void contents giving more water and more stripping pressures. This seems to be a faster kind of a damage rather than a longer range damage. Long range damage seems to start from the bottom of the pavement and works upward toward the surface.

QUESTION: Vaughn Marker -- The Asphalt Institute, College Park, Maryland

I had a little difficulty following your presentation with regard to the monitoring of moisture. It seemed to me you were talking about intrusion of moisture into the asphalt and yet you were talking about monitoring the moisture content of the aggregate coming out of the drier. The temperature equilibrium between the coarse and fine particles--the temperature derived evidently--I understand. With relationship to monitoring moisture in the mix, this is difficult to understand. Did I understand you to say you were trying to figure rate of loss in the mix after the asphalt had been added to the mix?

ANSWER:

This caused some of the foaming problems that happened years ago in Michigan and Ohio. This was essentially due to rate but it couldn't be measured and controlled easily at that time so you had to go to moisture content determinations and control that.

QUESTION: Vaughn Marker

My question -- have you been working on developing a measure for these systems? That is what I don't understand.

ANSWER:

We did this at Ohio State awhile ago in the early sixty's. This involved aggregate types, how they dried, what their temperatures were at times of mixing and the approximate rates of moisture loss at that time. Also, there probably have been some data on rates of moisture loss after hot mixing with asphalt. But further development would be necessary to arrive at a control test for moisture "specifications."

LABORATORY MEASUREMENT OF THE EFFECT OF MOISTURE ON WORKABILITY AND PERFORMANCE OF ASPHALT TREATED MIXES

SPEAKER: R. J. Schmidt, Chevron Research Company, Richmond, California (deceased)

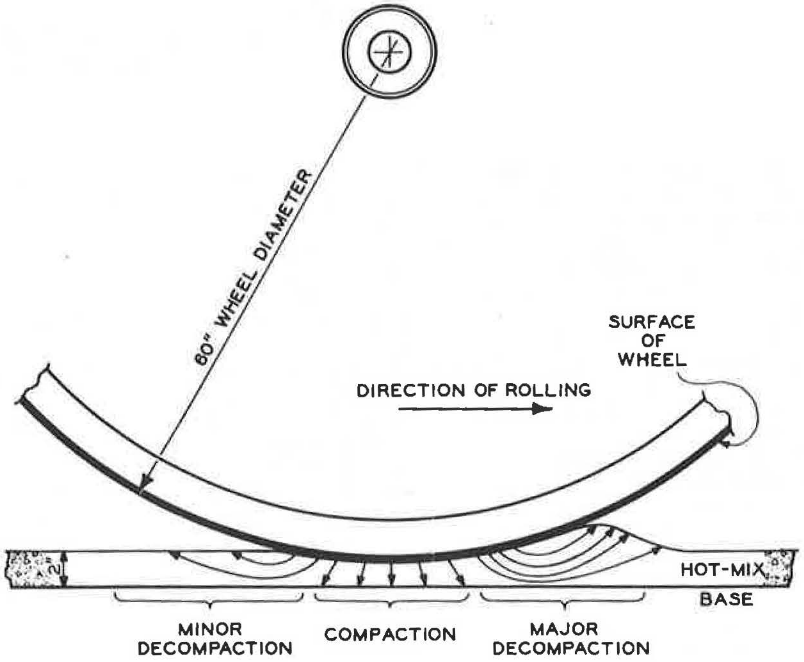
(An account by L. C. Krchma based on a presentation given without benefit of a prepared manuscript)

Schmidt has been associated with studies of rolling and the physical properties of laboratory specimens and drew on these in considering the laboratory measurement of the effect of moisture on workability and pavement performance (1-5).

To measure the hot-mix workability involved in rolling required full scale rolling under laboratory conditions. Part of this study was concerned with the way differences in the "voids filled" with asphalt influenced roller compaction. This provided an insight to the effect of residual moisture on compaction to the extent that moisture, either as a liquid or steam, would also occupy void space. This, like the asphalt, would be expected to lubricate the mix, which in turn would affect the stability of the mix under the roller, and hence the compaction. Figure 1 from "Behavior of Hot-Mix Asphaltic Concete under Steel Wheel Rollers (1)" was shown to illustrate the compaction mechanism and how the stability of the mix contributes to the uncertainty, what with decompaction in front of the roller, offsetting the compaction under the roller.

