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SECOND LOOK AT MOISTURE RESTRICTIONS IN HOT-MIX PLANT OPERATIONS AND CONSTRUCTION

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Special credit for this publication is due Frank M. Drake, L. C. Krchma and David G. Tunnicliff who assembled this material and helped to prepare it for publication.

FOREWORD

This conference was held during the Highway Research Board Annual meeting in January 1974. There were seven presentations, each followed by discussion, and a general discussion at the end of the conference. At that time there were no plans to publish any part of the conference; however, the entire proceedings were recorded on tape, and eventually it was decided to publish the presentations and all discussion. Of the presentors, only R. W. Beaty declined the opportunity for publication. It was concluded that the proceedings could be published by omitting this presentation and the discussion pertaining directly to it without detracting from the remainder of the document. Some editing has been done in order to clarify the meaning, but the text is essentially still in the verbal presentation form. There are some statements in the proceedings that are definitely "dated", that is, statements which were correct in 1974 but which are not necessarily correct in 1983. Nevertheless, the vast majority of the material is correct. The committee decided that despite its age the report contains much information which has not appeared elswhere in the technical literature and would otherwise be lost. This information has added significance in light of the present questioning of maximum limits of moisture content and minimum temperatures for mixing, laydown and compaction of hot mixes.

Gerald S. Triplett, Chairman
Committee A2F02

CONFERENCE SESSION -- SECOND LOOK AT MOISTURE RESTRICTIONS IN HOT-MIX PLANT OPERATIONS AND CONSTRUCTION

HRB Committees -- A2F02 and A2D02

L. C. KRCHMA - (Opening Remarks)

Two HRB Committees, A2F02 (Flexible Pavement Construction), and A2D02 (Effects of Natural Elements on Bituminous Aggregate Mixes), have been converging on the moisture problem. A2F02 is chaired by Frank M. Drake; Herb Schweyer chairs A2D02. About this time last year, these committees arrived at the same point, asking, "Are past moisture limits and controls still best in today's situation?", "What are the new priorities with need for more emission controls, more fuel conservation, wider use of local, even marginal aggregates, etc?"

A2D02 proceeded to prepare a "Research Needs Statement" on 'Reducing Dependence on Low Moisture for Good Hot-Mix Plant Operations, Good Construction and Good Pavement Performance'. A2F02 meanwhile was concerned that the optimum use of existing equipment and new developments might suffer if we continue with moisture controls that were found appropriate for conditions that no longer apply.

In all of this there is agreement that (1) to make more progress or do research, the moisture problem needed restructuring, and (2) time was of the essence.

Events were moving too fast to obtain this restructuring by the customary processes -- a speeded-up, give and take was needed.

In this situation, a conference was indicated to thrash out the concerns and at least start developing the right questions. So, Mr. Drake and I were asked to organize such a conference. Through the good offices of Jack Dillard, Morland Herrin, Herb Schweyer, Bill Gunderman, Ian Kingham and others, this conference was scheduled for this date, an unprecedented few months ago.

The subcommittee that carried out this assignment was made up of members from both committees:

For A2F02 -- R. W. Beaty
Duncan McCrae
For A2D02 -- R. P. Lottman
Gene Morris
C. Potts

The subcommittee recommended the discussion topics and speakers indicated in the program.

Strange things come to light as one examines the questions that might be asked and debated. Among these - "Are the moisture controls set at too low a level?", "Are we measuring moisture correctly?". Then as we go further, we might ask, "Is percent moisture a good measure of moisture's effects?" "Is the basic problem moisture or workability?" "Should workability be measured directly or do we accept an indirect measure like percent moisture?" "Are there other factors like equipment design, equipment operation, mix design and character, as well as moisture to reconsider?" If so, how do we examine and control them? In the present situation, can we continue to say the drier the better? If not, how high can we go and what should we control?

The SECOND LOOK AT MOISTURE program included the following:

R. P. Lottman -- Moisture Monitoring;

R. J. Schmidt -- Laboratory Measurement of Workability and Performance;

Bill Kellam -- Plant Operations: Conventional;

R. L. Terrel -- Plant Operations: Drum-Mixer;

Duncan McCrae -- Hauling, Spreading, and Rolling - Conventional;

R. W. Beatty -- Hauling, Spreading, and Rolling - Drum-Mixer (The text of this presentation was not submitted for publication.) and;

Synopsis of Paul Serafin's paper Effect of Moisture in Bituminous Mixtures as Experienced in Field Pavement Operations in Michigan by Frank Drake.

MOISTURE MONITORING
R. P. Lottman, University of Idaho

I would like to speak about two areas of moisture control in hot-mix plant-field operations which I think are of prime importance. These areas are workability and durability.

Workability is needed to achieve initial mixture properties during the paving operations that will affect the eventual outcome of the mix -

such things as achieving adequate mixing, finishing, compaction. The initial voids and other physical properties become established at this level.

Present moisture monitoring is essentially but not exclusively related to achieving workability. Foaming or unstable mixtures at paving are examples of problems that have required a limit of moisture in aggregate or in the mix.

To begin with, the conventional asphalt plant dryer is really a heater in terms of objective. Aggregates need to be hot enough to maintain mix workability after asphalt mixing. This has required average aggregate temperatures about 75-80°F over the atmospheric boiling point of water. Aggregates having moisture on their surfaces require enough heating in the dryer to boil off the surface water before their surface temperatures will rise above water boiling point. If the aggregates are porous then also some pore water needs to be driven off to achieve average aggregate temperature above water boiling point. Thus is the connection to the common term: "dryer."

Larger aggregates, the coarse aggregates, take longer to heat than the sand or fine aggregate because of the greater distance that heat must penetrate under constant thermal diffusivity. Also, sand surface area (area exposed to heat) is greater. In many dryers, especially 10-15 years ago, the sand was always hotter than the coarse aggregate. It was common to find coarse aggregate temperatures about 230-240°F and sand temperatures about 375-400°F. A mixture of these two sizes when combined in the pugmill produced an average temperature that was desirable.

Although some hot bin residence time would reduce sand temperature and allow some additional vaporization of moisture from coarse aggregate pores, differentials of temperature persisted in the pugmill during mixing. The additional heating of the coarse aggregate by the hotter sand would drive out more moisture from the coarse aggregate and, when mixed with hot asphalt, uncontrolled foaming and other instability would occur.

Several contractors and manufacturers made changes in dryers so that coarse aggregates would have greater heating and drying and that sand would have lower heating relative to the previous situations. This was accomplished by changes in drum flights, veil patterns and residence times. These changes produced lower temperature differentials and helped to reduce further moisture loss in the coarse aggregate after mixing.

However, there was enough variability that uniform results were not achieved for all dryers in operation. Consequently many agencies set moisture content maximums in the aggregate. Sampling and control was usually at hot bin discharge into the mixer (pugmill). Some of these maximums were small, especially when one considers the moisture amounts to be weighed versus the total weight of the aggregate sample and the problems of rate loss of vapor at sampling and after sampling. However, these restrictions did bring about some improvement in controlling mix workability.

It is difficult, however, to set limits since each aggregate type contains different kinds of pores and volumes, and gradation and the fines-asphalt mastic also affect moisture sensitivity to some extent.

The inherent problem of uniform moisture restrictions is due to the different volumes of pore moisture (moisture supply) and the ease of moisture removal from the pores (rate of loss) due to different aggregate types. Conventional moisture content monitoring is related to moisture supply - being measurements of moisture sensible by weighing. The rate at which this moisture is leaving under a driving force of heat differential is not measured. Perhaps it is the rate of moisture loss, and its uncontrolled nature, that is really the problem here. This, however, is difficult to measure and control.

Durability of the compacted mix is a very much needed consideration. There really isn't much in the way of moisture monitoring of the hot mix or compacted mix from conventional plants. However, this monitoring has been or is being considered by agencies when dryer-drum mixer plants are involved.

The durability question is, What effect does residual moisture have in the mix after it has reached its "final" compacted state? In addition, What equilibrium moisture content will be achieved, finally? Is it dependent upon climate, time of year of paving, the type of drying and mixing operation? Does this residual moisture have any effect on the eventual (long-range) moisture susceptibility of the pavement mix? In this regard, is a better, worse or the same condition of durability being produced by the different drying and mixing operations?

Perhaps specifications that restrict the retained moisture in aggregate in order to eliminate stripping are necessary for durability. Two types of specifications known are (1) limiting moisture content in aggregate and (2) eliminating the use of highly absorptive aggregates. These types of specifications refer to conventional plants. The success or non-success of these specifications can best be evaluated by the experience of the agencies involved.

In summary, existing moisture monitoring is related to the amount of moisture available. At best, this monitoring is only indirectly associated with the rate of moisture loss. The rate of moisture loss, could be the significant variable but, unfortunately, it is difficult to measure. Also, existing moisture controls in most specifications are mainly associated with workability. Some specifications, however, have dealt with durability. From a viewpoint of pavement performance, durability is an important consideration. It appears possible that latitude should be given regarding moisture specifications for achieving a desired workability, but the trade-off on durability, if the trade-off exists, needs to be known. In this regard the application of moisture damage tests now found in the current literature may be useful.

DISCUSSION: "MOISTURE MONITORING" - R. P. Lottman, University of Idaho, Moscow, Idaho

QUESTION: L. C. Krchma.

Concerning the moisture rate feature you have brought to our attention, how is this measured?

