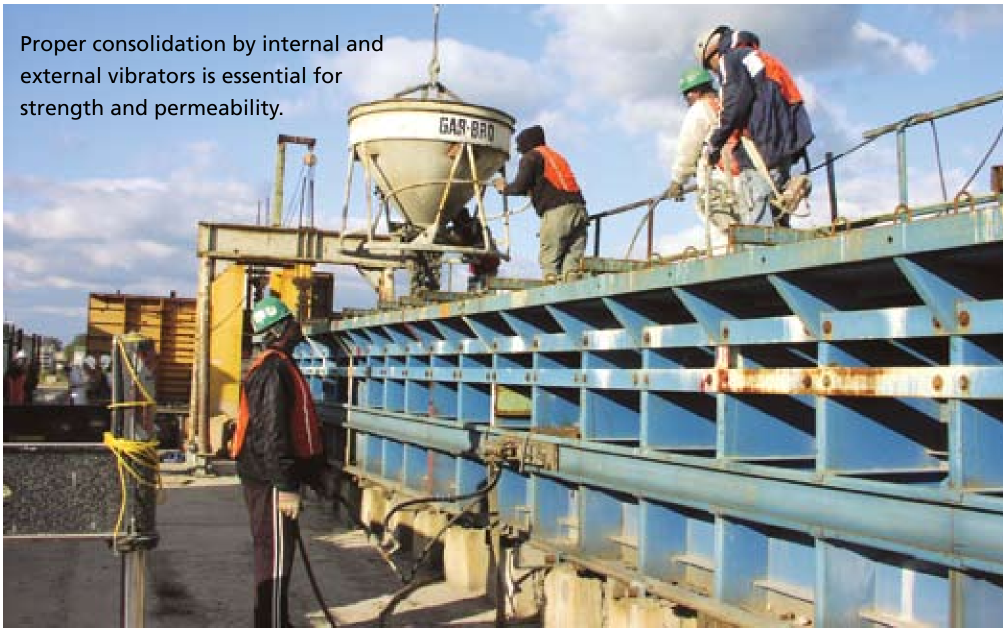
It is not uncommon for poorly executed concrete exposed outdoors to experience reinforcement corrosion, cracking, and spalling within a couple of decades. The same concrete situated indoors and away from the aggressive solutions could have lasted for centuries. Chlorides that reach the steel reinforcement accelerate the corrosion process necessitating costly repairs. Low permeability concretes can resist the penetration of chlorides and thus minimize the damage due to corrosion. In addition, low permeability concrete minimizes other environmental distresses due to cycles of freezing and thawing, alkali-silica reactivity (ASR), and sulfate attack because, in each case, water or aggressive solution entering the concrete is part of the problem. For damage due to cycles of freezing and thawing, another important factor is the proper entrainment of air voids in the concrete. However, low permeability and a proper air-void system do not always ensure durability if the concrete contains excessive cracks that facilitate the intrusion of aggressive solutions. This cracking can be due to many factors related to both environmental effects and structural loads (TR Circular E-C107, 2006).

Building durable bridge structures requires innovation and the use of available resources in an efficient manner. An ideal durable structure needs to have a low permeability concrete with a proper air-void system, no cracks, and not be subject to deleterious chemical reactions. These characteristics are discussed below in relation to design practices, material selection, construction practices, and specifications.

Design Practices

Certain design parameters can assist in achieving durable structures. Good drainage details can minimize ponding and prolonged exposure of bridge components to solutions. Leaking deck joints enable chloride solutions to penetrate onto the substructure elements such as the beam ends, pier caps, and columns causing corrosion. Jointless bridges can minimize such occurrences. Bridge decks supported by more rigid concrete beams exhibit less cracking compared to decks supported by flexible steel beams. Thicker concrete cover provides more resistance to the penetration of solutions to the level of reinforcement. Avoidance of skews on structures can aid in durability as this design feature introduces torsional stresses that lead to diagonal cracking at the corners near the abutments.

The selection of reinforcement is important as well; bars made of tough and intrinsically corrosion-resistant materials can minimize the corrosion potential (Clemena and Virmani, 2004). Bars clad with stainless steel and solid



Proper consolidation by internal and external vibrators is essential for strength and permeability.

stainless steel bars appear to resist corrosion at least 15 times longer than carbon steel bars. Low-carbon, chromium steel bars appear to be a cost-effective option for extending the service life of future concrete bridges. They cost about the same as epoxy-coated reinforcement—another alternative—and are 4.5 times more corrosion resistant than carbon steel bars.

