Moisture in Portland Cement Concrete

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Moisture gradients in concrete pavements cause differential shrinkage between the top and the bottom of the pavement. This leads to curling stresses in which the top of the pavement is in tension while the bottom is in compression. The magnitude of these stresses is determined by the moisture distribution, the volumetric aggregate content of the concrete, and the elastic modulus of the concrete. Pavement moisture contents were determined by field moisture measurements, laboratory measurements, and computer simulation. These indicated that substantial drying occurred only at the top surface, to a depth of less than 2 in. The rest of the pavement remained at 80 percent saturation or higher. A typical pavement moisture distribution was determined, and using an aggregate content of 74 percent and an elastic modulus of 3.6 × 10⁶ psi, a stress distribution was calculated. The tensile strength of the concrete at the surface was exceeded, and cracks could be expected to form to a depth of ³/₄ in. Because the tension in the concrete was concentrated near the surface instead of decreasing linearly with depth, the actual moment in the pavement caused by the moisture gradient was only 40 percent of the moment capacity of the unreinforced concrete.

Portland cement concrete shrinks as it dries, and, if this shrinkage is restrained in any way, tensile stresses will develop in the concrete. If there is a moisture gradient in the concrete, the concrete will have a tendency to curl. The weight of the concrete tends to resist the curling in installations such as pavements, and this leads to curling stresses. This has been recognized in pavements for many years. Normally moisture gradient curling stresses in pavements are ignored because of the difficulty in estimating their magnitude and because it is believed that they are cancelled out by the effect of temperature gradient–induced warping *(1)*. It is the purpose of this paper to estimate the magnitude and locations of moisture gradient–induced curling stresses.

BACKGROUND

Drying shrinkage in concrete is complex and has been investigated in detail by others *(2–6)*. Essentially shrinkage occurs when water is removed from the hardened cement paste. Figure 1 is adapted from Mindess and Young *(2)* and shows drying shrinkage for a typical cement paste as a function of degree of saturation. Saturated moisture content for this paste is 28 percent, defined by drying to constant weight at 115°C. Aggregate in concrete restrains this shrinkage, and the amount of restraint depends on the volumetric aggregate content of the concrete. This is shown in Figure 2, taken from Powers *(4)*. As the aggregate content increases, the amount of shrinkage in the concrete decreases. For a typical pavement concrete with approximately 74 percent of the volume filled with aggregate *(7)*, the total concrete shrinkage would be approximately 10 percent of the paste shrinkage for the same amount of drying.

If the concrete is restrained from moving as it shrinks, the stresses that develop can be calculated by elasticity. The elastic modulus of normal weight air-entrained concrete can be calculated *(8)* by

$$E_c = 57{,}000 \sqrt{f'_c} \qquad (1)$$

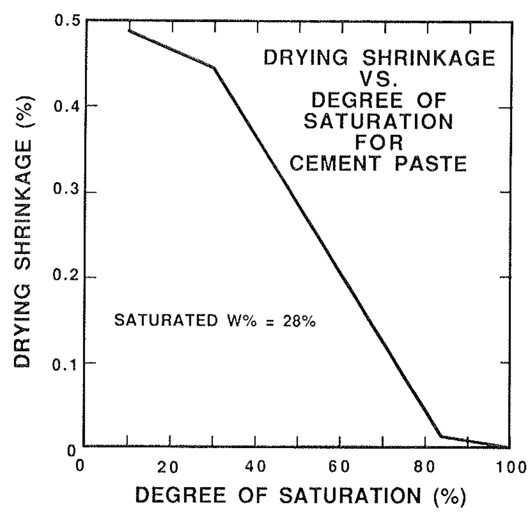

FIGURE 1 Drying shrinkage for a typical cement paste, after Mindess and Young *(2)*.

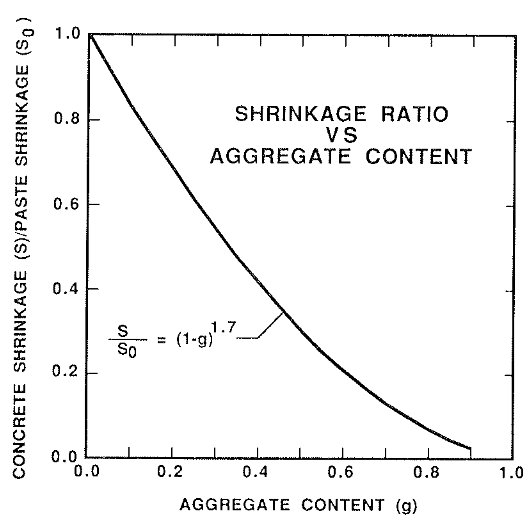

FIGURE 2 Relative shrinkage as a function of aggregate content *(4)*.