ANSWER:

If you have moisture inside the pores of the aggregate and it is not coming out, then the rate is about zero and it may be "inert"; as far as affecting the mix is concerned, I don't know. But, what is coming out as diffusion into the asphalt during mixing and maybe afterwards seems to be the problem. This requires a rate in addition to supply, so it can't be measured very easily unless you measure the change of moisture supply over a period of time; in other words, the moisture content changes over a period and, from that, one can get an idea of the rate to see if it is satisfactory. But the problem has been that this is maybe an uncontrollable thing; you sort of get it and if the rate is too high, then you drop the moisture content down by additional drying, and you try to write the kind of moisture specification needed for a region or a state. But this changes with aggregates and also changes with the actual value of the moisture content in a given aggregate source. Some days when aggregates are wetter, you will have a different rate than when they are a lot drier, so the rate is quite a variable thing, which cannot be controlled easily in a practical sense. I mentioned this has only been indirectly related to the present monitoring test which was simply a measure of the supply of water or the amount of water available, but it doesn't really have anything to do directly with the rate of moisture loss. That is the problem I think.

QUESTION: Anonymous

We recall a break-down of pavement in the last few years. Due to the heavy rains, the aggregates were more wet when going into the drum. Unless we lengthen the drum time, can we control the moisture?

ANSWER:

The residence time in the drier can be changed; some people do it by changing the cold feed, by dropping that down. You can change the drum slopes a little bit, flatten them out, and increase the burners -- usually for efficiency you run the burners at the highest settings. But it's residency time no doubt that helps through slope and flight changes. If aggregate is wetter, you just leave it in there longer to dry it out. Many times you cannot rely on hot-bin storage for the more complete drying so if you have been having problems in making the mixture, one just has to go back to heating aggregate longer. Now you might not get much of an increase in temperature by leaving aggregate in the dryer for a longer time if they are wetter. A lot of your heat is going into vaporization of the water on the aggregate and so it is costing you more money, but in order to get aggregate up to the temperature, you unfortunately have to dry them out. And this has been the problem, a dryer is really a heater, but one has to dry in order to heat.

QUESTION: Anonymous

What about pavement performance, wet vs. dry years?

ANSWER:

I don't know; maybe this is the part that I touched on in durability versus residual moisture in the mix. Now and then residual moisture is in the mix. It may be between the aggregate and the asphalt; it might be diffused in the asphalt eventually. This might make the mix more moisture sensitive; it may go to an equilibrium moisture content relative to the air, after it is on the road for awhile perhaps increasing to a fairly high humidity, if it is at that time of year, and this might make the mix more moisture sensitive. I think Bob Schmidt will be showing a few slides about how much the modulus does go down even with a 1/4 of one percent moisture left in the mixture. This modulus drop and also a strength drop could be enough to start causing stability problems under traffic. This is a tie-in to durability. We really don't know that much about it except what we monitor in the laboratory right now. I don't know that there are field data on this durability problem insofar as residual moisture is concerned. Maybe some of the people here have some data on the effect of residual moisture on stripping or other properties connected with durability. We can see it in the lab; we can see the long-range effects of water coming into the voids, but we haven't seen much field data on just the long-range effect of residual moisture going into equilibrium after paving. Maybe someone could shed some light on that. Does that touch on your problem? I didn't give you an answer but maybe we just sort of extented it a little bit.

QUESTION: Bob Gallaway - Texas A&M, College Station, Texas

What field experience do you have with wheel track distress in plant mixed seals in areas where ice forms in the voids?

ANSWER:

No direct experience with plant mix seals. However, when water intrudes into the voids for the dense graded mixes, the damage is almost proportional to the voids content. When you get up to the plant-mix seals, especially open-graded ones where water is just sitting there with lots of room that is a little different kind of a problem. If the mix starts to close up in the wheel tracks bringing the void content down to 12-10 percent for example, then the water may build up some internal pressures under freeze-thaw. Also, traffic might build up pressures. If you have residual moisture in the mix it might make it even worse. The best approach for an answer is to core and run some tests on your plant-mix seals under freeze-thaw in saturated conditions.

QUESTION: B. Gallaway

Have you observed stripping at the interface between layers of hot-mix? How does this type distress first appear--that is, how is it detected when it first starts? Is this an emulsification process?

ANSWER:

Yes to your first question. Most of the time we find the stripping damage starting from the bottom of the pavement going up - sort of like a rotting log concept in the woods -- a lot of rot on the bottom and the top is sometimes pretty good. Usually when it occurs only at the top it is mainly ravelling. Interfaces may have higher

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

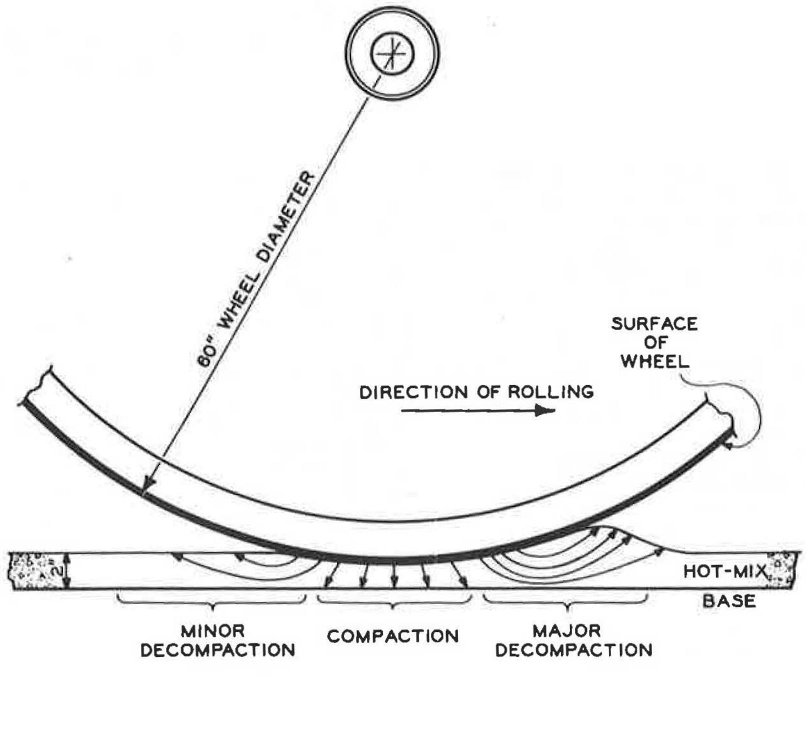


Figure 2. Normal Behavior: Density Increase with Breakdown Temperature and Roller Pressure

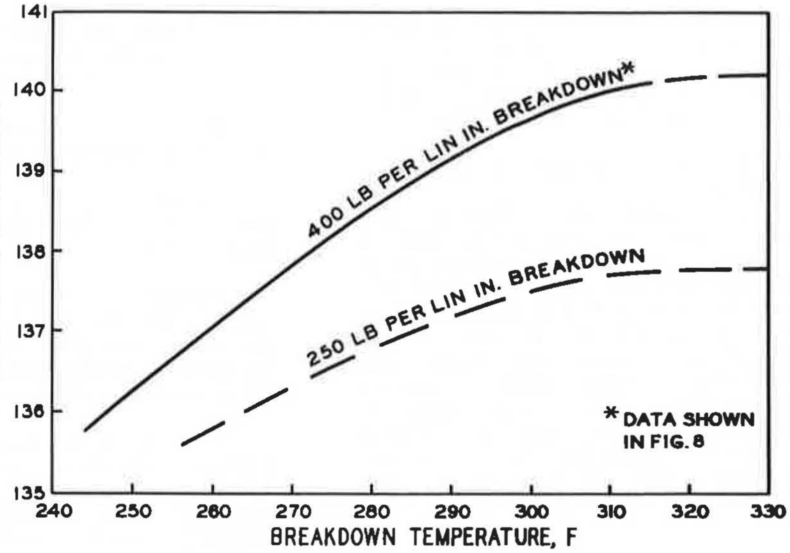
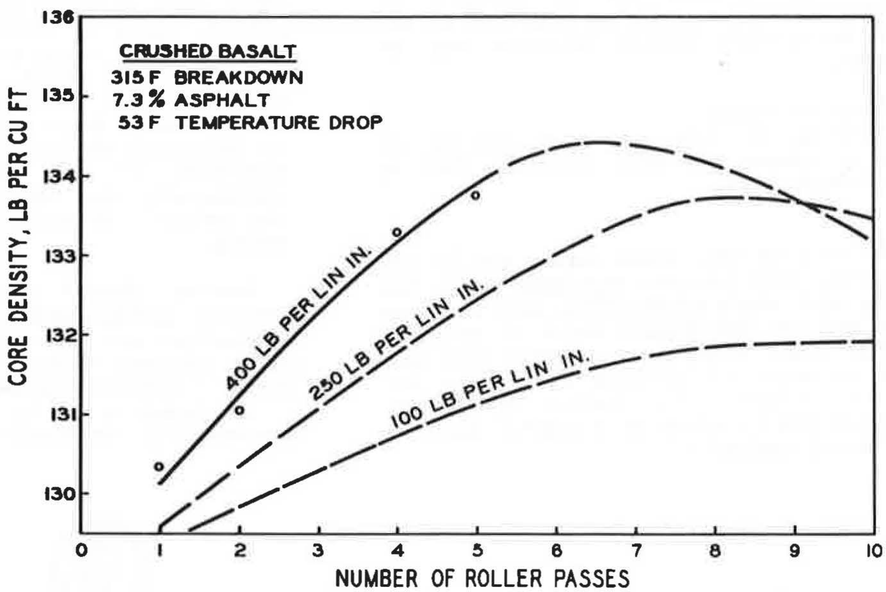


Figure 3. Core Density vs Number of Roller Passes for Different Wheel Pressures



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.

