Contractors can evaluate the potential for thermal cracking that is caused by rapid concrete strength gain in bridge deck repairs

Predicting Thermal Cracking in Bridge Deck Repairs

By John M. Simpson and Edwin G. Burdette

The increased traffic load on interstates and major highway systems has led to ever-shorter time requirements for the completion of deck repairs. Repair contractors often must pay penalties when roadways are not open to traffic on time. When concrete bridge decks are repaired, the required rapid strength gain results in a quick and significant temperature rise in the concrete. Many DOT requirements for opening roadways to traffic with concrete as little as 18 hours old leave no possibility for gradual cooling. As a result, the newly poured concrete repairs crack.

Thermal cracking

Thermal cracking is an inevitable consequence of three mechanisms:

1. Rapid temperature gain from hydration of concrete (expansion phase)
2. Rapid cooling of the repair areas (contraction phase)
3. Restraint of concrete deck repair patches

When restrained bridge deck patches cool, tension develops. Cracking occurs when the tensile stress exceeds the tension capacity of the newly cast repair. We decided to study the early-age deck cracking that resulted from temperature changes in a recent project where such cracking occurred.

Concrete gains strength and generates heat during its hydration process, and it expands as a result. Until the concrete hardens, it can accommodate the thermal expansion without significant changes in stress. But, after the concrete hardens, changes in temperature can create stress in a restrained member. Although many factors can potentially contribute to deck cracking, no simple analytical model has been widely available for contractors to predict when early-age cracking is likely to occur in restrained slabs.

Effects of restraint

When concrete is cast, it hardens to the exact size of the form and begins to cure. Figure 1, on the next page, depicts the as-placed length of a typical concrete patch. When the concrete cures and reaches the maximum temperature rise due to hydration, it has hardened and then begins to cool as it loses heat to the atmosphere and the

Above: A typical restrained deck repair patch has cracked and is marked for replacement. Left: The construction crew places a repair patch on a bridge deck.

surrounding structure. If the newly poured concrete is not restrained, it will shorten as it cools (Fig. 2).

But if the concrete patch is restrained, tensile stresses develop as the cooling concrete tries to shorten. This restraint may be caused by stiff supports, by reinforcing bars that tie the repair area or member to the structure, by beams or stringers, or by structural connections to other parts of the structure (Fig. 3).

If, at any age, the net tensile stress in the member exceeds the tensile strength of the concrete (f_t), a crack or cracks will develop. Thermal cracking occurs in structures through the process by which restrained, early-age concrete develops cracks due to cooling (Fig. 4). Tensile stresses in the member can be reduced by creep (Fig. 5).

Case study

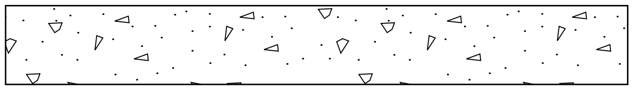
For the contractor, the value of an accurate model to evaluate the potential for thermal cracking is best illustrated by a case study from a recent bridge deck repair project. This job included repairs to bridge approach slabs and concrete paving.

The new concrete patches were bonded to the remainder of the bridge deck by reinforcing steel, which restrained the slabs. The concrete specified for the repairs to the pavement and approach slabs was very similar—in some cases, identical—to that used for the bridge deck repairs. Unlike the deck repairs, however, the concrete pavement and approach slabs were designed with expansion and contraction joints, thereby eliminating the restraint affecting the bridge deck repairs.

The project specification required that the concrete used for the bridge deck repairs contain a minimum of 714 pounds of cement per cubic yard and produce a compressive strength of 3000 psi after 18 hours. The contract also required that all repair work be performed between 7 p.m. Friday and 1 p.m. Sunday. Lastly, the contract included provisions for significant liquidated damages for the contractor should traffic lanes not be opened within the time specified. Pours for the project initially occurred in March, April, and May 1999.