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where E_c is the elastic modulus of the concrete (psi) and f_c' is the 28-day compressive strength of the concrete (psi). For concrete with a compressive strength (f_c') of 4,000 psi, the elastic modulus (E_c) would be approximately 3.6×10^6 psi.

Elastic stresses could be calculated by

$$\sigma_E = E_c \times e\%/100 \qquad (2)$$

where

σ_E = elastic stress (psi),
E_c = elastic modulus (psi), and
$e\%$ = percent strain.

For a percent strain in the concrete of 0.01, with 4,000 psi concrete the elastic stress would be 360 psi.

PROCEDURES AND RESULTS

To determine reasonable estimates of the degree of saturation at various depths in a concrete pavement, three methods were used. The methods are briefly described; detailed descriptions are given in Janssen *(7)* and Janssen et al. *(9)*.

Field Testing

Field moisture contents were determined by installing psychrometers in three pavement sections. Psychrometers measure relative humidity, which is converted to degree of saturation by means of laboratory calibrations. A description of the procedures can be found in Janssen *(7)*. The psychrometers were installed in a ramp for I-72, west of Champaign, Illinois, and in two locations in a ramp on I-57, north of Champaign. The I-72 installation was at depths of 2 and 4½ in., and the I-57 installations were at 2 and 5½ in. and at 2, 5½, and 7 in. Each installation was in triplicate at each depth.

Readings were taken for the I-72 location on March 22, 1984, and from July 10 through November 13, 1984. Following the March 22 readings, a snowplow destroyed the electrical leads and considerable work was required to repair them before readings could resume. The first I-57 location was monitored from June 8 through July 10, 1984, and readings were taken at the second I-57 location from June 7 through June 27, when this location was overlaid. Saturated moisture content for the I-57 locations was determined to be 7.6 percent *(7)*.

Results of the field moisture content determinations are given in Tables 1–3. Each value shown is the average of the readings taken for that location and depth. It should be noted that readings were not always possible because of equipment problems. Missing data are indicated in the tables by dashes. The mean, high, and low values for each depth and location are shown in Figures 3–5. These figures indicate that there was little change in degree of saturation for the depths shown.

Laboratory Testing

Laboratory moisture determinations were made after conditioning three laboratory-cast cylinders by slow freeze-thaw cycling. It is believed the freeze-thaw action is a major driving

TABLE 1 DEGREE OF SATURATION, I-72 LOCATION

	Degree of Saturation (%)	
Date	2-in. Depth	4½-in. Depth
3-22	85	82
7-10	92	94
7-11	88	92
7-18	83	90
7-25	79	95
7-30	78	–
7-31	90	86
8-3	87	88
8-14	87	87
8-21	79	82
8-22	83	83
8-28	79	83
9-4	79	88
9-6	78	78
9-11	90	87
9-13	92	–
9-18	83	–
9-19	85	94
9-20	83	–
9-25	88	86
9-27	90	–
10-2	79	–
10-4	81	–
10-8	82	85
10-10	87	86
10-24	79	94
11-2	78	77
11-12	85	94
11-13	91	–

TABLE 2 DEGREE OF SATURATION, I-57 LOCATION A

	Degree of Saturation (%)	
Date	2-in. Depth	5½-in. Depth
6-8	95	94
6-11	–	77
6-13	82	–
6-19	87	–
6-21	88	87
6-22	85	94
6-25	–	91
7-3	–	83
7-5	–	87
7-6	83	87
7-10	87	–

TABLE 3 DEGREE OF SATURATION, I-57 LOCATION B

	Degree of Saturation (%)		
Date	2-in. Depth	5½-in. Depth	7-in. Depth
6-7	87	–	–
6-8	95	95	95
6-11	–	85	92
6-13	82	–	–
6-19	85	–	–
6-21	87	94	94
6-22	90	90	95
6-25	–	92	96
6-27	85	94	–