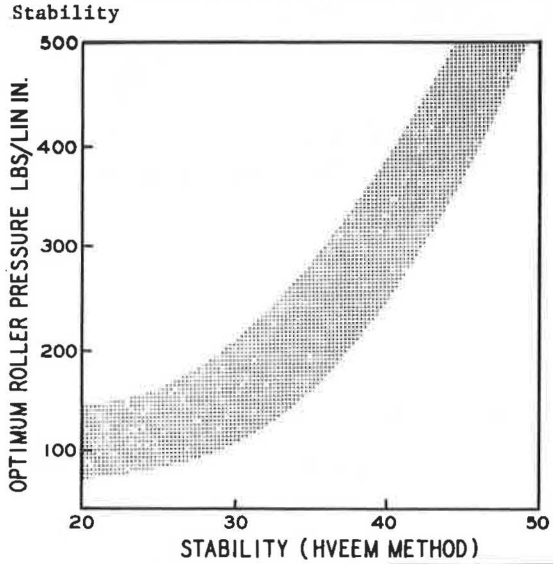
While this study dealt with only asphalt as the liquid component being absorbed, Schmidt pointed out moisture would lower the asphalt absorption and in effect increase the volume of

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

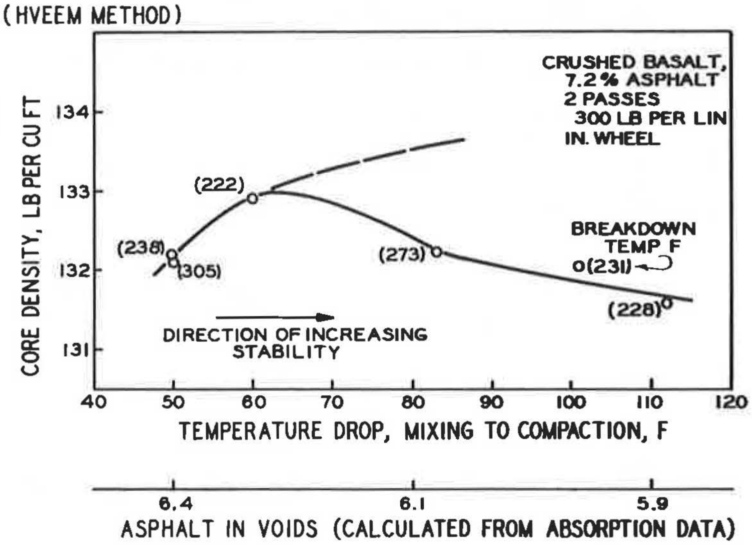


The moisture found in Figure 6 resulted in the modulus changes shown in Figure 7 from the same study (3). The modulus fell when the cores were first vacuum saturated and held at this condition for seven days. But, on drying at 50 percent and 95 percent RH, the modulus by and large remained unchanged 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



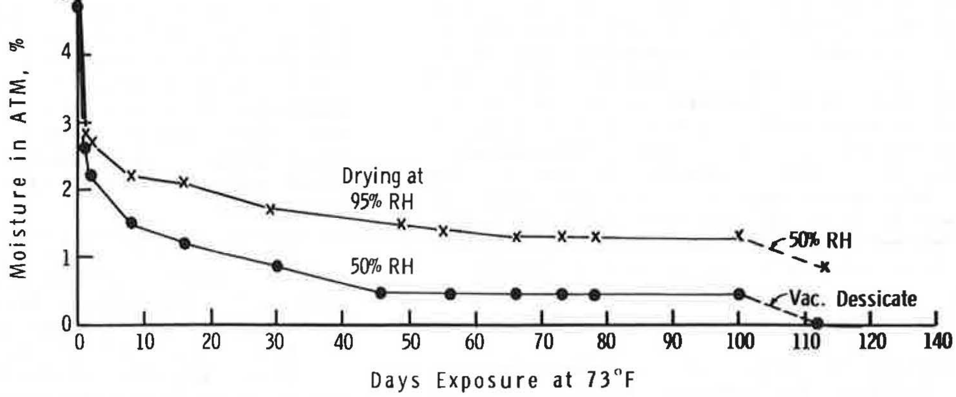


Figure 6. Humidity During Drying Controls Equilibrium Moisture Content of Asphalt-Treated Mixes

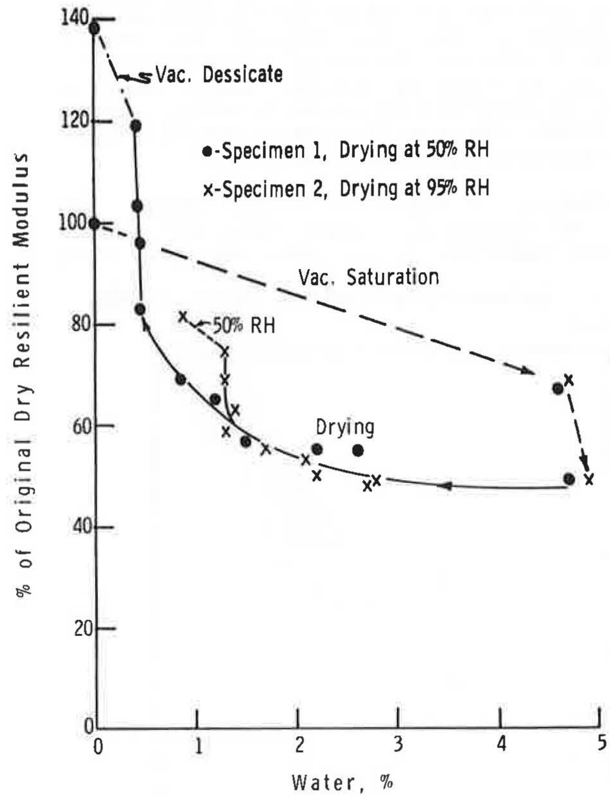


Figure 7. Humidity During Drying Affects Relationship Between Water Content and Resilient Modulus of Asphalt-Treated Mixes

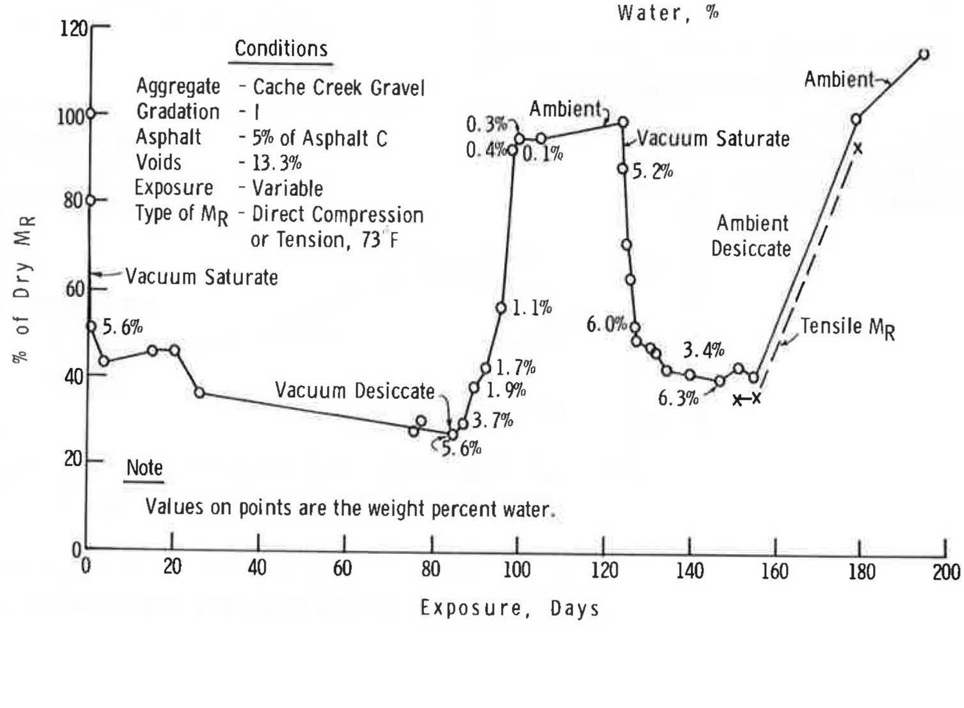
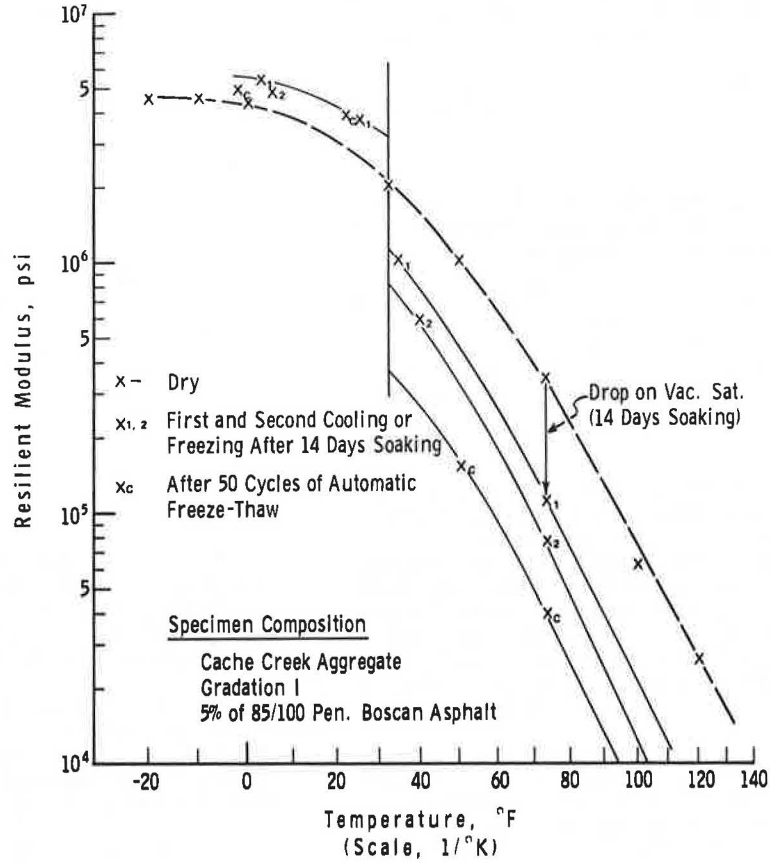


Figure 8. Effect of Moisture on M_R is Reversible

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.

