Figure 8. Pulverization by using a heavy duty Hammermill pulverizer.

Figure 9. Pulverization by using a pulvimixer.

needed with this equipment. A production rate of about 610 m (2000 ft) of two lanes/d was obtained. Figure 8 shows this equipment in operation.

Highway 17

Highway 17, near Thunder Bay, Ontario, is 8.4 km (5.2 miles) long. This pavement, about 18 years old, showed the following pavement conditions prior to pulverization: (a) fair rideability that became very rough and uncomfortable during the spring, (b) transverse cracking with 0.6 to 3.0-m (2 to 10-ft) random spacing, and (c) severe lipping.

The pavement, 7.3 m (24 ft) wide and 7.6 cm (3 in) thick, was pulverized by a pulvimixer. It was not necessary to rip the pavement because this equipment was used. One to two passes of the pulvimixer were required to pulverize the material to a minus 2.54-cm (1-in) size. A production rate of about 366 m (1200 ft) of 2 lanes/d was obtained. Figure 9 shows this equipment in operation.

CONCLUSIONS

The Trout Creek experimental road has provided valuable information on the performance of various alternatives to conventional resurfacing for rehabilitating thermally cracked asphalt pavements. Of the seven alternatives tried, the economic analysis and other implications indicate that

1. Pulverizing the existing pavement surface and using it as a base for resurfacing is the most viable alternative;
2. Removing and replacing the existing pavement surface is also a viable alternative, if it is environmentally acceptable;
3. Placing interlayers between the old pavement and the resurfacing such as crushed stone screenings, different thicknesses of granular material, and open-graded binder course is not cost-effective; and
4. Enriching the pulverized material and using it as a base for resurfacing is not a cost-effective alternative.

The three full-scale contracts undertaken to date have demonstrated that construction difficulties associated with the pulverization operation can be resolved.

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Analytical Modeling and Field Verification of Thermal Stresses in Overlay

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This paper describes analytical and graphical procedures for computing thermal stresses at joint locations in pavement overlays. Equations and nomographs are used to calculate stresses caused by horizontal and vertical movements of slabs. Both average temperature drop and maximum temperature differential expected in pavement slabs are determined from temperature distribution noted at time of overlay construction. Stresses caused by slab movement are calculated for different overlays. The results confirm that these stresses often exceed the maximum stresses in asphalt-concrete overlays; therefore, reflective cracking occurs when asphalt concrete is laid over jointed pavements.

The movement of pavement slabs under flexible overlays has been well known for its damaging effect on overlays. This effect is usually manifested by the phenomenon of reflective cracking. The slab movements induced by temperature are usually considered from two points of view: One arises from slow changes in average temperature of pavement, and the second arises from quick changes in average temperature of pavement, i.e., a cool night to a hot day and vice versa. In the first case, pavement slabs contract and expand because of a change in the average temperature of pavement. In the second case, pavement slabs curl and warp because of a definite temperature gradient in pavement.

In relation with a current research project at the Ohio State University, actual field data on movements at joint locations in joint-reinforced concrete pavement (JRCP) were collected under different temperature distributions. The data were fitted to theoretical models to study the induced thermal stresses in the overlay at the joint locations.

FIELD INSTRUMENTATION

Instruments for measuring temperature distribution and vertical and horizontal movement of the slabs were placed at joint locations and in the middle of pavement slabs. Temperature sensors measured temperature distribution, and special strain gauges detected and measured slab movement. Figure 1 shows a schematic view of the field instrumentation. The field study was conducted on slabs of various lengths and thicknesses and at different times and locations. Some of the slabs were newly constructed and others were overlaid with asphalt-concrete layers. The overlaid slab data were taken before and after the occurrence of reflective cracking.

HORIZONTAL MOVEMENT OF SLABS

The previously mentioned field set-up was used to study the horizontal movement of the slabs. The average slab temperature, measured by the temperature sensors, was plotted against the distance between the strain gauges embedded at both sides of the joints, and a regression analysis was made. A typical curve of temperature-joint horizontal movement is shown in Figure 2. Comparisons were made between different slab curves similar to the one shown in Figure 2. The following results were concluded.