Schmidt showed Figure 2 from the same reference giving normal rolling behavior where decompaction was not a problem with a normal mix having adequate voids to accommodate the fluids present (asphalt) provided it was not overloaded by too heavy a roller or too small a roller diameter (1). He showed good compaction could be

Figure 1. Behavior of Hot-Mix During Rolling



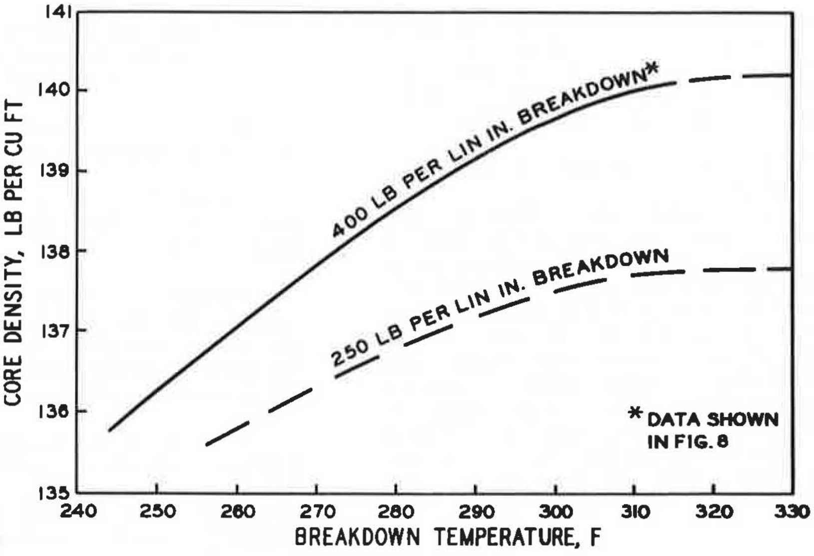


Figure 2. Normal Behavior: Density Increase with Breakdown Temperature and Roller Pressure

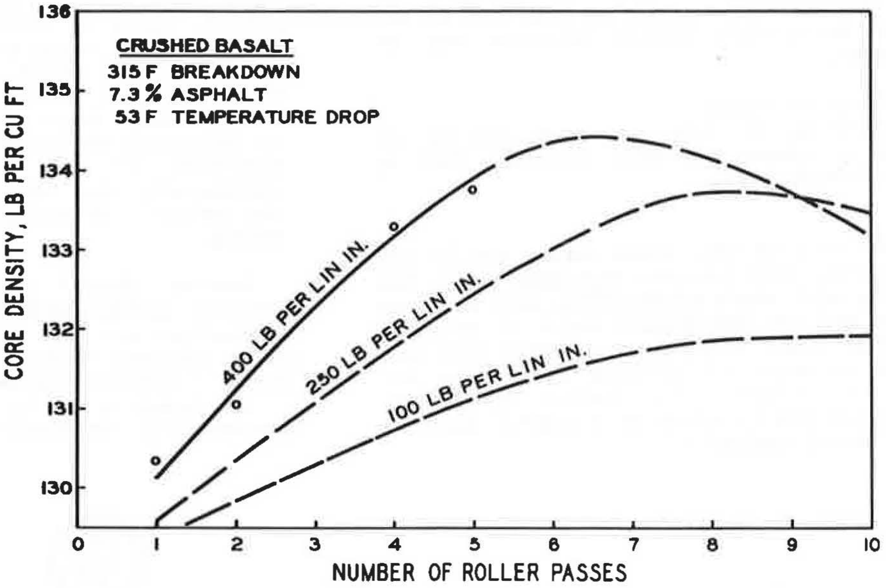


Figure 3. Core Density vs Number of Roller Passes for Different Wheel Pressures

obtained with even a 400 lb/lineal inch roller where the aggregate and asphaltic binder are in balance. This was not the case in the situation examined in Figure 3 from the same reference. Here the increased roller pressure at some point caused a decrease in core density as decompaction due to pushing, ahead of the roller, exceeded the initial compaction under the roller.