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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°F 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°F.

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

the upper side of the amount specified for the job mix formula due to the loss of moisture in the sample. In some cases, the maximum allowable tolerance of 0.3 percent to 0.5 percent of asphalt from the amount specified for the job mix formula is exceeded depending on the percentage of moisture in the mix.

(4) During the hauling of the hot mixture from the plant to the project, some of the surface moisture is lost. When the mixture is dumped into the truck from the pugmill, it tends to slump in the truck if excess moisture is present. Slumping occurs when moisture, in the form of steam, escapes from internal voids in the aggregate. Bubbles form, which are trapped in the mass, and tend to cause the mix to be liquified.

(5) In most instances involving spreaders and their operation that bear on handling mixes with different workabilities due to moisture and other factors, finer mixes such as surface course and sand asphalt tend to snag or tear behind the spreader. This requires fanning or scattering fresh mix over the torn areas. Even when this is done it can cause additional irregularities by coarsening the surface or creating small bumps.

To reduce bubbling and slumping of the mixture, when the moisture is escaping, silicone can be added to the asphalt cement. For example, the dosage of about 1 oz of DC200 per 5000 gallons of asphalt is added to the hot asphalt storage tank or supply tank.

One theory related to lay down of the mix is that the silicone coats the screed and makes it slide or glide over the mix without tearing. Another explanation is related to the moisture escaping from the mix, this is that the bubbles so formed increase the volume of the mix and this forces it against the screed to the point of tearing. The silicon tends to depress the formation of bubbles and hence improves laydown in most mixes that are tearing.

There is a danger in using too much silicone because higher dosages result in asphalt mix that is soft and tender when compacted.

DISCUSSION: "Influence of Moisture and how much you have to Control in a Convention Plant"

B. Kellam - Thompson-Arthur Paving Co.

COMMENTS: L. C. Krchma
The conventional plant obviously has problems by preconception; namely that there must be a low percent moisture. Obviously if we didn't have to dry in a conventional plant as much, the emissions would not be as high and fuel demand would be lower. So, it is worthwhile considering whether or not the moisture requirements are realistic. Our speaker suggests that on occasion when they have laid mixes with higher than two tenths or five tenths moisture, and that the job went down right and the job performed properly. Any questions?

QUESTION: Mr. Coolidge - Warren Brothers (Maine District)
What method was used to determine the percent of moisture in the mix itself?

ANSWER:
They go out and take a sample, which can pick up moisture from the time they get it out of the hot elevator until they get it to the lab - weight it and redry it. It usually will run about one to two tenths percent by weight of the aggregate. Now, if the humidity is high, it can pick up another tenth or two from the time they get it from the plant to the lab, which is on the same site - maybe 50 to 100 feet apart.

QUESTION: Vaughn Marker - The Asphalt Institute, College Park, Maryland
Are the aggregates in North Carolina more absorptive to start with?

ANSWER:
Most of them are granite-base aggregates, which are good aggregates. They are not highly absorptive. We have a seal coat mix we might discussed. It is strictly a 3/8" top-size and liquid asphalts are the binder. This stone can be heated only to 250°F temperature to remove some of the internal moisture discussed earlier by Lottman. We have good success with this.

QUESTION: Anonymous
What about the minute bubbles that appear in the mix at the time?

ANSWER:
This arises when there is excess moisture and the materials are not thoroughly dry. You can see it in the truck; it tends to become liquified. You can hear it sizzling. Usually when you stick a thermometer on the side of the truckload - that load goes "over the bank" because it is below the 250° minimum of the specifications.

QUESTION: L. C. Krchma
The mix that's leveling in the truck - is it segregating? Is anything wrong?

ANSWER:
No. At this particular state the mix was not segregating. It could be used.

QUESTION: L. C. Krchma
But this does say that the moisture requirement was imposed for some reason. It would appear that we should have some other way of regulating the amount of moisture than simply 0.2 to 0.5 percent?

ANSWER:
That's true.

QUESTION: R. J. Schmidt - Chevron Research, California
I have the impression from your discussion that your problem with moisture is one of meeting specifications rather than a problem resulting from excessive moisture.

ANSWER:
There are no problems as long as the temperature is up, because then the moisture is below 0.5 percent. We have produced mixes for our own roads with 3/4 to 1 percent moisture out of the dryer and cored samples for density, etc. and have found no problems other than the bubbles in the truck.

QUESTION: R. J. Schmidt
That's not an actual problem, is it?

ANSWER:
No. That just scares you. It is a visual scare. It is not detrimental to the pavement.

QUESTION: Anonymous
What are they looking for when they are questioning you about your moisture? Are they expecting 6 months from now is it going to ravel, push, shove, or what have you?

ANSWER:
I think the State of North Carolina's main concern is ravelling of the mixture with the moisture in it. They like to keep you down to around 0.2 to 0.3 percent moisture in the aggregate.

QUESTION: L. C. Krchma
Have they confirmed that ravelling occurs when you exceed that 0.2 - 0.5 percent?

ANSWER:
To my knowledge - they haven't.

QUESTION: Herb Schweyer - University of Florida, Gainesville, Florida
Is there any documented proof that a mix with 5 percent moisture in it does cause problems?

ANSWER:
To my knowledge there is no documented proof as to what causes the problems. If they had 1 percent, 1/2 percent, 0.2 percent - you could take a mix of 0.2 percent and be subject to ravel just as much as a mix with 5 percent that was laid under the same conditions.

QUESTION: L. C. Krchma
Do you really mean 5 percent?

ANSWER:
That's what he said. He said 5 percent. At 5 percent it is going to run out of the truck with asphalt; it's not going to be there. But, to my knowledge, there is no documented proof that the moisture causes it to ravel.

ASPHALT PAVING MIXTURES -- DRUM DRYER

R. L. TERREL

ABSTRACT

The dryer-drum mixing process can accommodate a wide range of apshalt mixtures, particulary regular hot-mix asphalt concrete. The system includes a cold feed unit for aggregate which goes directly to the drum at which point the asphalt is added. Blending and heating takes place in the drum and mixtures with temperatures ranging from 180° - 300°F are produced. The asphalt is aged less than the conventional plants and well-coated mixtures are readily compacted at low temperatures because of the moisture present. In addition, stack emission of dust is reduced considerably.

INTRODUCTION

The manufacturing and placing of hot asphalt mixtures has become a standardized and routine process for most producers throughout the world. Consumers such as state and federal highway departments, as well as private developers, have come to trust the product of well-controlled plants operated by conscientious producers and contractors. Unfortunately, this state of affairs was established many years ago and very little has been done to modernize the technology of asphalt paving at a rate consistent with other contemporary industries.

Many years of experience have taught the engineer and contractor that several basic steps are necessary to produce high quality mixtures. Basically, these include the following:

1. production, handling, storage and measurement of materials;
2. heating and drying of aggregate;
3. mixing the materials; and
4. transporting, placing and compacting.

During the past several years, however, through research and experience developed in the Pacific Northwest and elsewhere, it has been shown that the total production system may be simplified considerably without sacrifice of quality or production. In this paper the author attempts to describe briefly a new process for manufacturing asphalt paving mixtures using the dryer-drum or Shearer Process as developed by Pavement Systems, Inc. of Seattle, Washington. This drum mixer type of plant is now being manufactured and marketed under license by the Boeing Construction Equipment Company, Seattle, Washington.

BACKGROUND AND SCOPE

Blending of asphalt mixtures in a revolving drum is not a novel idea, but its history is not well documented. K. E. McConnaughay Co. of Lafayette, Indiana has produced emulsion mixes under a patent for several years and also holds a patent on a similar process for hot mixes. Prior to this in 1959, however, the Asheville (N.C.) Paving Company [1] attempted to promote the production of paving mixtures using the dryer from a conventional plant.

In West Germany, a "dust free" asphalt is being marketed by the Wibau Company. In this plant the materials are blended first with a pugmill and then heated in the dryer-drum or activator. Both this process and the one of McConnaughay's [2] utilize chemical admixtures to promote coating and adhesion. To the author's knowledge, the success of the processes discussed above has not been reported in technical journals, but rather, this information is of a proprietary nature.

The Shearer Process (patent pending) was developed beginning in late 1969 with modifications of standard plant components, and several concepts which appeared to be vital to the needs of the paving industry. These include at least the following: (1) overall reduced cost through higher production rates with lower equipment and production costs; and (2) improvements in the control of dust and other stack emissions in order to become more compatible with new environmental controls now in vogue; and (3) decrease in move and set-up costs of portable plants due to mobility and less equipment handling.

The first testing by an outside agency of the Shearer Construction Company plant was conducted in July 1970 and sponsored by the National Asphalt Pavement Association. Although results of these tests were not published in total, the basic conclusions were presented by Foster (3) of that organization. Further evaluation of the process

was presented in two other reports [4,5], which along with Foster's report, attested to the general suitability of this process for producing acceptable materials provided that appropriate quality control practices were adopted and maintained. The general properties of the asphalt mixture were very similar to that produced by conventional hot plants.

During the Spring of 1971, the Federal Highway Administration Division Office of Olympia, Washington initiated a study of the Shearer Process as a part of an overall evaluation of all such methods being proposed for use on Federal projects. This initial study was conducted at two private construction projects during the 1971 construction season in Western Washington [7,8].