1. The diagram of the friction forces between the concrete slabs and the subgrade is triangular. (This assumption is also made for calculating the minimum steel required in the pavement.)
2. When the slabs were subjected to the same temperature changes, the use of relatively thin overlays [between 0 and 9 cm (0 and 4 in)] showed no significant effect on the movement of the underlying slabs.
3. When reflective cracking occurred, the horizontal movements of the underlying slabs followed the same temperature-movement curve as the before cracking curve.

It was concluded that the horizontal movement of the overlaid slabs at the joint location could be predicted by using the following formula:

$$\Delta_h = (\alpha \Delta T_h L) - (\gamma_c h_c + \gamma_{ac} h_{ac}) f (L^2/2)(1/A_c E_c) \qquad (1)$$

where

Δ_h = horizontal movement at joint location,
α = temperature coefficient,
ΔT_h = average temperature drops,
L = length of slabs,
γ_c, γ_{ac} = unit weight of concrete and asphalt concrete,
f = coefficient of friction between subgrade and slab,
A_c = unit cross section of slab, and
E_c = modulus of elasticity of concrete.

EFFECT OF HORIZONTAL MOVEMENT AT JOINT LOCATION ON FLEXIBLE OVERLAYS

The effects of the horizontal movement at joint location on overlays was studied by using the finite element method for a two-dimensional structural analysis. Figure 3 shows a sample of the mesh used for this analysis. The model consists of two concrete slabs with an asphalt overlay on the top and a thin asphalt-tack coat between the slabs and the overlay. The thicknesses and moduli of elasticity for both the asphalt-concrete overlays and concrete slabs in addition to the joint width were made variable. A horizontal movement was induced into the slab at the joint location and the resulting overlay stresses were studied. From this study it was concluded that

1. For a given movement at the joint the overlay stresses are not affected by either the modulus of elasticity of the concrete or by the slab thickness;
2. There is a one-to-one relation between the induced movement at the joint and the stresses in the overlay; and
3. When the induced movement at the joint exceeds 0.000 50 cm (0.000 20 in), the shearing stresses between the slabs and the overlay would exceed the allowable bond strength between the pavement and overlay, and this condition could result in the sliding of the overlay on the top of the slab.

The results of field observations and analytical simulation of finite element were used to construct the nomographs shown in Figures 4 and 5, which facilitated the computation of stresses in the overlay.

VERTICAL MOVEMENT OF SLABS

The model of slabs on elastic foundation was used to fit the vertical movement of slabs to field data. A computer program was developed at the Ohio State University, Columbus, to calculate the curling and warping shape of slabs under temperature differential (ΔT_v) conditions. The interrelation between deflected shape of pavement and temperature differential is written as follows:

$$[(d^4w/dx^4) + (2d^4w/dx^2dy^2) + (d^4w/dy^4)] = \{(q/D) - [K(w - c)/D]\} \qquad (2)$$

where

w = plate deflection in x, y plane,
q = load,
$D = [E_c h_c^3/12(1 - \nu^2)]$ = plate stiffness,
E_c = concrete modulus of elasticity,
h_c = concrete slab thickness,
ν = concrete Poisson ratio,
$c = (\alpha \Delta t d^2/2h_c)$ = curling,
α = temperature coefficient of concrete,
Δt = temperature differential in slabs, and
d = distance from center of the slab.

The program is generalized to consider any pavement geometry, and, at the same time, it takes the partial subgrade contact condition into consideration by assuming zero subgrade reaction at the points where temperature curling is greater than slab deflections.

The program results were checked against the vertical movement of the slab edges obtained from the field data. The case of partial contact gave a better confirmation with the field data than the case that used an assumption of full contact (Figure 6). Comparison of different field results on different slabs showed that the asphalt-concrete overlay does not significantly affect the vertical movement of the slab.

EFFECT OF VERTICAL MOVEMENT AT JOINT LOCATIONS ON FLEXIBLE OVERLAYS

The vertical curling and warping in concrete slabs causes bending-type stresses in the overlay at the joint location (Figure 7). If the curling or warping slope in the pavement is known, the radius of curvature of the overlay at the joint location can be calculated as follows:

$$R = (j/2\theta) \tag{3}$$

from which the maximum stress on the overlay could be found as follows:

$$\sigma = (E_{ov}H_{ov}/j)\theta \tag{4}$$

where

R = radius of curvature of the overlay,
j = joint width,
θ = edge slope of the slab,

Figure 1. Schematic view of pavement instrumentation.