Figure 4 from HRB Bulletin 251 was shown to illustrate that the existence of an optimum roller pressure to obtain maximum compaction is a function of mix stability (1). To the extent the fluids present (asphalt and moisture) contribute or detract from this stability an adjustment in rolling is indicated. It was pointed out this adjustment extends to equipment such as pneumatic and vibratory rollers which have extended the ability to compact problem mixes.

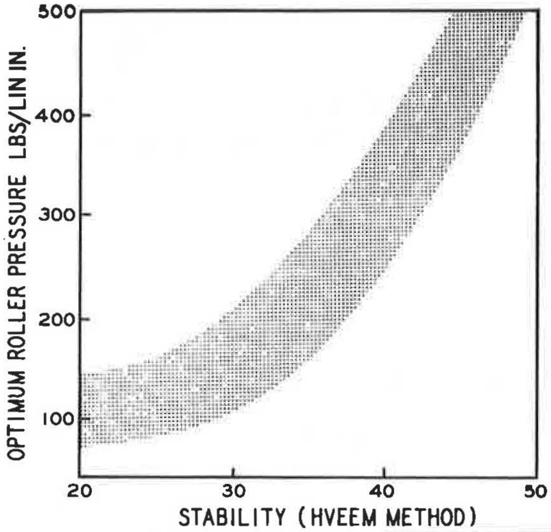
That the stability, influencing compaction, can suffer even with an ordinarily accepted gradation and asphalt content was shown by Figure 5 from (1). This demonstrated the pervasive nature of the liquids (asphalt and moisture) occupying the voids. In the example studied, the voids occupied depended on the temperature drop from mixing to compaction, and the resulting differences in the amount of asphalt absorbed. With the total asphalt content selected, the combination of higher rolling temperature, and hence less absorbed asphalt, reached a point where there was too much asphalt in the voids space for the stability for best compaction. Conversely at the lower rolling temperatures, that is after a larger temperature drop, too much of the asphalt was absorbed, again resulting in a mix difficult to compact.

While this study dealt with only asphalt as the liquid component being absorbed, Schmidt pointed out moisture would lower the asphalt absorption and in effect increase the volume of asphalt in the voids. He concluded that if such secondary volumes are too high, adequate rolling would suffer, though less so with pneumatic or vibratory equipment. These examples, applied to moisture, led to the observation that each situation needs to be examined as to whether the amount of moisture left in a mix is interfering or aiding in the laying of a hot mix. Extra moisture in a mix could help compaction because of its greater lubricating ability. Too much moisture could contribute to the overfilling of the voids, making the mix unstable under rolling conditions. It was felt this could occur for a variety of reasons, such as moisture left on the aggregate or absorbed moisture.

To examine the effect of moisture on hot-mix asphalt pavement performance, Schmidt drew on several published studies of the resilient modulus of laboratory specimens exposed to various moisture conditions. This included introducing or expelling moisture to several levels under a variety of conditions by vacuum saturation, vacuum dessication, drying at 50 percent and 95 percent relative humidities, freeze-thaw, etc.

Referring to Figure 6 of his paper, The Effect of Temperature, Freeze-Thaw, and Various Moisture Conditions on the Resilient Modulus of Asphalt-Treated Mixes , he showed a water saturated specimen will reach a stable continuing equilibrium moisture level (3). Using as an example the 95 percent RH drying condition and the 1-1/2 percent moisture equilibrium so obtained, he concluded this was normal condition for that particular aggregate, and for that environment there would be very little difference were this 1-1/2 percent moisture left in this mix in the first place.

Figure 4. Optimum Roller Pressure Depends on Mix Stability



The moisture found in Figure 6 resulted in the modulus changes shown in Figure 7 from the same study (3). The modulus fell when the cores were first vacuum saturated and held at this condition for seven days. But, on drying at 50 percent and 95 percent RH, the modulus by and large remained unchanged until the moisture approached the 1-1/2 - 2 percent level. Only then was an increase in modulus observed. Schmidt concluded that up to this point, free liquid water was in the voids, and that only after this was removed could the cores physical condition be improved. This water at the asphalt-aggregate interface or dissolved in the asphalt, causing damage could not be reduced until free water in the voids was removed. On this basis, Schmidt was of the opinion that once free moisture was present, additional moisture did not materially add to the harm.