During the 1972 construction season several projects were monitored by FHWA [9] in North Dakota, Iowa and Minnesota. A total of more than 800,000 tons of hot mix was placed on several projects. Most of this tonnage was in North Dakota where the contractor, Northern Improvement Company of Fargo, North Dakota, operated two plants of Shearer Process design. The successful experience on these projects under normal construction conditions has done much to promote the acceptance of dryer-drum mixing by both contractor and highway agencies alike. At the time of this writing, there are plants operating in many states of the U.S. with a total mix production to date approaching three million tons.

PRODUCTION OF MIXTURE

The production and laydown of hot-mix asphalt materials has been suggested [6] as a total system similar to that shown in Figure 10, which depicts a conventional plant. As indicated earlier, one goal of the Shearer Process is to reduce the amount of equipment required. The simplified Shearer Process essentially eliminated item nos. 4, 5, 6, 7, and 8 (actually no. 4 is included in no. 16).

The Shearer Process incorporates two basic features which tend to simplify the overall production process:

(1) aggregate cold feed control; and
(2) mixing drum with parallel flow of air and materials.

The system is depicted schematically in Figure 11 showing the general arrangement of equipment.

Shearer's first plant as used at Port Ludlow, Washington, produced about 20,000 tons of hot-mix asphalt concrete including asphalt treated base (pit run aggregate up to 2" maximum size). A gate-controlled single-bin cold feed was used with 6-ft diameter by 24-ft long modified dryer-drum. This prototype plant was modified frequently throughout 1970 while it was being used to produce mixtures for numberous paving sites [4].

By the 1971 construction season, Shearer had a completely new plant as shown in Figure 12. Basic changes included the addition of a three-bin feeder system and conversion to parallel flow within the drum (i.e., air and materials move in same direction).

In May of 1972, the first commercially built plant using the Shearer Process was delivered to Northern Improvement Company of Fargo, North Dakota. The large 10-ft by 40-ft drum had an apparent capacity of about 600 tons per hour, but was limited at this site by the slot conveyor system which could handle only 450 tons per hour.

The major components of the Shearer Process plants are noted in Figure 11, and can be further seen in the photographs in Figures 13 and 14.

Three-bin feeder. Aggregate gradation is controlled by a combination of variable speed belts on each bin and variable gate opening. By calibration and control of the stockpile gradation, very uniform gradations can be produced. An alternative system has been individual weigh belts for each bin.

Aggregate conveyor. Combined aggregate moves to the drum on a conveyor belt which is fitted with a load cell type weighing system. This electronic scale is linked directly to the

Figure 10. Scheme of a conventional plant for the production and laydown of hot-mix asphalt materials

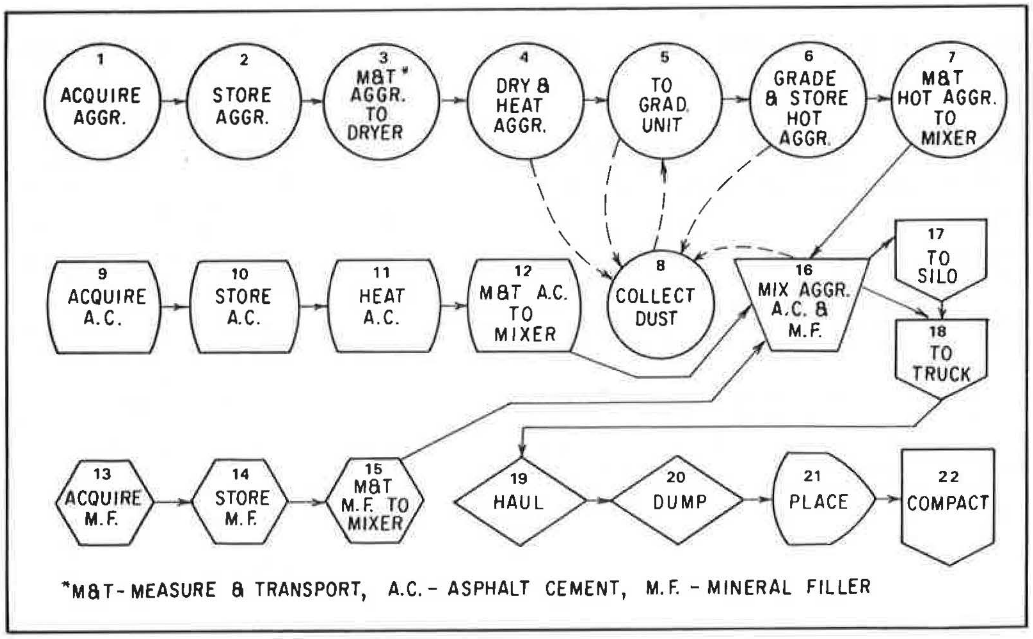


Figure 11. General management of equipment for production of mixes.

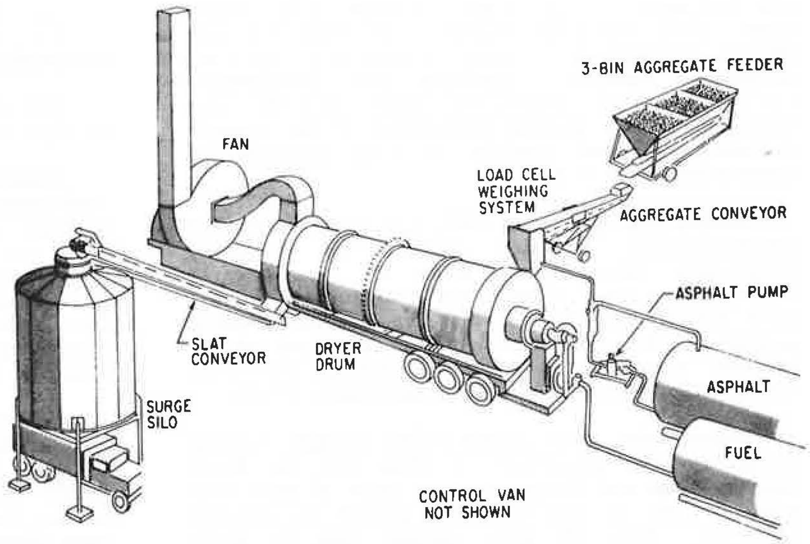


Figure 12. New Shearer plant used in 1971 included dryer-drum

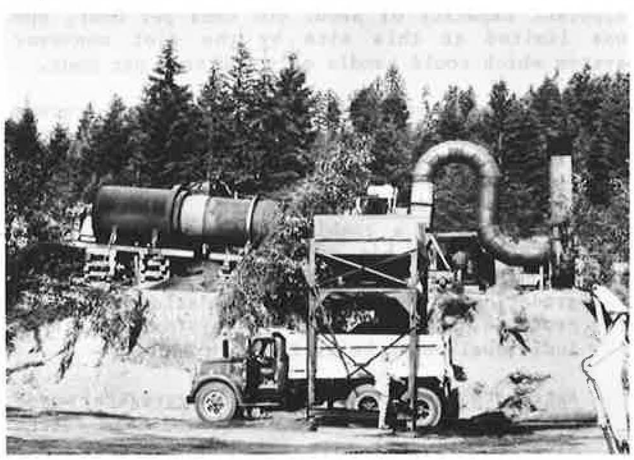


Figure 13. Three-bin feeder system also part of new Shearer plant system

asphalt pump so that a predetermined asphalt-aggregate ratio is constantly maintained.

Asphalt pump. A positive displacement type asphalt pump that sprays hot asphalt directly on to the aggregate as it enters the hopper at the top of the drum.

Dryer-drum. The heart of the system; the drum is fired by a conventional type burner using either diesel or propane-type fuel. Flite design is such that the aggregate-asphalt blend is directed away from the hottest part of the flame. A combination of heating, drying and mixing produces a uniform paving material. The low-oxygen atmosphere reduces hardening and the presence of steam enhances coating. Retention time in the drum is about 3 - 3 1/2 minutes and the discharge temperature is usally maintained at about 210°F. The discharge mixture at this lower than normal temperature generally contains about 1 - 2 percent water, which aids the handling and compactablity at lower temperatures.

Slot conveyor and surge silo. This type of temporary storage is convenient for most operators of the plant. Since the plant normally runs continuously, the silo eliminates the usual need to shut down when trucks are delayed. However, even if the plant needs to be temporarily stopped, the fire is simply shut off and the drum stopped. Once the silo can accept more mix, the plant is started and production continues as before, with no loss or damage of materials.

Control van. All switches and other plant controls operate from a central point. Material proportioning and temperatures are controlled and recorded. A single operator usually monitors the plant and loads trucks from his vantage point within the van.

Of some concern to most engineers is the hardening process that takes place in the drum in the presence of the high temperatures. Figure 15 indicates the behavior of asphalt within the mix thoughout the construction process [8]. The dashed lines show that the original asphalt was

Figure 14. Slat conveyor, surge silo, and dryer-drum components of Shearer plants

Figure 15. Behavior of asphalt within the mix during construction

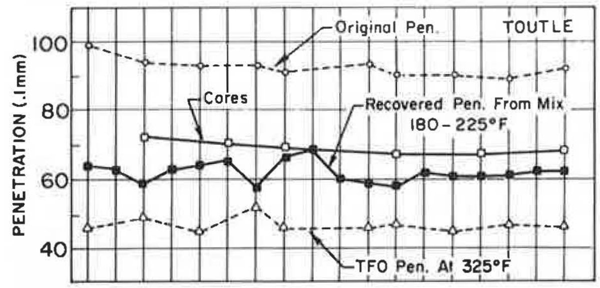


Figure 16. Paving operation in progress in Washington State at 16 F.

reduced in penetration from about 93 to about 47 following the TFO test. The data in this figure represent about 15,000 tons of mix produced on a project in Washington. The solid lines show the penetration of asphalt recovered from mix samples at the plant and from the road several weeks after construction. Since the TFO test generally represents the aging after about one year and from a conventional pugmill type plant, the reduction in penetration is somewhat less for the drum mixer. These data indicate that hardening is not as severe as might be anticipated, and in many instances is less than for a conventional type plant.