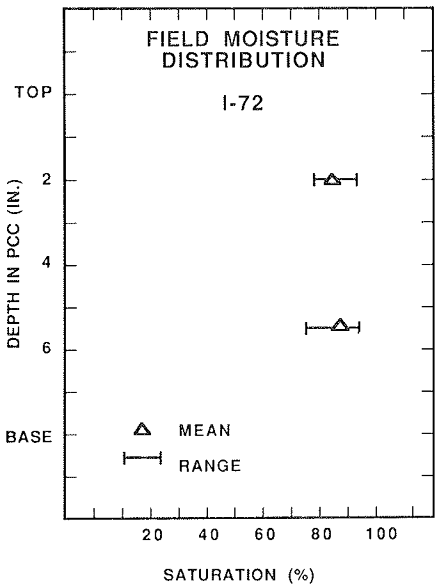

FIGURE 3 Degree of saturation (mean, high, and low) I-72.

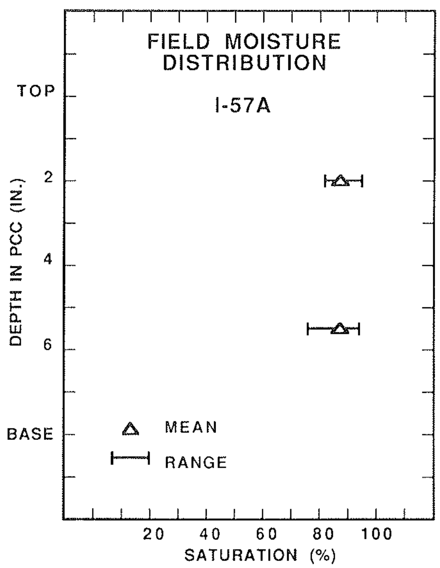

FIGURE 4 Degree of saturation (mean, high, and low) I-57A.

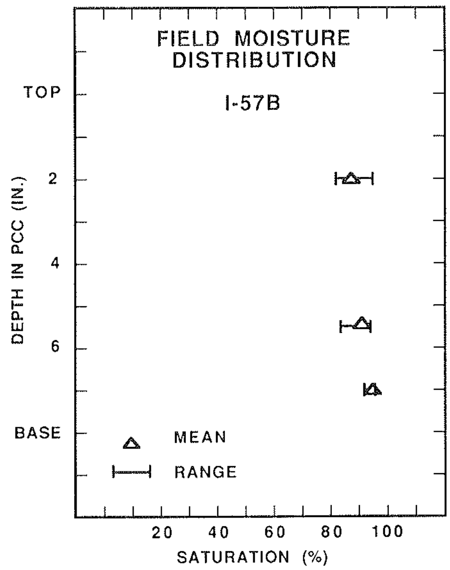

FIGURE 5 Degree of saturation (mean, high, and low) I-57B.

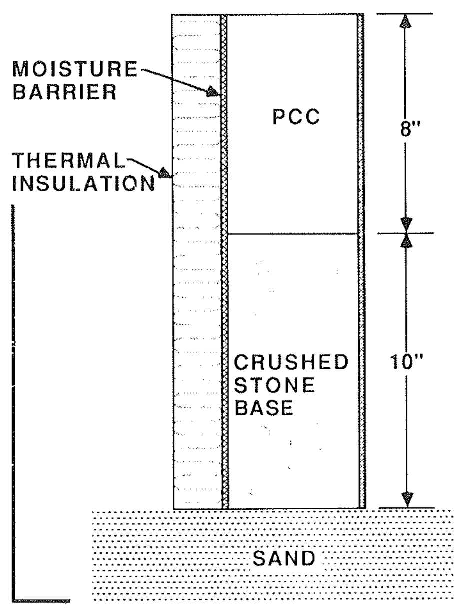

FIGURE 6 Laboratory sample.

force for moisture movement in concrete pavements *(7)*. Concrete samples, 4 in. in diameter by 8 in. long, were placed vertically on a 10-in. dense crushed-stone base. Horizontal moisture and thermal movements were prevented by use of moisture barriers and thermal insulation. The top surface of the concrete was open to evaporation, and the bottom of the crushed-stone base was in contact with free water (Figure 6). The samples were subjected to 200 freeze-thaw cycles over a period of 5 months. This is the equivalent to about 4.3 years of field exposure for central Illinois. Details of the freeze-thaw work can be found elsewhere *(7, 9, 10)*. The saturated moisture content for the samples was 7.8 percent. The initial degree of saturation before freeze-thaw conditioning was 73 percent.