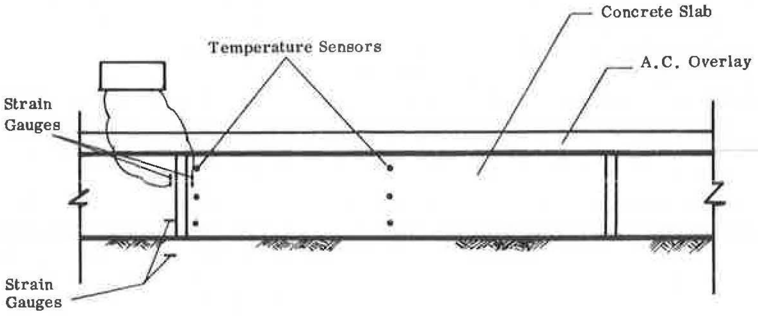


Figure 2. Horizontal movement because of temperature change.

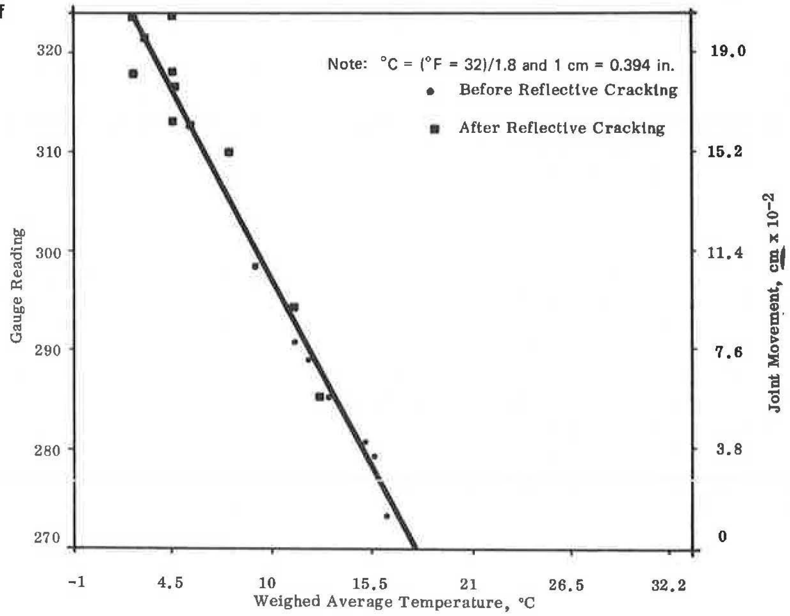


Figure 3. Finite element mesh to study stress in overlay.

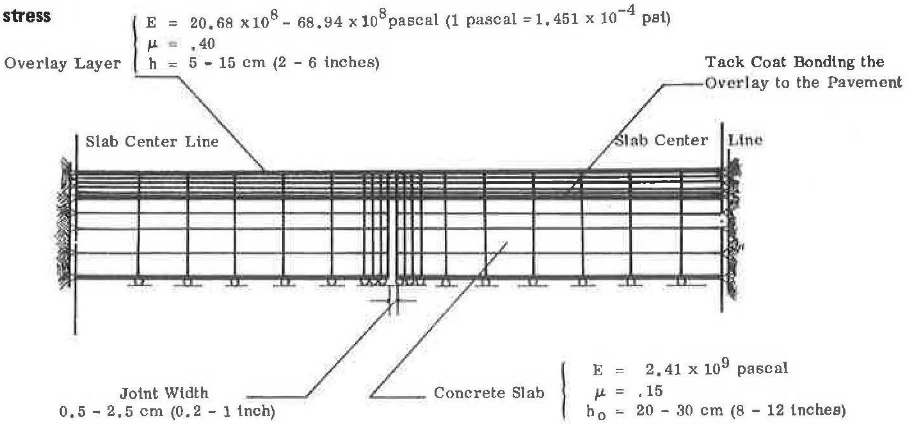


Figure 4. Top fiber stress in overlay because of joint movement in a joint-reinforced concrete pavement.