Asphalt pavements with a full range of asphalts have been constructed. All paving grade asphalts have been used, from 60-70 pen to 200-300. In addition, both MC-800 and emulsion mixes have been produced successfully.

Paving operations and laydown of mixtures produced by the dryer-drum process are very similar to those for conventional plants. The mass viscosity of the mix is the key factor. The characteristics of the mix at 220°F with 2 percent water is similar to the conventional dry mix at 300°F. Moisture continues to evaporate from the mat during laydown and compaction. Earlier photos taken in North Dakota were during warm weather, while Figure 16 was a scene in Washington with the air temperature at 26°F where evaporation is much more noticeable.

It would appear that the moisture is a key factor in the success of dryer-drum mixing. Production of mix at lower temperatures is possible with moisture present. However, mixes have been made with this type of plant at the usual temperatures of 300-325°F with no serious problems. Operation between these limits may not be advisable because the moisture is insufficient and the temperature too low to provide the low mass viscosity needed for handling.

Most aphalt pavements in service have a residual or equilibrium water content of about 1 percent or even more depending on the nature of the aggregate and void structure. This equilibruim is reached after the first year or so of service following construction. By following the water content changes throughout the mixing-paving process, one can note that the dryer-drum process may permit the mix to approach this equilibrium in a normal manner. Figures 17 and 18 show the water content change for two different material combinations and situations in general. In Figure 17 the aggregate stockpile had about 4 percent water and eventually leveled out to about 1/2 percent. The aggregate material shown in Figure 18 was more porous and the stockpile was wetter (this was November, while Figure 17 was in August). Again, the mixture tended to seek an equilibrium water content, but somewhat higher than for that shown in Figure 17. In summary, the water content in the dryer-drum produced materials tend to approach an equilibrium from the wet side, while in conventionally produced mixtures, it is approached from the dry side.

The compaction process itself is similar to that for other materials. As an illustration of what occurs during compaction, Figure 19 indicates (in the upper curve) that increased density is obtained as the number of roller passess increase. The lower curves show that the temperature drops from the laydown at 190°F to 155°F during this same period. In addition, as shown by the water plus asphalt curve (as measured by the nuclear gauge), water continues to evaporate, and eventually may level out. The final water of 2 percent content is the same as in Figure 18 and the asphalt content was 5.5 percent. The total water and asphalt content of 7.5 percent then checks with the curve shown in Figure 19. In summary, it appears that Figure 19

is a reasonable illustration of what occurs during the compaction process and that increasing densities are possible at these lower temperatures.

In general, most engineering properties of mixtures produced by the dryer-drum process are comparable to those produced by conventional plants. There appears to be some concern with both the short-term and long-term effects of the added moisture. It is possible that in some situations a temporary "tenderness" may be observed, but in projects known to the writer to date, this has been minimal. Longer range durability is still somewhat unknown, but after more than 3 1/2 years since the first project paved in Washington, no adverse effects have appeared.

The particulate emissions from the stack of a dryer-drum plant can be reduced dramatically. All factors relating to stack emissions have not been evaluated to date. However, the writer has observed several dryer-drum plants which would no doubt meet existing requirements without any collection equipment being used. In other situations, because of material and fuel

Figure 17. Water content change: 4 percent water leveled out to about 0.3 percent (August).

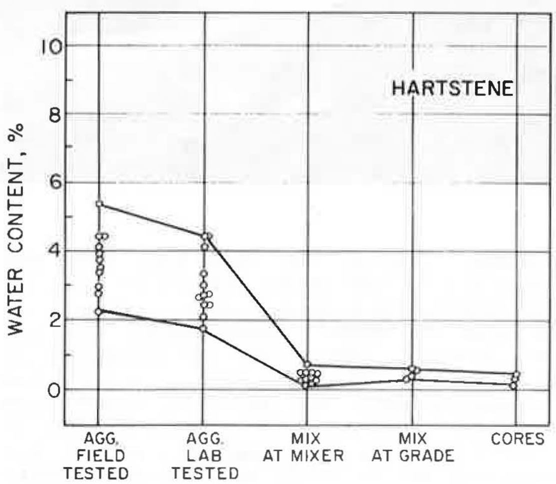
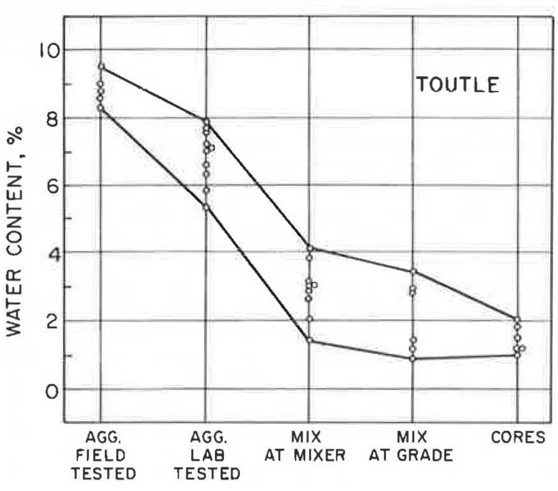


Figure 18. Water content when aggregate is more porous and stockpile is wetter (November).



combinations, a cyclone or some other add-on unit would be appropriate. Figure 14 shows the asphalt plant in full production and Figure 20 is a

Figure 19. Density and temperature during compaction.

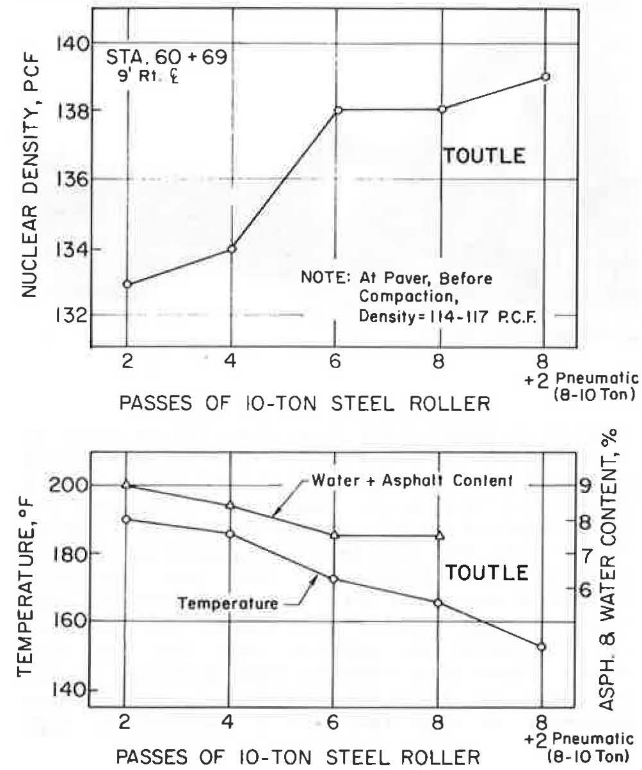


Figure 20. Close-up of plant stock.

close-up of the stack, indicating how clean the plant can operate.

In addition to the large (10-ft. diameter by 40-ft. long) size plants which can probably operate at a consistent 600 tph, there are medium size and small or "mini-plants" available.

CURRENT USE OF DRUM MIXER PLANTS IN THE U.S.

During the 1972 and 1973 construction seasons, drum mixing has blossomed in the United States. From the handful of "pioneer" contractor operations in 1972, at least 34 drum mixer plants were producing in 1973. Several plant manufacturers have configurations or variations of the basic drum mixer and include at least the following:

Manufacturer	No. of Plants Operating 1973
Boeing Construction Equipment Co.	21
Barber-Greene	6
Stan-Steel	1
CMI	3
Cedar Rapids	1
Aztec	2
TOTAL	34

Acceptance by state agencies, particularly highway departments, has been remarkable, and the trend would indicate that acceptance will soon be nationwide. Although many states have used the process, the bulk of production (2,525,000 tons) has been in the following states:

State	No. of Plants	Production
Alaska	1	50,000
Arizona	2	200,000
Michigan	2	100,000

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DISCUSSION: "Asphalt Paving Mixtures -- Drum-Dryer -- R. L. Terrel

QUESTION: Claude Marais, South African Council for Scientific and Industrial Research.

Please comment on the effect of performance of a lesser drop in penetration and additionally on the effect of the moisture present on the early performance.

ANSWER: Terrel

I believe that several things happen with regard to these factors, and I don't know if I really have that ability to explain them. First, if we consider the moisture effect on early performance, it is probably best to think in terms of the compaction process, or workability in general. The viscosity of the asphalt binder will be somewhat less because of reduced hardening; however, at this point, it is probably not too significant. Our feeling is that there is a direct relationship between the amount of water in the mix and the temperature. In other words, I like to emphasize that the drum mixer is a lower temperature process, with typical recommended mix temperatures at about the boiling point of water, 210° to 220°F., as compared to conventional mix at, say, 275° to 300°F.

The phenomenon here is that we are trading water for heat. The moisture, usually one to two percent, provides lubrication which restores the mix viscosity lost due to lower temperature.

In answer to your question regarding the early performance of these mixtures, I have often heard questions and comments to the effect that "we don't know what is going to happen when we try these mixtures." The natural tendency is probably to expect a 'tender' mix. On occasion, this may happen, but probably no more often than with conventional mixes. At worst, it is a very temporary situation and is not detrimental as Bob Schmidt has repeatedly pointed out in earlier discussions. It is temporary, if it happens at all, and since the moisture is rapidly evaporating during laydown and compaction, the normal equilibrium water content is eventually reached in either case."

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

I observed on a job they were adding lime to the aggregate. What effect would this have on a job and on stripping?