Schmidt showed that the effect of the alternate exposure to moisture and drying of cores seems to be completely reversible using for this purpose Figure 8 from the report "The Effect of Water on the Resilient Modulus of Asphalt-Treated Mixes" (5). The conclusion drawn from what Schmidt called the "yo-yo" effect was that there did not appear to be any permanent damage due to moisture cycling such as might occur in a pavement. It further appeared that a mix with some initial residual moisture would be starting at a different point in the wetting-drying cycle but beyond that would not show a permanent difference, other than differences in compaction discussed earlier. Here, choice of rollers and their operation could aid in obtaining desired results.

Residual moisture was a concern to Mr. Schmidt in the area of freeze-thaw. Referring to Figure 9 (3), he showed a core vacuum saturated to approximately 5 percent moisture was damaged when

Figure 5. Asphalt Absorption Caused by Drop in Mix Temperature Influences Core Density

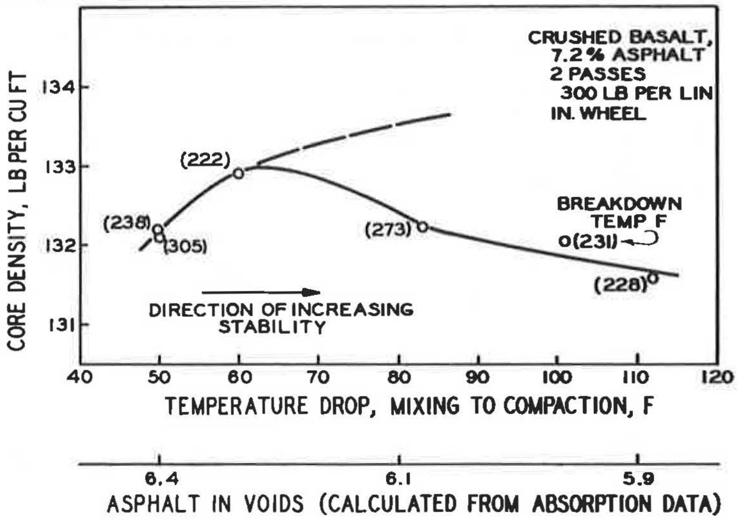


Figure 6. Humidity During Drying Controls Equilibrium Moisture Content of Asphalt-Treated Mixes

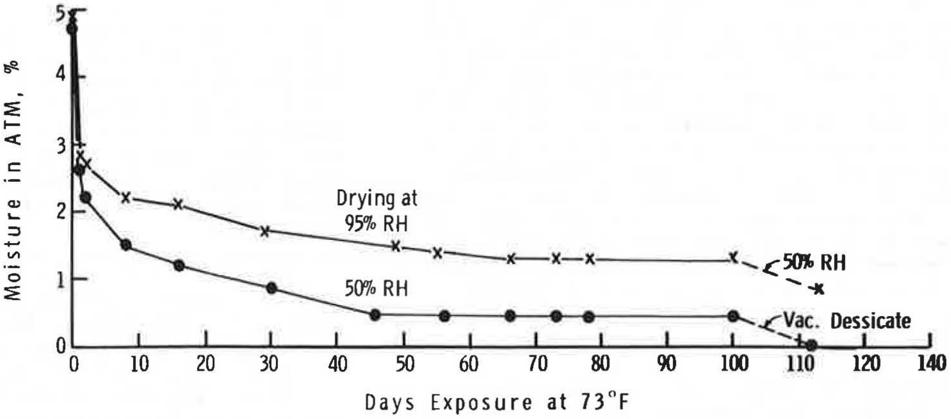


Figure 7. Humidity During Drying Affects Relationship Between Water Content and Resilient Modulus of Asphalt-Treated Mixes

