STRESSES CAUSED IN CONCRETE PAVEMENT BY SUDDEN TEMPERATURE CHANGE

R. K. Ghosh, Central Road Research Institute, New Delhi

ABRIDGMENT

This paper discusses the effect of a sudden increase or decrease in the top surface temperature of a concrete pavement slab, due to, for example, the jet blast from aircraft on airfield pavements, the action of deicing salts for removal of snow or ice from a pavement in snowbound areas, and the stresses developed because of these. Methods for theoretical determination of temperature gradients in the slab and calculation of stresses caused thereby are suggested. To support the theory, some flexural strength test results on beam specimens subjected to sudden change of temperature at the top are also reported on.

•THE effect of sudden temperature change on concrete pavements has not received the attention deserved. Its significance becomes obvious, however, if one considers the sudden high-temperature change in the order of 150 C that occurs on airfield pavement slabs under jet blast of an aircraft with inclined jet engines during landing or takeoff or during test runs of these engines. A case of sudden cooling of pavement slabs, on the other hand, is encountered when deicing salts are applied on their frosted surface. The negative temperature change in such cases could be as much as 15 C. Sudden temperature change, though less severe, may also occur in pavement, when in summer after a very hot day there is a sudden rainstorm.

THEORETICAL DETERMINATION OF THERMAL GRADIENTS

Sudden temperature change inducing thermal gradient in the slab may be caused either through convection, when the change is brought about all at once as in the case of hot blast from a jet aircraft, or through radiation, when the change is effected rather gradually as in the case of sudden weather change.

If the surface temperature changes suddenly from θ_A to θ_0, then in case of semi-infinite solid medium, the temperature θ_z at any instant t on a plane at a depth z below the top surface may be calculated from the following Fourier equation (1, 2):

$$\theta_z = \theta_0 + (\theta_A - \theta_0)\, f_1\left(\frac{z}{2\sqrt{at}}\right) \tag{1}$$

where f_1 = Gauss's error integral (Figure 1) and a = thermal diffusivity of concrete. Equation 1 may be used for finite thickness d of pavement slabs provided $d^2/4$ at > 1.44. Under an initial steady-state condition, $\theta_z = \theta_A$, when $f_1 (z/2\sqrt{at}) = 1$ and (from Figure 1) $z/2\sqrt{at} = 2$ or $t = z^2/16a$, and when the slab thickness d is divided into r number of equal parts, we get

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$$t_z = d/r;\ t_z = 2d/r;\ t_z = 3d/r;\ \ldots\ t_z = d = 1;\ \ldots\ (r - 2)^2;\ (r - 1)^2;\ r^2 \qquad (2)$$

The process of heating or cooling of a pavement surface due to a sudden weather change like subjugation to or shutting off from solar radiation is rather gradual. The rate of temperature rise of a surface through radiation depends on its absorption index, which in turn is related to the radiation wave length. When the initial steady-state temperature of the slab and the change in top surface temperature with time are known, the time-dependent thermal gradients may be calculated by applying Schmidt's finite difference method (3), in that the slab thickness d is divided in equal parts of Δx each and the finite time interval Δt is so selected that $\Delta t = \Delta x^2/2a$. The changed temperature at the m th interval of depth after the n th interval of time may then be calculated by averaging the temperatures after the (n-1) th interval of time at (m+1) th and (m-1) th intervals of depth, such as, for example,

$$\theta_{3\Delta t,\,2\Delta x} = \left(\theta_{2\Delta t,\,3\Delta x} + \theta_{2\Delta t,\,\Delta x}\right)^{1/2} \qquad (3)$$

where m = 2 and n = 3. Near the bottom of a slab of finite thickness, the temperature at any instant cannot be found by this method, but from the following heat-transference equation (2):

$$\theta_{p\Delta t,\,d} = \frac{\alpha_a \cdot \Delta_x \cdot \theta_A + \lambda \cdot \theta_{p\Delta t,\,(d - \Delta x)}}{\lambda + \alpha_a \cdot \Delta_x} \qquad (4)$$

where

$\theta_{p\Delta t}$ and $\theta_{p\Delta t,\,(d - \Delta x)}$ = the temperatures after the p th interval of time at the bottom surface and at a distance of Δ_x from the bottom surface respectively,
θ_A = the initial steady-state temperature, and
α_a and λ = the coefficients of heat transference and thermal conductivity respectively.