ANSWER: Terrel

I really don't know, since I haven't seen any reports on this job. With regard to early stripping, we don't have extensive data as yet. However, we do have test results from immersion-compression tests that show more than 100 percent retained strength. This test may not be sophisticated, but it does indicate something with regard to water susceptibility. Some preliminary tests were made by Professor Bob Lottman using the procedure being developed in the NCHRP Project. Results from an Oregon project indicate that mix may be more susceptible to moisture damage than we might expect. However, these tests were very limited and the samples used were considered non-representative.

QUESTION: Anonymous

What was the aggregate absorption on that last slide that had about 2 percent residual water, and were these paved under traffic conditions?

ANSWER: Terrel

From memory, I believe the aggregate absorption averaged about 3 percent. It was glacially deposited volcanic material with a mixture of dense granitic material and pumice, which is quite porous. The project was paved under traffic conditions. It was a private logging road and traffic was permitted on the fresh mat within four hours after laydown. Traffic consisted primarily of 5-axle, 150 kip logging trucks spaced at 2 to 3 minute intervals, 24 hours per day.

QUESTION: Anonymous

Did the water content in the mix exceed the absorption of the aggregate?

ANSWER: Terrel

I don't recall, since I didn't bring that information with me. Furthering my comment on traffic conditions, there have been quite a variety of projects using drum mixers. Extreme environments have been encountered from Arizona to Nome, Alaska. Rural highways and Interstate Projects have been completed, but I can't recall any major urban paving. In total, quite a few million tons have been placed to date.

HAULING, SPREADING, AND ROLLING - CONVENTIONAL MIX SYSTEM

DUNCAN A. McCRAE, District Manager
Lane Construction Corp.
Cumberland, Foreside, Maine

From my Northern Maine observations, I feel qualified to state that a reasonable amount of moisture in bituminous concrete does not seriously effect the operations of hauling, spreading and rolling this product. After I had written that statement I sat back and discovered that it really wasn't profound; in fact, I suspect that among pavement engineers and contractors that is reasonable accepted knowledge. Based on recent papers and on Charlie Foster's statements to Committee A2F02 of last year, we know that moisture in mixes manufactured in "Drum Mixers" is acceptable and, in fact, perhaps even necessary. However, these considerations posed two additional questions to me.

1. What is a reasonable amount of moisture?
2. Can moisture contents be readily determined in the field and at what point should the control be established?

My experience is that gained from observations made at our Northern most plant location in Caribou, Maine. As a construction engineer, and later as a construction superintendent, I have lived or travelled in the New England States, New York and the Middle Atlantic States and I felt that this range of experience made me qualified to observe and reasonably rate the quality of construction raw materials. The first time I was able to see typical Aroostock County Gravel I knew my experience had just included the lowest quality range of gravels.

Our aggregate processing plant was a multi-wash on both fine and course aggregates with special adaptations designed to remove soft pieces of aggregate not destroyed in the crushing process. The bituminous plant when originally set-up had one dryer, designed I suspect for average drying conditions. It was almost immediately that a second dryer was purchased in order that even a minimum production level could be maintained.

However, after all this aggregate preparation and drying we still produced bituminous concrete, on occasion, with excessive moisture.

Hauling wet bituminous concrete, I use the term loosely, presents no problems. Depending, on the amount of moisture, the load might flatten in the truck. Other times free water would run out of the tailgate. The haul distances would usually affect its physical appearance.

As far as I have observed the spreading of high moisture bituminous concrete required no special adjustments or considerations. The most notable occurrence was numerous blisters that would form most frequently in the middle of the mat. When the material is augured to the side, then most of the moisture was freed. These blisters would quickly subside and leave no trace.

Rolling did not require special tactics. The only consideration would be to hold back until all blistering had ceased. This usually occured within a few minutes after laydown.

The paradox that I now find puzzling concerns the pavement in its final position. Does it in fact contain moisture in excess of 1/2 or 1 percent. I know the aggregate had moisture in it for I have seen steam rising from hot bins. On occasion I have actually seen water dripping from those bins. I have seen loads level out in trucks. I have seen water drip from loaded trucks. I have seen steam escape from laydown mats. From this it appears the moisture content was high though we did not collect the confirming data. Yet after all these adverse situations I now seriously doubt that in our final mat we exceeded 1 percent moisture.

From observations I conclude that as long as bituminous concrete can be spread and rolled in the conventional manner, then the moisture content should not be a restrictive specification.

DISCUSSION: Duncan McCrae's presentation -- "Hauling, Spreading, and Rolling - Conventional Mix System"

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

I do not usually associate slumping in the truck with the problems of tearing under screed. Did you observe this, and did you use silicone in your asphalt?

ANSWER:

No. We did not use silicone but with Kellam's talk about it this morning, I am going to look into it. We do use silicone in making certain of our cold mixes - at least in the summer time. But the workability was excellent. We never had a tender mix; we never had any experience with tearing, except when you let the temperature get down. It is necessary to work these mixes, in general above 275°; better around 290° to 300°. As the temperature dropped under 275°, the speading was more difficult and it was more obvious there was some tearing. In the normal temperature range it worked very well. I think this might just be true of a gravel aggregate. When we moved out of the gravel and into the quarry stone the mix did not

spread and handle quite as nicely as the nice, smooth rounded pieces of gravel.

QUESTION: C. Parker (Gorham, Maine)
What has been the durability of these pavements using the type of gravel aggregate you have described?
I know that you had some interesting Marshall stability values, using these aggregates. Will you tell us about the values obtained?

ANSWER:
To answer the question on durability - I think the durability was quite good. There are pavements up there in Maine right now, made with these types of aggregate and never sealed, that are 20 years old. Yes, they have wheel ruts in them, etc., etc., but the pavement does not look too bad. The thing that really detracts from the quality of this pavement is that within two seasons the surface appears as if it has been sandblasted. Still it doesn't seem to deteriorate after that. In this very rough surface you can observe a certain amount of stones (I had experience with them in concrete) that can be called pop-outs, where apparently they either had moisture in them or they have absorbed moisture and expanded and popped out. I don't know much about the Marshall design methods in answer to Mr. Parker's second question. We had an FAA contract there. We had a difficult time making anything fit but we had stabilities in the range of 4,000 and the density of this material is greater than the density of concrete.

QUESTION: Clinton Coolidge - Warren Bros., Fairfield, Maine
What experience did you have with testing agencies as to what moisture they found in these materials and the method they went about doing this?

ANSWER:
I talked with the Maine Department of Transportation. That plant had been operating in gravel, typical gravel, for approximately 16 years before I went up there and I am sure that somebody in the State Department of Transportation and in perhaps the Federal Bureaus, spent much time trying to figure how you can make better gravel out of something that is just there. You can't really do it and the State of Maine does not specify allowable water count. I always felt that they were working on a basis of 1/2 of one percent and, just from recollection, they found great deviations as Lottman said eariler. They also found deviations in the temperatures of the various aggregates in the hot bins. Still I don't think they ever convinced themselves that there was excessive moisture in the final mat.

SYNOPSIS OF PAUL SERAFIN'S PAPER EFFECT OF MOISTURE IN BITUMINOUS MIXTURES AS EXPERIENCED IN FIELD PAVEMENT OPERATIONS IN MICHIGAN

given by
Frank M. Drake, The Asphalt Institute
Lenexa, Kansas*

HISTORICALLY
In 1951 Michigan Highway Department made a moisture study of mixtures where the contractor was experiencing difficulty in laying and rolling. During this investigation, it was apparent that very small amounts of moisture 0.05 percent or more were causing the problems. At this time moisture content requirements were lowered to 0.05 of one percent.

The following season all possible adjustments were made on the plants to effect moisture contents that would comply with the new restrictions. Further, the use of additives were tried to reduce foaming and deter the chances of stripping due to the presence of moisture.

Associated with these studies it was noted that a change in sand gradation from the traditional high percentage in the middle of the gradation to a uniformly graded sand appeared to offer more tolerance to the residual moisture in the resulting mix without causing problems. Further improvements in mix design such as reducing the material finer than the 200 mesh sieve from about 6 or 7 to 4 or 5 percent, also resulted in further tolerance of the mixture to moisture. It was also during this period that the contractors were replacing worn-out equipment. This probably was the biggest factor in Michigan that helped correct the moisture situation to a point where today this type of problem is almost non-existent. This, we feel, is attributed to more uniformity in the mixture produced by the more sophisticated equipment. Periodic investigations by the Michigan Highway Department indicate that when cores are extracted during the wet part of the season or when a pavement was recently submerged in water, stripping is apparent. However, it is also noted, even though stripping is present, there is no adverse effect on the performance of the pavement. When the same pavements have been cored in dry seasons, stripping seems to disappear.

In summary, the contribution to this conference would be that the experience in Michigan is that the critical moisture in a given pavement in regard to performance would depend on materials and mix components. However, in most cases that amount would be well above the moisture content tolerable through the construction operations and procedures. Or if the moisture content is held below the level critical to construction operations, there should be no detrimental effects of moisture on performance. Different aggregates will produce different performance.

QUESTION: L. F. Erickson - Idaho
Can you tell me whether these were limestone aggregates or siliceous aggregate?

ANSWER: Drake
I think these were largely siliceous aggregate. I believe this is primarily what Michigan has.

QUESTION: Anonymous
How about Kansas?

ANSWER: Drake
In this area that I speak of, the aggregate is siliceous also.

*Paul Serafin's paper was not presented in full at the session but is published here.

EFFECT OF MOISTURE IN BITUMINOUS MIXTURES AS EXPERIENCED IN FIELD PAVEMENT OPERATIONS IN MICHIGAN

given by

PAUL SERAFIN

In 1964 a questionnaire was distributed by the Highway Research Board Committee MC-A2 to the state and provincial highway departments to obtain information concerning the effects of moisture on bituminous mixtures. As in many questionnaires, the questions often do not lend themselves to a "yes" or "no" reply, resulting in some personal interpretations by the reviewers.