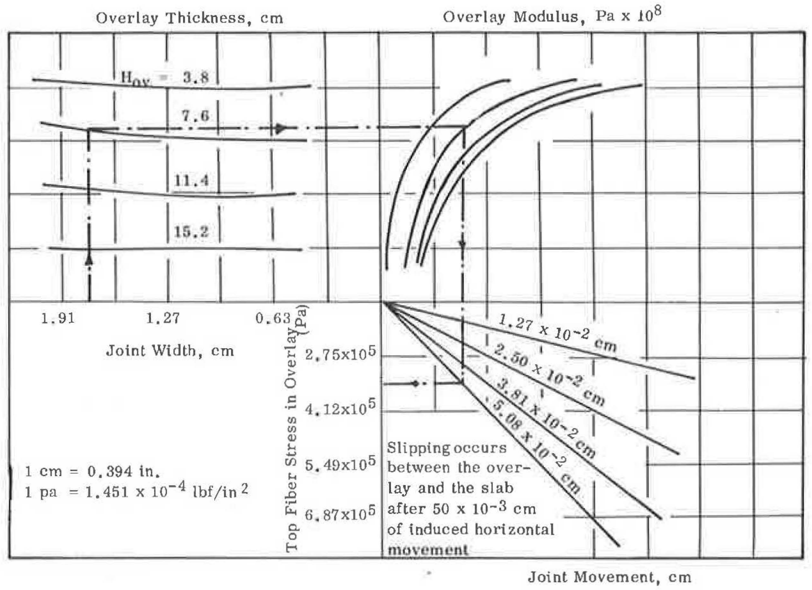


Figure 5. Bottom fiber stress in overlay because of joint movement in a joint-reinforced concrete pavement.

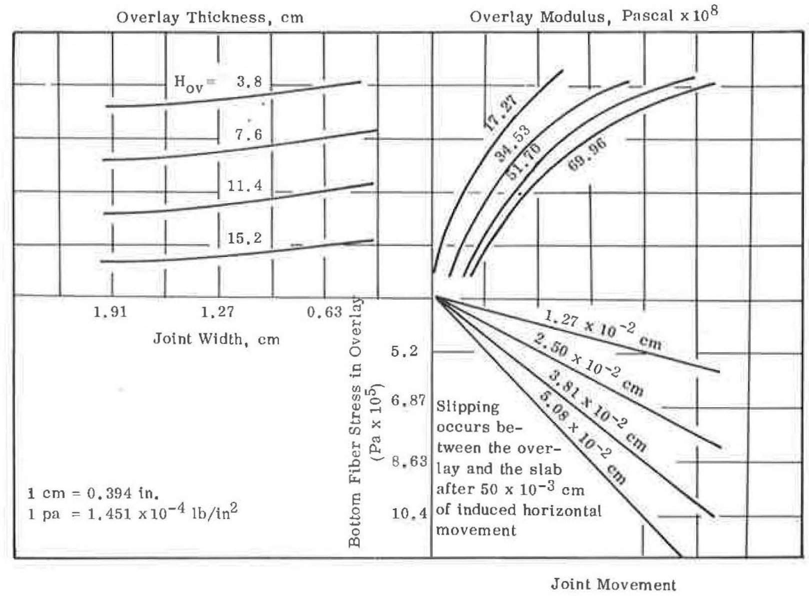
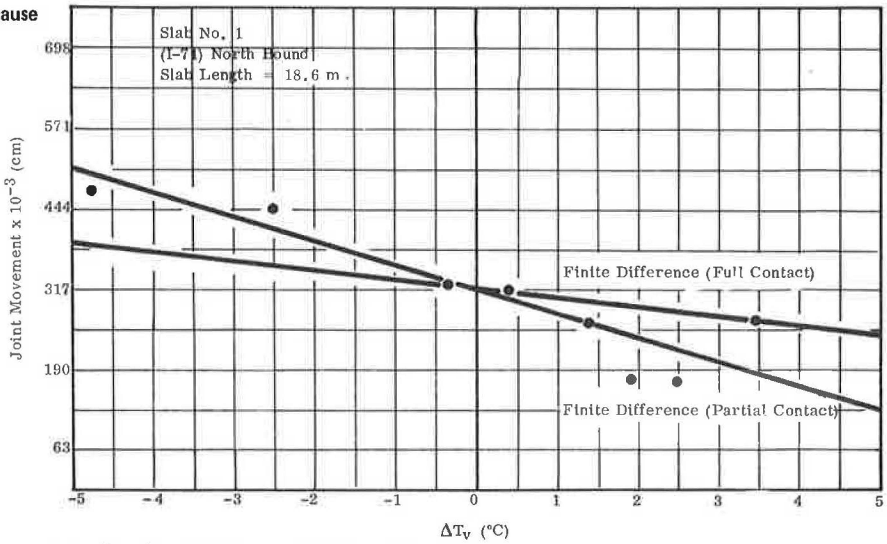


Figure 6. Vertical movement of joint because of temperature differential.