After this conditioning, the concrete cylinders were broken into approximate quarters and dried at 115°C to determine moisture contents. Degrees of saturation for the three samples are shown in Figure 7. As did the field moisture measurements, the laboratory samples show little variation in moisture from top to bottom. It should be noted that the samples were broken into approximately 2-in. pieces for the moisture content determinations, and any shallow surface drying would not show in these data.

Computer Modeling

Moisture movement was modeled in the concrete by means of a finite-difference computer program developed by Boast *(11)*. This program, although developed for moisture movement in soil, is applicable to any porous solid for which the appropriate inputs are known *(7)*. The system modeled consisted of an 8-in. concrete layer in contact with a free water source on the bottom

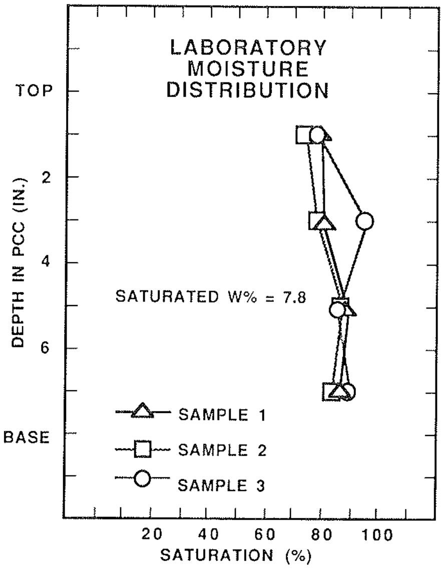

FIGURE 7 Laboratory moisture distribution.

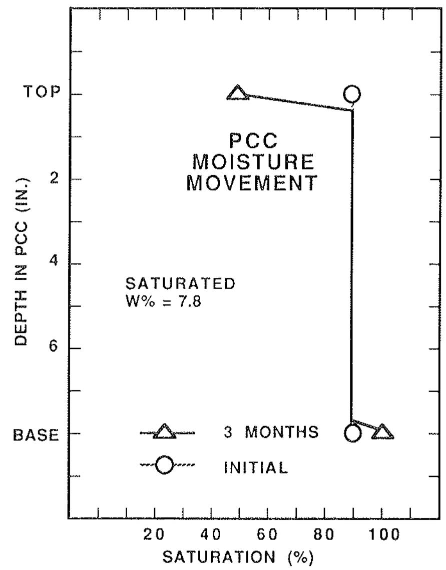

FIGURE 9 Simulated moisture profile, initial 90 percent saturation.

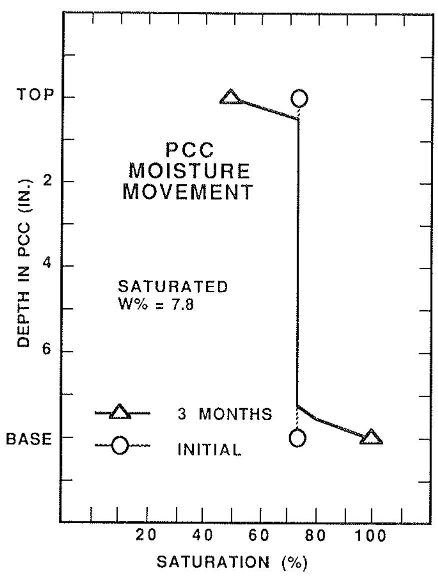

FIGURE 8 Simulated moisture profile, initial 73 percent saturation.

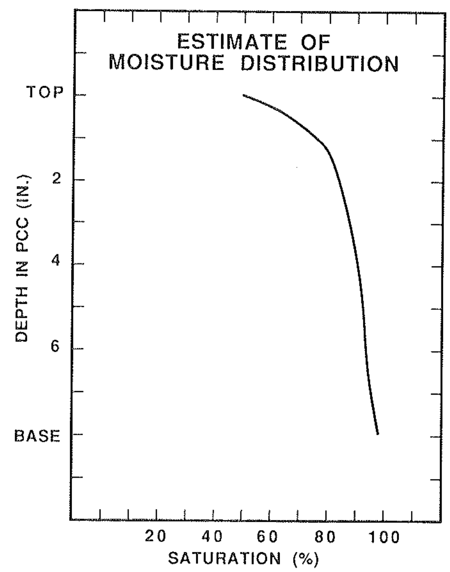

FIGURE 10 Estimate of moisture profile.

and 50 percent relative humidity on the top. Two initial conditions were tested: an initial degree of saturation of 73 percent, which corresponded to the concrete laboratory samples before freeze-thaw conditioning, and an initial degree of saturation of 90 percent, which corresponds to typical values found in the field investigation. The modeling was simulated for a period of 3 months, and the results are shown in Figures 8 and 9. It appears that the surface drying does not extend very far into the concrete, which probably explains why surface drying was not measured at the 2-in. depth in the field and was not pronounced in the top 2 in. in the laboratory samples.