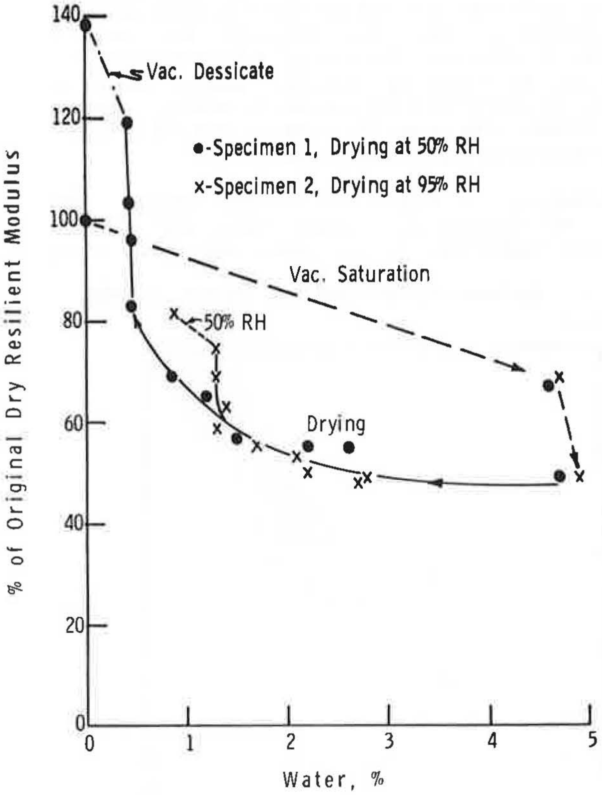


Figure 8. Effect of Moisture on M_R is Reversible

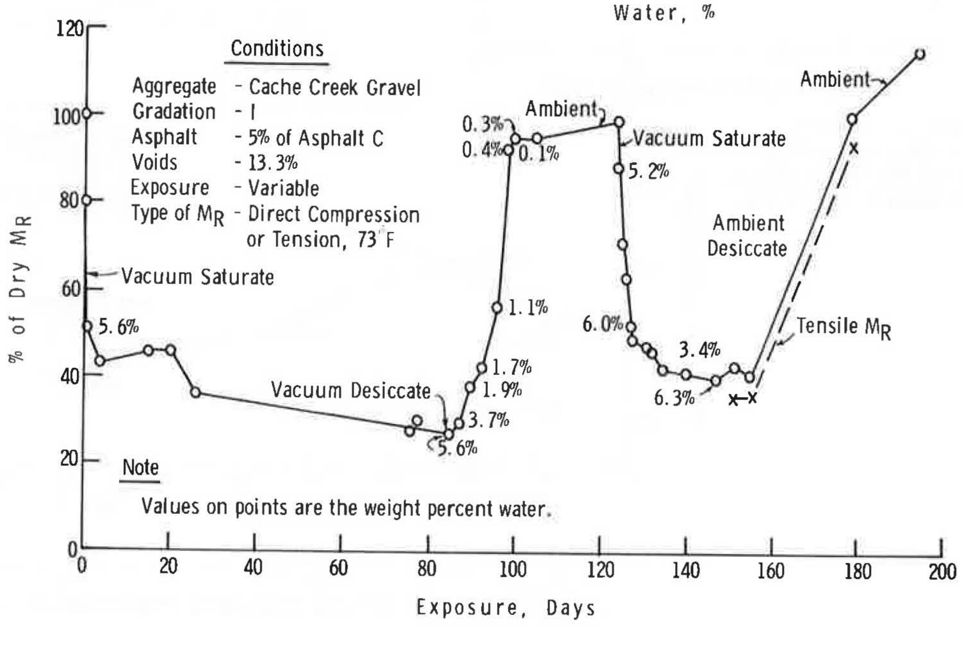
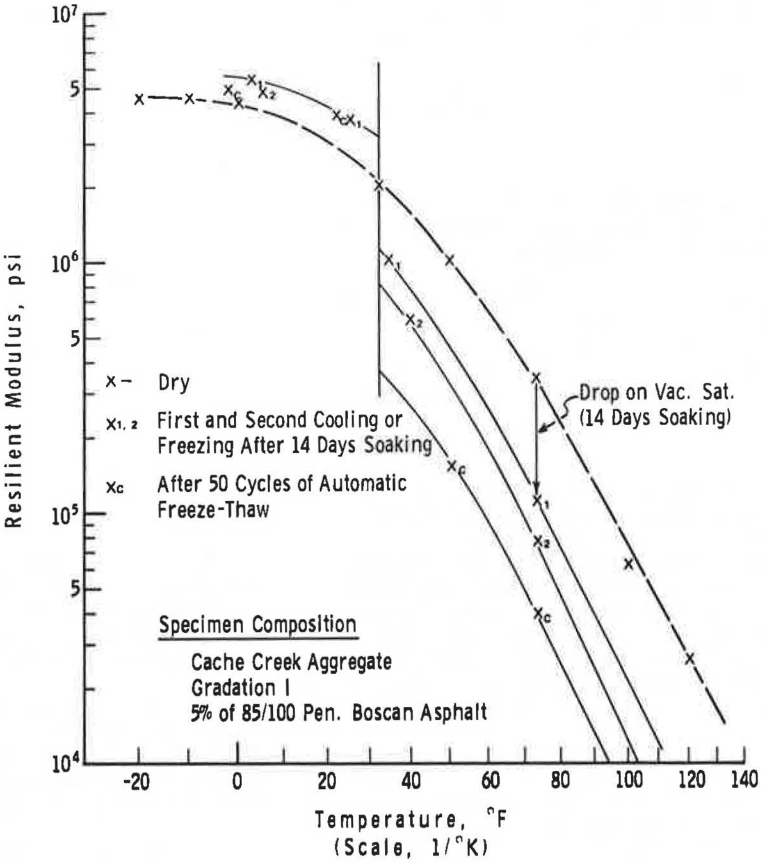