CALCULATION OF STRESSES

A sudden change of temperature at the top surface of a slab causes thermal gradients that in turn induce internal stresses. When the temperature rises, compression is induced near the top and bottom of the slab and tension occurs in between. A sudden cooling, on the other hand, causes tension at the top and bottom of the slab and compression in between. In the former case, if the temperature rise is high, as is the case with hot blast from inclined jets, fine tensile cracks may be formed in the central region of the slab, unless the flexural strength of the material is adequate. These cracks may eventually lead to separation of layers and their subsequent fragmentation. The magnitude of stresses developed may be calculated from the following equation (3):

$$\sigma_z = \frac{E \cdot \alpha}{1 - \mu}\left[\frac{1}{d} \cdot \int_{-d/2}^{+d/2} \theta \cdot dz + \frac{12z}{d^3} \cdot \int_{-d/2}^{+d/2} \theta \cdot z \cdot dz\right] \qquad (5)$$

where

σ_z = stress at any plane at a distance z from the neutral plane,
θ = temperature of the plane when determined in respect to the prevailing bottom surface temperature of the slab,
E = elastic modulus of concrete,
α = coefficient of thermal expansion of concrete,
μ = Poisson's ratio of concrete, and
d = slab thickness.

LABORATORY TESTS TO CONFIRM THEORY

Certain laboratory tests conducted (2) showed that concrete beams when suddenly cooled or heated at the top surface exhibited respectively effective reduction or increase in their flexural strength. Sudden cooling was effected by pouring melted ice mixed with common salt in a container (having a thin polyethylene sheet bottom) placed directly on top of the 2.35 by 2.35 by 12-in. (6 by 6 by 30-cm) beam. A number of concrete beams were tested after different periods of cooling. The top surface temperature of the beams was between 19 and 20 C initially. The cooling was rapid, and the top surface temperature fell down to 6.0 C after 2 min. The maximum effective reduction (18.3 percent) in flexural strength occurred after about 2 min of cooling. Sudden increase in the top surface temperature was realized by letting in hot water (70 C) from a thermostat into the container. After 2 and 3 min of heating, the top surface temperature increased from about 27 to 50.0 and 54.5 C respectively. The maximum effective increase (21.2 percent) in flexural strength occurred after about 2 min. Temperature gradients were recorded with thermocouples in both the series of tests. The test results are shown in Figure 2.

Based on the values of the time-dependent thermal gradients, the theoretical values of internal stress developed at the bottom surface of the beams were calculated from equation 5. These have also been plotted in Figure 2 for comparison with test results. Figure 2 confirms that sudden temperature change at the top surface of beams induces internal stresses resulting in effective alteration of standard flexural strength of the beams determined under the zero stress condition. The variation between the experimental and theoretical values may be attributed to the thermal loss, inaccuracies in temperature measurements and assumption of thermal and elastic constants, and material, process, and testing variances.

STRESSES DEVELOPED IN A SLAB UNDER JET BLAST

In my tests on a concrete airfield with a jet blast from a Gnat aircraft (jet engine inclination 20 deg) the maximum 14-in. (36-cm) slab surface temperature reached almost instantly (15 to 20 sec) was in the range of 150 to 170 C. Based on θ_A = 30 C, θ_0 = 150 C, and a = 0.0323 ft^2/hour (0.0030 m^2/hour), the thermal gradients were determined from equations 1 and 2. The stresses induced in the pavement after different periods of jet application were then calculated by using equation 5 for $E \cdot \alpha/(1 - \mu)$ = 42.7 psi/deg C (294 kPa/deg C). The results shown in Figure 3 indicate that the plane about 2.35 in. (6 cm) below the top surface would be subjected to very high tensile stress of 589 psi (4061 kPa) after about $2\frac{1}{2}$ min of jet blast. Even after about $\frac{1}{3}$ min, the tensile stress at a plane 1.57 in. (4 cm) below the surface would be as high as 320 psi (2206 kPa). These tensile stresses can, therefore, cause deterioration inside the slab, unless concrete flexural strength is adequate.

SUMMARY

Methods have been suggested for theoretical determination of thermal gradients and

Figure 1. Gauss's error integral.