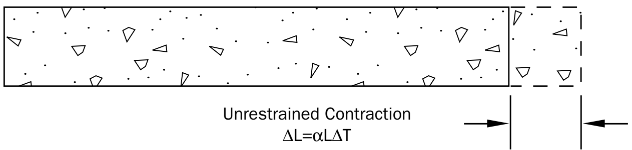
The initial design mix approved by the owner for use on this project contained 900 pounds of cement per cubic yard. During the first weekend of deck repair operations, air temperatures were about 35° F, and the test cylinders and the deck repair areas were insulated. However, the compressive strength of the test cylinders was only 520 psi after 24 hours. Because of the low cylinder breaks, the opening of two lanes of the roadway was delayed approximately 3 hours for a total contractor penalty of $15,000. During the second weekend, air temperatures remained cold and the insulated test cylinders were able to attain a compressive strength of only 2200 psi at 24 hours.

Figure 1



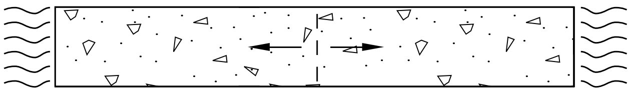
Original Length, L

Figure 2



Unrestrained Contraction
$\Delta L = \alpha L \Delta T$
If allowed to cool without restraint,
the member exhibits contraction (ΔL), but no stress.

Figure 3

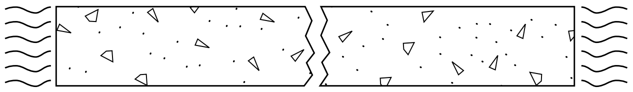


Restrained Contraction Develops Tensile Stresses, σ

$$\text{Strain, } \epsilon = \frac{\Delta L}{L} = \frac{\alpha \Delta T L}{L} = \frac{\sigma}{E}$$

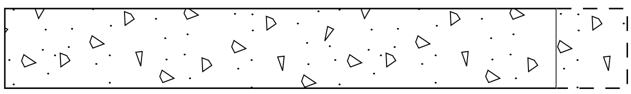
$$\text{Stress, } \sigma = E\alpha\Delta T$$

Figure 4



If net tensile stress, σ, is greater than
concrete tensile strength, f_t, cracks occur.

Figure 5



If long term cooling occurs *and* net tensile stress does not exceed
concrete tensile strength, tensile creep occurs in concrete and
produces a reduction in tensile stress.

From the third week forward, air temperatures were higher and the compressive strengths of the test cylinders were greater than the required strength. During most of this period, the concrete patches were insulated to accelerate strength development. The 24-hour concrete compressive strength test values for the deck repair operation averaged 5780 psi, and the 28-day strengths averaged 7711 psi. In May 1999, the bridge owners noticed significant cracking in bridge deck patches on two of the bridge sites. Project records indicate that these patches, placed in April, had a 24-hour concrete strength of 7049 psi. The cracked patches were removed and repoured in June using a bagged deck repair material from the owner's list of prequalified products. This material was used in order to minimize the repair time and facilitate completion of the project.

For the next year and a half, the bridge deck slab repairs continued to fail due to cracking. In May, after the first cracking problems were observed, the concrete repair contractor recommended that a revised concrete mix be formulated for repairing the failed deck repairs. It was suggested that the failure of the deck patches was, in part, due to drying shrinkage and that using less cement would thus reduce the potential for drying shrinkage. Although a newly formulated mix was approved using 714 pounds of cement per cubic yard, problems with cracking of the deck patches continued to occur, and the replacement of additional bridge deck slab repair areas continued to be required. During June, work also began on removing and replacing the deteriorated concrete paving, and, in September, replacement of the damaged and cracked approach slabs started. Although the concrete paving and bridge approach slabs were placed under similar weather conditions, used a similar or identical mix, and cured in the same manner as the deck repairs, they failed to exhibit a single instance of cracking. At one bridge site, both an approach slab and deck repairs were placed from the same load of concrete and cured identically. The restrained deck repair areas cracked and required replacement after approximately 5 months in service, but the unrestrained bridge approach slab remains in service today.