Figure 9. Freeze-Thaw Behavior of Asphalt-Treated Mixes



exposed to freeze-thaw cycles. Information was not available for more modest moisture contents. However, it was felt the equilibrium moisture set the moisture level in a pavement and that this, rather than initial "bone-dry" condition determined the normal pavement's sensitivity to freeze-thaw.

Schmidt concluded that the major detrimental effects of residual moisture in a mix that are now evident are, on initial compaction, a reduced modulus, and possibly a problem with freeze-thaw damage.

REFERENCES

1. Behavior of Hot Asphaltic Concrete under Steel-Wheel Rollers, R. J. Schmidt, W. J. Kari, H. C. Bower, and T. C. Hein, HRB, Bull. 251, 18-37, 1960.
2. Full-Scale Asphalt Concrete Construction in Research Laboratory, R. J. Schmidt, HRB, Bull. 251, 1-11, 1960.
3. The Effect of Temperature, Freeze-Thaw, and Various Moisture Conditions on the Resilient Modulus of Asphalt-Treated Mixes, R. J. Schmidt, TRB, Transportation Research Record 515, pp. 27-39, 1974.
4. Performance Characteristics of Cement-Modified Asphalt Emulsion Mixes, R. J. Schmidt, L. E. Santucci, and L. C. Coyne, Proceedings of the Association of Asphalt Paving Technologists, Vol. 42, 1973, pp. 300-319.
5. The Effect of Water on the Resilient Modulus of Asphalt-Treated Mixes, R. J. Schmidt and P. E. Graf, Proceedings of the Association of Asphalt Paving Technologists, Vol. 41, 1973, pp. 118-162.

DISCUSSION -- R. J. Schmidt's presentation, - "Laboratory Measurement of the Effect of Moisture on Workability and Performance of Asphalt Treated Mixes"

QUESTION: Frank M. Drake - The Asphalt Institute, Lenexa, Kansas
Among your early slides you show a given mix with a given roller, base and a given thickness and you show a term of compaction effort, which I agree with. Now, are you speaking of Marshall stability?

ANSWER:
Not necessarily. The kind of stability I had in mind is more like a triaxial stability at a low confining pressure.

QUESTION: Anonymous
If we reduced the thickness of the lift - could we reduce the mushiness under the particular compactive effort?

ANSWER:
I would think so. Mushiness becomes more of a problem in thicker lifts.

QUESTION: Frank Drake
Is there not a relationship in addition to the compactive effort and the stability of the mix you referred to, consisting of compactive effort, the stability, and the thickness of the mat?

ANSWER:
Yes indeed. Nijboer related many of the variables you mention in an AAPT paper, "The Compaction of Asphaltic Road Mixtures by Rolling,"

Proc. AAPT, Vol. 17, 1948. He also included much of this in a book he wrote: "Plasticity as a Factor in the Design of Dense Bituminous Carpets."