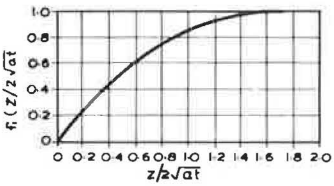
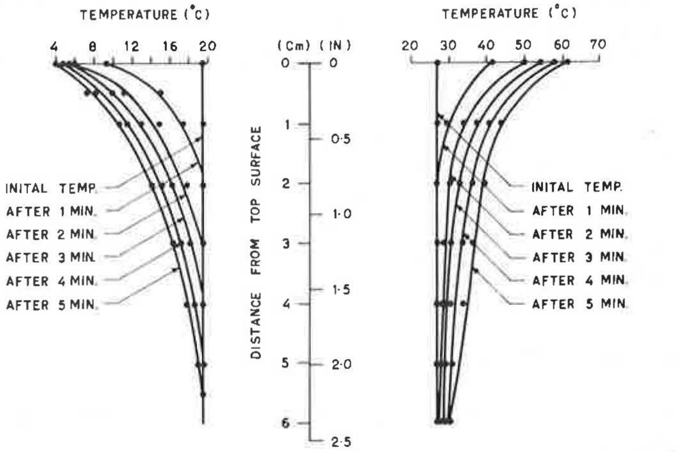
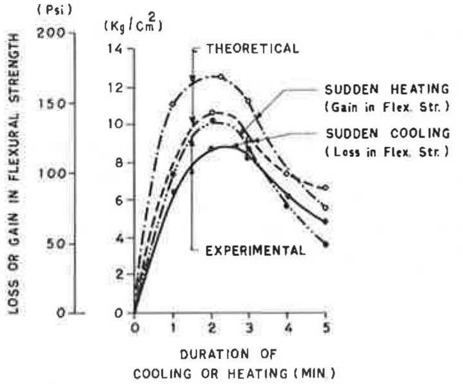


Figure 2. Thermal gradients and loss or gain in flexural strength caused in beams under effect of sudden cooling or heating of top surface.

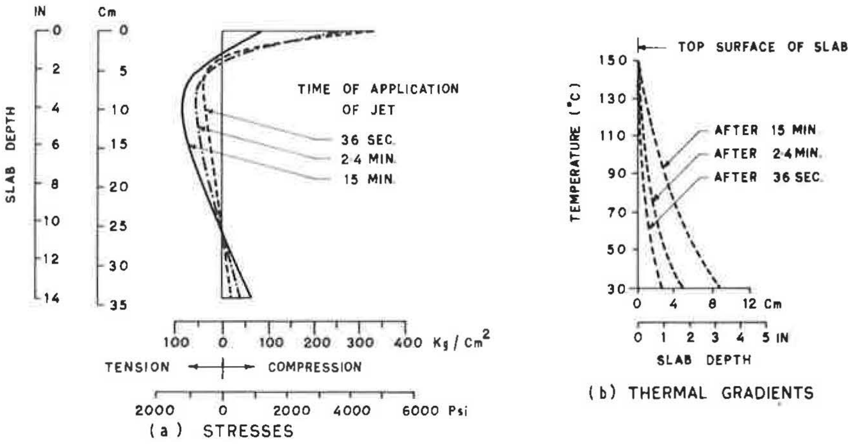


(a) THERMAL GRADIENTS (Cooling) (b) THERMAL GRADIENTS (Heating)



(c) LOSS OR GAIN IN FLEX. STR.

Figure 3. Thermal gradients and stresses caused in paving slab under effect of sudden temperature change from 30 to 150 C at top surface.



(b) THERMAL GRADIENTS

(a) STRESSES

internal stresses caused in a concrete pavement by sudden temperature change at the top surface, encountered, for example, under the action of jet blast or deicing salts. Although sudden temperature rise causes tensile stress in the interior and compressive stress at the top and bottom of the pavement slab, the latter resulting in apparent gain in flexural strength of concrete, a sudden temperature reduction induces compressive stress in the interior and tensile stress at the top and bottom of the slab, the latter causing apparent loss in flexural strength.

The findings of the experiments conducted on concrete beams subjected to sudden heating or cooling confirm the validity of the theoretical analysis suggested. In a 14-in.-thick (36-cm) concrete airfield pavement, a 20-deg inclined jet of an aircraft may induce internal tensile stresses of 320 psi (2206 kPa) at 1.57 in. (4 cm) below the surface and 589 psi (4061 kPa) at 2.35 in. (6 cm) below the surface after about ½ min and 2½ min of jet blast respectively. The effect of deicing salt causing sudden cooling of the top surface, though not very severe, may result in effective reduction of flexural strength by about 70 psi (483 kPa) in a 14-in.-thick (36-cm) concrete slab. The value will be higher for thinner slabs.

ACKNOWLEDGMENT

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REFERENCES

1. Grober, Erk, and Grigull. Principles of Heat Transference. Springer Verlag, Berlin, 1955, pp. 82-83.
2. R. K. Ghosh. Influence of Temperature on the Stress Conditions of Concrete Pavements. Technical Univ. of Dresden, PhD thesis, 1960, pp. 41-44, 61.
3. R. K. Ghosh. Action of Temperature on Concrete Roads. Schriftenreine Ingenieurwesen Theoretisch. Deutsche Bauakademie, Berlin, Grundlagen 411.013, 1961, pp. 71, 101-103.

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