Note: °C = (°F = 32)/1.8, 1 cm = 0.394 in, and 1 m = 3.3 ft.

Figure 7. Bending of overlay by vertical movement of joint.

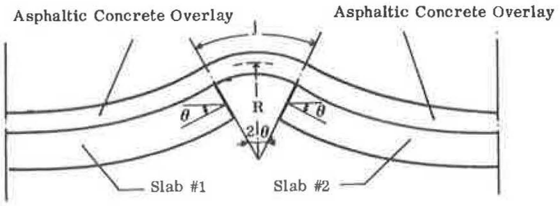
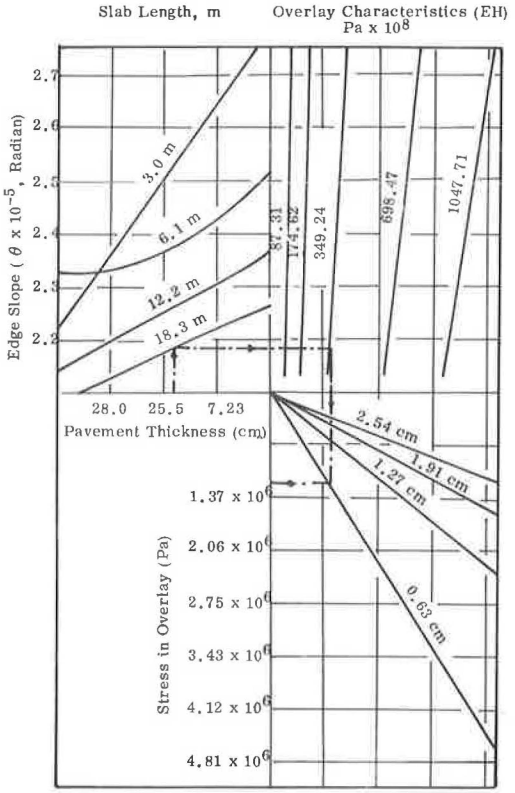


Figure 8. Maximum stress in overlay because of 1/1°C temperature differential in a rigid pavement.



Note: 1 cm = 0.394 in, 1 m = 3.3 ft, 1 Pa = 0.000 145 lbf/in².

E_{ov} = modulus of elasticity of the overlay,
H_{ov} = thickness of the overlay, and
σ = maximum stresses in the overlay.

The slope (θ) of different slabs caused by temperature differential can be calculated by using the computer program that had been previously checked against the field data. The following results were concluded.

1. The subgrade reaction modulus does not significantly affect the edge slopes of the slab nor does it significantly affect the partial contact resulting from temperature differential, and
2. The only factors affecting the edge slopes of the slab are the slab thickness and length.

The output of the edge slopes was used in conjunction with the formula for overlay stresses to construct the nomographs shown in Figure 8. These nomographs were used to compute the maximum stresses in the overlay that result from a temperature differential in the pavement slabs. For any other temperature differential values (ΔT_v) the result of the nomographs should be multiplied by ΔT_v. The curling case would give maximum tensile stress in the uppermost fiber of the overlay. The opposite is true in the case of warping.

CONCLUSIONS

The maximum stresses in the overlay at the joint location caused by horizontal slab movement can be calculated by using Equation 1 and nomographs shown in Figures 4 and 5. For stresses caused by vertical movement, the results of the nomograph shown in Figure 7 should be multiplied by the expected temperature differential in the pavement slabs. It is important to know the temperature distribution at the time of overlay construction so that both the average temperature drop and the maximum temperature differential expected in the pavement slabs can be found. Calculation of stresses in different overlays caused by movement at joint location showed that these stresses often exceed the maximum tensile stresses in asphalt-concrete overlays; therefore reflective cracking occurs when asphalt concrete is laid over jointed pavements.

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