The patching crew is finishing a repair patch. By using the results of this study, contractors can reasonably predict the thermal cracking potential of deck repairs.

Theoretical Model

Investigating the temperature change that will lead to cracks in a restrained concrete member is best illustrated by an example. A typical 3000-psi concrete specimen with limestone aggregate will have the following properties:

- The modulus of elasticity of 3000-psi concrete (E_c) equals 3,122,019 psi, according to equations in ACI 318.
- Concrete tensile strength, (f_t) is defined by ACI 224.2R-92 as 0.09 times the concrete compressive strength, and therefore equals 270 psi.
- The coefficient of thermal expansion (α) for hardened concrete is a constant that may vary from 4 to 9 x 10^{-6} inches/inch/°F; a typical value for limestone aggregate is 4 x 10^{-6} inches/inch/°F.

The change in length of an unrestrained member (ΔL) due to temperature changes is equal to the length of the member times the change in temperature times the coefficient of thermal expansion:

$$\Delta L = \alpha \times \Delta T \times L$$

The compressive or tensile strain (ε) in a member is the change in length (ΔL) divided by the original length:

$$\varepsilon = \Delta L / L = \alpha \times \Delta T$$

The compressive strain also equals the stress in the member (σ) divided by the modulus of elasticity of the material:.

$$\varepsilon = \sigma / E_c$$

When a restrained concrete member undergoes a reduction in temperature, there is an increase in tensile stress. If this increased tensile stress exceeds the tensile strength of the concrete member, cracking will result. To determine the change in temperature that will create tensile stress that exceeds the tensile strength of the member, set the stress equal to the tensile strength:

$\varepsilon = \sigma / E_c = f_t / E_c = 270 \text{ psi} / 3{,}122{,}019 \text{ psi} = 0.0000864825$ inches/inch

and since $\varepsilon = \alpha \times \Delta T$ then $\Delta T = \varepsilon / \alpha$

and therefore the temperature change that will cause the member to crack is:

$\Delta T = 0.0000864825 / 0.000004 = 21.6°$ F

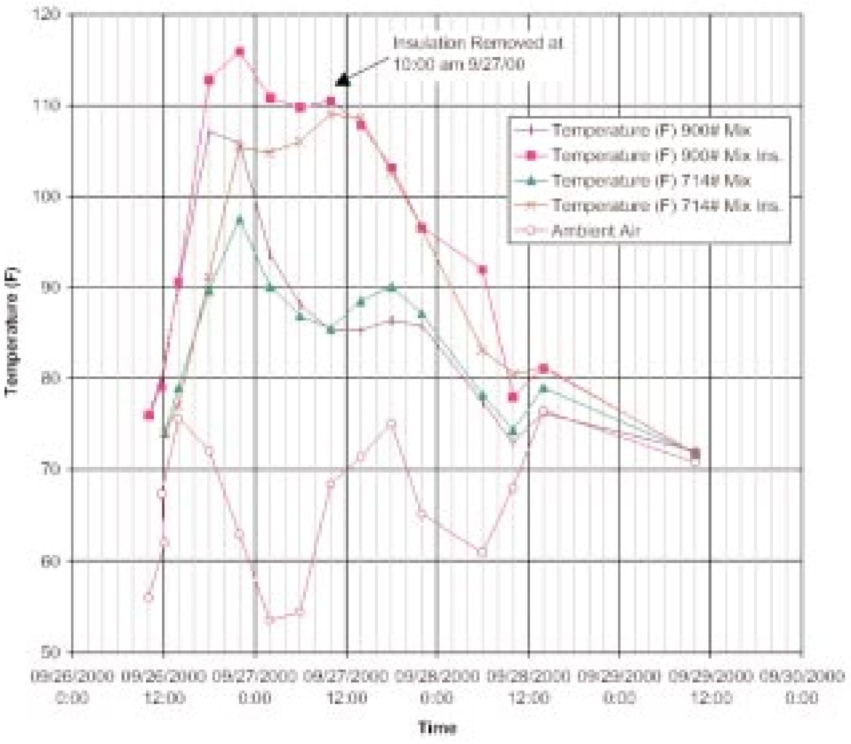
We therefore conclude that a temperature decrease of about 22° F in a restrained member of 3000-psi concrete is likely to produce tensile stresses that exceed the tensile strength of the member, causing the member to crack.