Materials Selection

The use of pozzolans and slag, either alone or in combination, is very effective in reducing the permeability of concrete (Lane and Ozyildirim, 2000). Supplementary cementitious materials (SCM) are readily available, widely used, and extremely helpful in improving the durability of concrete. In addition to reducing the permeability, concrete with SCMs also resists chemical degradation caused by ASR and sulfate attack.

Besides the use of SCMs, a proper water-cementitious materials ratio (w/cm) is effective in achieving low permeability. A lower w/cm leads to lower permeability; however, low w/cm concretes usually have higher autogeneous shrinkage, stiffer consistency, higher cement content, less bleed water, and are more prone to cracking, which negates the concrete impermeability. Therefore, the w/cm should not be too low; a range between 0.40 and 0.45 is commonly used for bridge decks. This, in combination with minimum 28-day design strengths of 4000 psi and the use of pozzolans and slag, provides for low permeability (Ozyildirim, 1998, 1999).

Concrete that gets critically saturated can be damaged by cycles of freezing and thawing unless necessary precautions are taken. Concrete must be properly air entrained, have sound aggregates, and have the maturity to develop sufficient strength for long-lasting service (Mather, 1990). A minimum compressive strength of 4000 psi is often specified for bridge decks. Air entraining admixtures provide small, closely spaced, and uniformly distributed air voids, with a diameter less than 1 mm. The size of the air voids is indicated by the *specific surface*, which is equal to the average surface area divided by the volume of the voids. The average distance water must travel to reach a protective air void in concrete undergoing freezing is indicated by the *spacing factor*. It is generally accepted that a specific surface greater than 24 mm^2/mm^3 (600 in^2/in^3) and a spacing factor less than 0.2 mm (0.008 in) are needed for adequate protection during freezing and thawing (Whiting and Nagi, 1998).

Air void parameters in terms of total air content, spacing factor, and specific surface are affected by many factors including material properties such as water and admixture type and content, and construction practices such as pumping and consolidation (Ozyildirim, 2004). Satisfactory air-void systems indicated by the spacing factor and the specific surface can be established in the development of the mixtures and related to the total air content. Then, field quality control can be achieved through the measurement of the total air content. Too much air in the concrete should be avoided since it reduces the strength of concrete. In precast, prestressed concrete beams, the stringent air requirements used for bridge decks are not needed unless critical saturation occurs. Since these beams are under the deck and generally have low permeability concrete, they are protected from water intrusion and critical saturation is not expected.

A steady flow of concrete and no large free drops are necessary during pumping.

Cracking in bridge structures is mainly attributed to moisture loss and temperature change. Selection of materials also affects the extent of cracking. Mixtures with high water and paste content are prone to shrinkage cracks that occur over a period of time. Use of large-size aggregate and well-graded aggregates reduces the water and paste contents and minimizes shrinkage. In fresh concrete, when the rate of evaporation exceeds the rate of bleeding, plastic shrinkage occurs. The rate of evaporation can be determined using a chart. Means of reducing the evaporation rate can be established. Concrete with low bleed water, stiff consistency, and low w/cm are prone to plastic shrinkage cracking. Prevention of plastic shrinkage cracking depends on prompt and effective curing.

To reduce cracking, shrinkage should be reduced; however, cracking also depends on other factors such as restraint, modulus of elasticity, and creep. Low modulus of elasticity and high creep help to minimize cracking. All these factors should be considered in predicting the

At least 7 days of curing with wet burlap and plastic sheeting are essential for bridge decks.

cracking potential (TR Circular E-C107, 2006). The use of post-tensioning virtually eliminates the presence of cracks.

Cracking can also occur in cast-in-place bridge decks when temperature management is not used. High temperatures and high temperature differentials can cause cracking. In bridge structures, a maximum temperature differential of 22°F between the beams and the deck is recommended for at least 24 hours after concrete is placed (Babaei and Fouladgar, 1997). To minimize the potential for temperature-related cracking, the amount of portland cement should be minimized, concrete delivery temperature reduced, and pozzolans and slag included.

The desire to reduce cracking due to shrinkage has led to studies with fibers and shrinkage reducing admixtures. Use of structural fibers in large amounts has shown to reduce the severity of cracks

Fog misting can be used to reduce the evaporation rate.

in terms of length and width (Ozyildirim, 2005). In one study, an overlay with a shrinkage-reducing admixture demonstrated that the least shrinkage occurred when this admixture was used (Sprinkel and Ozyildirim, 1998). However, due to prompt and proper curing, none of the overlays in that study exhibited shrinkage cracking making this the more important factor.