APPLICATION

Using the laboratory and field measurements along with the computer modeling as a guide, Figure 10 was prepared as an estimate of degree of saturation versus depth for an 8-in. concrete pavement in a moderate climate subject to freeze-thaw cycling. The surface is only at 50 percent saturation, but the moisture content increases rapidly with depth to close to saturation at the base. This agrees with the measured laboratory and field moisture. The shallow drying at the surface is in agreement with the computer modeling. The reason that the drying does not extend very far into the pavement is the very low permeability of concrete *(7)*.

Percentage of saturation is converted into shrinkage using Figures 1 and 2 and assuming that all of the moisture loss in this range of saturation occurs in the paste. Converting shrinkage strain into stress for 4,000-psi concrete using Equation 2 yields the stress distribution shown in Figure 11. This stress distribution has been balanced for zero resultant force (tension on top of slab causes compression on the bottom) and

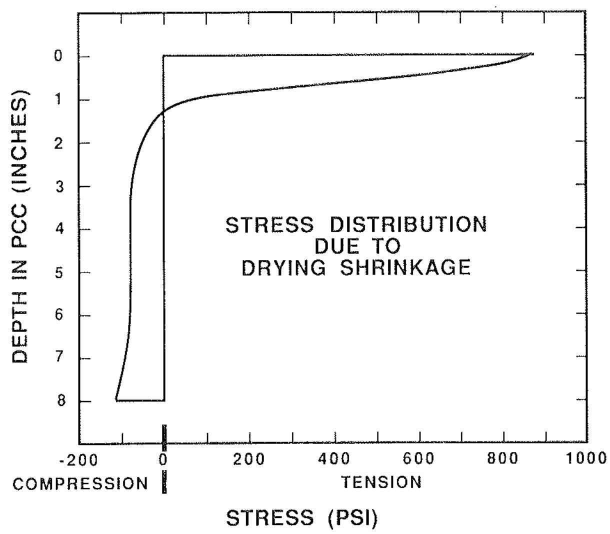

FIGURE 11 Moisture gradient stress distribution.

ignores any outside forces. The effect of reinforcing steel in the concrete is also ignored, though concrete shrinkage would cause compression in the steel. This would have minimal effect on the concrete stress distribution. The resultant moment due to the moisture gradient in the concrete is approximately 2,500 in.-lb per inch of slab width. The failure moment for 4,000-psi concrete, 8 in. thick, in pure flexure is about 6,200 in.-lb per inch width *(8)*. This assumes that the stress in the concrete up to failure is elastic and the stress distribution is linear with the neutral axis at the center. But the stress distribution shown in Figure 11 is far from linear. If the tensile strength of concrete is approximately equal to 10 percent of the compressive strength, Figure 11 indicates that the tensile strength is exceeded down to a depth of approximately 3/4 in. for this 4,000-psi concrete. This means that shallow hairline cracks can be expected to form in concrete slabs that exhibit moisture distributions similar to those shown in Figure 10. These hairline shrinkage cracks are probably what can be seen on concrete pavements as water evaporates after a rain.

CONCLUSIONS

This research has led to the following conclusions, which apply to the effects of moisture gradients in concrete pavements:

1. Significant drying in a concrete pavement can be expected only to a rather shallow depth;
2. The resulting moisture gradient can be expected to cause curling stresses in a pavement with the top of the pavement in tension and the bottom in compression;
3. Though the magnitude of the resulting moment would not cause failure in the concrete, the stress distribution is such that the tensile strength of the concrete would be exceeded to a depth of approximately 3/4 in.; and
4. This shallow cracking could be significant in situations in which concrete permeability is important, such as protective cover over steel reinforcement.

To evaluate the existence and extent of shallow cracking, cores that include a hairline crack should be taken. Hairline cracks are located by wetting the concrete surface and then allowing the water to evaporate. If present, cracks will appear as the surface dries. The cores can then be inspected in the laboratory by liquid penetrant inspection (ASTM E 165) to determine depth of cracking.

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