Using this method of analysis, we can compute values of temperature change that will cause cracking for other strengths of concrete, as shown below.

Temperature changes that will cause 3000-psi concrete to crack

f'_c (psi)	E_c (psi) ACI 318	$c = f_t / f'_c$ ACI 224.2R	$f_t = c \times f'_c$ (psi)	$\varepsilon = f_t / E_c$ (inch/inch)	$\Delta T = \varepsilon / \alpha$ °F*
2000	2549117	0.1	200	0.0000784585	19.6
3000	3122018	0.09	270	0.0000864825	21.6
4000	3604996	0.09	360	0.0000998614	25
5000	4030508	0.08	400	0.0000992431	25
6000	4415201	0.08	480	0.000108715	27

*Based on a coefficient of thermal expansion of 4 x 10^{-6} inches/inch/° F



Concrete test blocks—temperature vs. time

Experimental study

Following the cracking failure of additional bridge deck repairs, in September 2000 a study was conducted to determine the temperature change in the concrete mixes used in the concrete repairs. Four concrete test blocks were cast for this study using the approved project design mixes. Each block measured approximately 4 feet square and approximately 1 foot thick. Two of the blocks were cast using the mix containing 714 pounds of cement per yard, and two test blocks were cast using the mix containing 900 pounds per cubic yard. Of each mix, one test block was insulated and one was not. A thermocouple was installed in the middle of each test block to record the internal temperature, and results of the temperature of the air and the blocks were recorded for several days (see the graph to the left).

Although one could argue that the results obtained from the test blocks are not representative of every concrete pour on the project, it is certainly reasonable to conclude that data are representative of a significant portion of the concrete pours and weather conditions. The maximum temperature differential for each test block can be calculated, and the model (see theoretical model, p. 70) can predict reasonable conclusions regarding cracking potential in restrained conditions (Table 1).

The actual behavior of the deck repair patches verifies the data in Table 1. The restrained concrete deck repair areas poured with a mix using 900 pounds of cement per cubic yard exhibited significantly more problems with cracking and delamination than did the subsequent deck repair areas using 714 pounds of cement. Next, deck repair patches that were insulated to accelerate the strength development process likewise displayed greater cracking and delamination problems than did the uninsulated deck repair patches.

Conclusions

Thermal cracking of newly cast concrete cannot take place without restraint and significant cooling. Whether thermal cracking is likely to occur in restrained concrete members with a temperature drop of as little as 22° F or higher is usually not significant. What is significant is the contractor's ability to recognize the potential for thermal cracking before concrete placement occurs and thereby have an opportunity to take measures necessary to prevent it. Methods for preventing cracking are provided by ACI (ACI 224, "Cracking"). If contractors have a reasonably accurate value for the coefficient of thermal expansion for the concrete mix specified, the method presented here can predict the potential for thermal cracking. ■

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Table 1. Thermal cracking potential in concrete test blocks

Concrete in Test Block Mix (pounds)	Maximum Temperature ° F	Minimum Temperature ° F	Temperature Differential, ΔT ° F	Thermal Cracking Potential
900 (insulated)	115.9	71.8	44.1	Highly Probable
900 (uninsulated)	107.1	72.1	35	Highly Probable
714 (insulated)	109	71.7	37.3	Highly Probable
741 (uninsulated)	97.5	71.8	25.7	Likely