Construction Practices

Proper consolidation of concrete is essential to ensure satisfactory strength and permeability. This is usually achieved through the use of internal and external vibrators. For areas that are hard to reach, in areas congested with reinforcement, and when stiff concretes are used, self-consolidating concrete (SCC) may be a solution. SCC can flow into the formwork and encapsulate the reinforcement without any mechanical consolidation. SCC can be very useful for constructing precast, prestressed concrete bulb-tee beams with many strands in the bottom flange and other structural elements with thin walls and congested reinforcement.

Handling of concrete affects the final product. Delay in placement particularly on hot days should be avoided as it can lead to stiffening of the concrete. This may cause tearing of the surface during finishing and produce a poor surface finish. Delivery of the concrete to the forms through pumping can result in loss of slump and air content. Loss of air occurs because bubbles shrink due to

Solutions for Durable Concrete

- Design bridges with close attention to parameters that affect cracking such as joints, flexibility of superstructure, and skews. Use post-tensioning to prevent the occurrence of cracks. Use noncorrosive reinforcement in areas exposed to harsh environments conducive to corrosion.
- Use pozzolans and slag to reduce the concrete permeability, to resist chemical distress, and control heat of hydration.
- Use as much aggregate as possible. This can be achieved by using the largest size aggregate possible and better grading of the aggregates. This will lead to reduced water, cementitious materials, and paste contents.
- Use air entrainment to obtain well-distributed air voids to protect concrete from cycles of freezing and thawing.
- Ensure proper consolidation. Entrapped air voids reduce strength and durability.
- Provide adequate curing. Both moisture and temperature control must be addressed. Immediate attention to moisture loss after screeding and limiting the temperature differences between the core and the surface in mass concrete and between the deck and the beams are needed.
- Specify performance parameters and consider eliminating restrictive prescriptive requirements such as the minimum cement content and maximum water-cementitious materials ratio.

pressure in the pump line, bubbles crush from the impact of the falling concrete, and bubbles expand and dissipate due to the vacuum created when concrete slides in a vertical pipe (Yingling et al. 1992). A steady flow of concrete during pumping should be provided and a large free drop in the pump line eliminated. This generally results in satisfactory freeze-thaw resistance even though the total air content may be lower than specified (Ozyildirim, 2004).

Curing is essential to ensure that the desired properties are achieved. In bridge structures, the cast-in-place deck surfaces require special attention since they have large surface area where loss of moisture is a concern. Also, the temperature in the deck as it relates to the beams is important as explained above. In mass concrete, temperature control to minimize temperature differentials needs special attention. For bridge decks, wet curing involves at least 7 days using wet burlap covered with plastic followed by the immediate application of a curing compound. The wet burlap should be placed immediately after the screeding is completed. If there is a delay, the surface should be fog misted. Concerns that prompt placement of the burlap causes marring of the surface are unfounded. There is no problem with the surface marks from the burlap itself, especially since the transverse grooves cut on hardened concrete or a tined surface make surface marks unnoticeable. However, deep indentations from a footprint or heavy object placed on the burlap may be


Heaters inside plastic enclosures can be used in cold weather.

an issue. In some states, the wet cure is extended to 10 and even to 14 days as in New York.

Additional protection is needed in cold weather conditions. Thermal blankets to retain the heat may not be enough, and external heat may be needed. For example, the deck of the first high-performance concrete structure in Virginia was placed in December, and the cold weather necessitated the use of heaters and a plastic enclosure.

Specifications

Specifications may be either prescriptive or performance based. Most current specifications are of a prescriptive type requiring a recipe of ingredients. They restrict innovation by limiting the use of many possible combinations of materials. In performance specifications, the characteristics of the mixture are specified rather than the mixture itself,


Leaking joints cause concrete deterioration and reinforcement corrosion.

Temperature control is important to prevent thermal cracking.

allowing the producer to innovate in the selection of materials and proportioning of the mixture. The contractor and the user share responsibility; the contractor is responsible for the development of the product and the user in its acceptance. Compensation can be adjusted depending on the quality of the product. For example, the Virginia Department of Transportation has developed an end-result specification, where strength and permeability are specified without any limits on the minimum cementitious materials or maximum w/cms and has been evaluating it on pilot projects.


Large foundations require special attention to temperature control.

Improper consolidation of pier concrete.

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