QUESTION: Anonymous
Why did you use 73^oF as a basis of test temperature?

ANSWER:
Convenience and availability of a constant temperature room. The nearby wax laboratory had an environmental chamber operating at 73^oF.

QUESTION: D. Tunnicliff - Warren Brothers Company, Cambridge, Massachusetts
On the last slide you had, I noticed in particular asphalt-treated mixes. Are you talking about what most of us refer to as 'asphalt concrete' or something else?

ANSWER:
I refer to asphalt-treated mixes because that includes hot mixes as well as emulsion or cutback treatments. Although (in the particular slide in question) they were hot mixes, emulsion-treated mixes behave the same as hot mixes once they have dried out. Cement or lime treatment improves the water resistance of all asphalt-treated mixes. Cement is very effective with emulsion-treated mixes but less effective with hot mixes. Lime is better with hot mixes and less effective with emulsion-treated mixes.

I should emphasize that all of the moisture and freeze-thaw damage that we illustrated is reversible. As soon as the damaged mixes dry out, they recover their strength.

QUESTION: Anonymous
You feel moisture can come and go? Suppose we built a pavement with black base with 2 percent moisture in it. Is this the most it is ever going to dry out?

ANSWER:
I don't think it makes much difference to the final equilibrium. If the mix is permeable, it will either lose or pick up water, depending on the humidity of the air in contact with the mix. If it is impermeable, then it is more likely to retain its original moisture content.

INFLUENCE OF MOISTURE AND HOW MUCH YOU HAVE TO CONTROL IN A CONVENTION PLANT

Bill L. Kellam, Thompson-Arthur Paving Company
Greensboro, North Carolina

There are basically five physical properties that are required of asphaltic concrete mixtures produced in a hot-mix plant:

(1) Stability - The resistance to displacement and shearing stress caused by traffic loading.
(2) Durability - The resistance to changes in the pavement due to water, air, and temperature changes. Some qualities that complement its durability are its resistance to wear or abrasion, swelling, stripping and oxidation.
(3) Flexibility - The ability of a pavement to adjust to settlement of the base without cracking.
(4) Resistance to skidding - The frictional resistance of the surfaceof the pavement to insure safe driving and stopping of the vehicle. This is controlled by the surface texture and resistance to wear of the aggregate as well as the asphalt content of the mixture and per cent of voids in the mixture.
(5) Workability - The ease with which the material can be placed to the desired uniformity and compacted to the required density. This is governed by the gradation of the mixture, asphalt content, maximum particle size, temperature of the mix and the shape and surface texture of the aggregate.

This discusses and evaluates methods of producing asphaltic concrete with more moisture in the final product than is presently being allowed by conventional specifications, without greatly effecting the characteristics.

Most of my experiences with plant operations involving moisture have been with highway departments and governmental agencies whose specifications usually allow 0.2 percent to 0.5 percent moisture by weight of aggregate.

The drying and heating of the aggregates is accomplished by feeding or passing the aggregates through a drier which consist of:

(1) A revolving cylinder usually from 3 to 10 feet in diameter and from 20 to 40 feet long.
(2) A burner, which is either gas or oil fried.
(3) A fan which may be considered part of the dust collector system, but its primary function is to provide the draft air for combustion in the cylinder. The cylinder is equipped with longitudinal cups or channels, called "lifting flights", which lift the aggregates and drop them in veils through the burner flame and hot gases.

The slope of the cylinder, its speed of rotation, diameter, length, and number of flights control the length of time required for the aggregates to pass through the drier to be heated and dried to the desired temperature and moisture content. The aggregates pass from the drier to the hot elevator through a discharge chute near the burner end of the drier.

It has been found in our area that mix features change when the moisture content of the heated aggregates exceed the 0.5 percent to 1 percent range.

(1) The temperature of the mixture drops appreciably, often enough to exceed the allowable tolerances set forth in the specification requirements.
(2) The mixture appears to have minute water or steam bubbles on the coated aggregate, particularly in base and binder mixes, and gives off a frying or sizzling sound.
(3) On extraction the asphalt content will be on