A summary of the replies received did, however, indicate that moisture causes a critical condition in hot bituminous mixtures. It is not limited to a few areas but is widespread in the USA and Canada. What was recognized as a problem related to moisture by some people may have been ignored or even gone unnoticed by others. Some engineers, on observing flushing of the bitumen have interpreted it as due to moisture, others examining the same conditions claimed there was to much asphalt in the mix, while still others held that the mixture was too hot.

Prior to 1945, Michigan highway engineers on occasion observed segregation, flushing, loss of stability, blistering, and other conditions during the laying of a hot bituminous mat. Many reasons were given. It was not until people began noticing moisture dripping from the asphalt mix truck box, which was associated with slumping mixes in the truck and other related problems, that it was generally agreed that moisture was the culprit in many instances.

When methods of aggregate drying were improved, the conditions noted seemed to disappear resulting in a conclusion that residual moisture in hot asphaltic concrete, at the time of lay-down, caused these conditions. This resulted in greater effort to require more efficiency in the aggregate drying operation to reduce the residual moisture.

The improved drying operation caused a slow down in production and was an added expense to the contractor, therefore, these efforts were challenged by the contractors with claims made that the drying requirements were unrealistic and unwarranted.

In 1951 the writer made an investigation on the exact amount of moisture that was present in the critical mixtures. This was accomplished by a revision of the equipment for water determination by the trap method described in AASHO Method T55. In place of a circulating water jacket used to condense the vaporized solvent and water in the reflux tube, a tin jacketed reservior filled with cold water was used to condense the solvents releasing the water to the water trap. This method allowed measuring small quantities of water in a bituminous mixture in the field without the need for running water for condensing purposes. A metal container was used in place of a glass flask for the mixture sample, and a gasoline stove was used to supply the heat with a high flash naphtha for the solvent.

Tests were performed and it became apparent that very small amounts of moisture, at contents of 0.05 percent or less, were causing problems with certain bituminous mixtures containing calcareous and dolomitic coarse aggregates. Based on numerous such test results the specifications were written to require the aggregates to be dried to no more than 0.05 percent moisture in the bituminous mixture. After one season of experience with this requirement, it was recognized that other types of aggregates could tolerate higher amounts of moisture with amounts of 0.1 percent and more in some bituminous mixtures without detrimental affects.

Contractors and engineers used various approaches to improve on the drying efficiency. Holding the dried aggregate in the hot aggregate bins for additional short periods to allow for "sweating out" was one procedure. This was accomplished by "keeping the bins full". Increasing the dry mix time was another successful approach which allowed time for moisture to escape before the aggregate was coated with asphalt. Reduction of batch weights resulted in less aggregate going through the drier with better drying efficiency. Fan speeds were increased, slopes of driers were reduced and bigger driers were installed. Orfices in the burners were increased, changes were made in the flight arrangements in the drier, and even double driers were installed. All these changes improved the drying, however, on occasion, residual moisture still continued to plague the engineers and contractors alike in attempting good quality control of bituminous pavements.

Early in 1952 tests were conducted to determine the effects of silicone additives in bituminous mixtures. Additional studies were made in the field to determine the effect of silicone in eliminating mix foaming resulting from the residual moisture escaping through the hot asphalt film, which coated the aggregated particles. The use of this additive appeared to lower the surface tension of the asphalt.

Antifoaming agents of silicone material of the dimethyl polysiloxane type, preferably of about 1000 centistoke viscosity grade, were permitted to be added to the asphalt in amounts not to exceed 5 parts per million. Dow Corning DC-200, General Electric SF-96, and Union Carbide L-45 silicone products were among those additives that met these requirements. Perhaps because of the proximity of the Dow Corning manufacturer, most contractors used the DC-200 additive.

Presently the Department permits the addition to the asphalt of a solution of silicone in kerosene or No. 1 fuel oil. No observations have been noted of stripping or other detrimental conditions where more than 5 parts per million of silicone were added to the asphalt. However, amounts in excess of this quantity of this costly additive do not seem to improve the conditions. There has been some controversy above when the silicone should be added -- at the refinery during asphalt loading for delivery, or at the asphalt plant by the contractor. Because so many procedures were used by the contractors, some adding the silicone with questionable accuracy, it was decided the preferred place for addition was at the refinery. Some refineries now add 3 ppm to their storage tanks and supplement the balance of 2 ppm at the loading dock as requested by the contractor.

Associated with these studies it was further noted that a change in sand gradation from the traditional "belly sand" (high percentage in middle of the gradation) to a uniformly graded sand appeared to offer more tolerance to residual moisture in the resulting mix without causing problems. Further improvements in mix design such

as reducing the material finer than the 200 mesh from about 6 to 7 percent to about 4 or 5 percent, also resulted in further tolerance of the mixture to moisture.

It was during this period that contractors began using automatic controls for mixture proportioning. This ultimately became a requirement. Prior to these improvements the inspectors and contractors' personnel were noted to be lenient in permitting partially worn-out equipment to be used. In some cases this resulted in marginal quality bituminous mixtures. With automatic monitoring of the proportioning, this did not permit leniency with the use of worn-out equipment. This probably was the biggest factor in Michigan that helped correct the moisture situation to a point where today this type of problem is almost nonexistent.

These improvements have resulted in permitting greater amounts of moisture in the resulting pavements. What harm has this greater amount of moisture done as an immediate consideration and also as a long term effect? To date no stripping has been attributable to the extra moisture in the pavement.

This brings us to the question of what effect does moisture have in a bituminous pavement in service. Stripping of asphalt from the aggregate, in the presence of water, has been observed by many people. This may be caused by incompatability of certain asphalts with different aggregates in the presence of moisture. Most asphalt technicians recognize that the presence of asphaltic acids in the asphalt gives better adhesion to non-acid or limestone type aggregates, however in contrast this may cause stripping if used with siliceous aggregates. Numerous studies of these conditions have been made and many anti-stripping additives have been developed. However, the writers' observations indicate that the long range benefits of these additives are still to be proved. With the advent of the elevated grades on most modern highways, it is seldom that we find an asphalt pavement submerged in water for long periods of time. This, I believe, has pretty much solved the stripping problem in Michigan and, more than likely, in most other states.

GENERAL DISCUSSION: (Following conclusion of all presentations)

QUESTION: D. Tunnicliff
Both Mr. Kellam and Mr. McCrea do not feel there is much problem in conventional mixes. They can get it down all right, and I agree with them. If they get to where they cannot get it down all right, it is usually affected by temperature, and so the thing to do is raise the temperature. Of course, this then drives off more moisture; so, we don't know whether it is because we lost moisture or because we raised the temperature. That's where the problem has been. But in the discussion of drum mixing, then Wes, Ron and Bob were talking about temperatures that were lower than what Duncan and Bill were talking about, and I can't help thinking that there is something else different here. We are not talking about the same animal.

ANSWER: L. C. Krchma.
No I think they agree with you.

QUESTION: D. Tunnicliff
Then, what is the difference? This is really the question.

ANSWER: L. C. Krchma
If I understand Mr. Beaty's observations, based on his laboratory work, the drum mixer can be and should be compacted at a lower temperature, and it can be compacted at a lower temperature because the moisture adds to the lubrication. The moment the moisture is lost the system reverts back to conventional dryer temperatures.

QUESTION: D. Tunnicliff
O.K., that's fine, but I have to lay this stuff too.

ANSWER: L. C. Krchma
This concerns laying. Mr. Beaty did not see this in the laboratory. He saw it in the field.

QUESTION: D. Tunnicliff
As to what was the problem in laying the conventional pavement to cause tearing, I couldn't agree.........

ANSWER: L. C. Krchma (interrupting)
Due to what? To low temperature or moisture.

QUESTION: D. Tunnicliff
This is what I brought up earlier. We raise the temperature, we get rid of the moisture, but we don't know what causes the effect to be the way it really is.

ANSWER: L. C. Krchma
I understand in some instances tearing has been minimized in the case of conventional mixes by putting in silicones.

QUESTION: D. Tunnicliff
Yes, Bill mentioned this too, and I don't see any reason why we can't put silicone in the drums too. I feel there is a different animal involved here, and one thing I would like to question - is the consistency of the asphalt. Most of what I have read about the drums involves lower consistency asphalt (lower viscoisty asphalt) than most of the work done in this country in the last 50 years. I think this has to be a factor. I don't know how much of a factor, but I would like to find out.

ANSWER: R. Terrel
I'm not sure if I detect any contradiction in what you were saying. I think basically the idea is that you are trading water for temperature in a drum-mixer, but at a lower temperature, and part of what I tried to describe here is something that other people like Mr. Schmidt would perhaps agree on. The asphalt itself actually absorbs some of this water and tends to lower viscosities; in other words, a little bit of water actually is absorbed - would you agree with me, Bob? So, in effect, you have a lower viscosity, while the water is present, and this occurs in the drum-mixer rather uniquely because of the mixing process, the vapor pressures, etc. The same thing does not necessarily occur in a conventional mixer simply because we don't have these conditions in the drum, when the water and asphalt are present together.

I don't know if I am getting to your point or not. I could cite just a quick example in the way of experience. I mentioned a job in Nome, Alaska last summer, and this was built to FAA specifications, and you may recall that they also include the stability as a key factor in that specification. Incidentally, there is a very typical tendency for a first-time user of the

drum-mixer to hedge a little bit and say, "well, I don't want to go all the way down to 200°, so I will go to 250° for the first week or two." This is exactly what you don't want to do because you get into this "tough" area that we talked about earlier. So, to alleviate that, we bring the temperature down to 210°F., and also clean up the emissions. The inspectors on the job noticed that the stability was down at the lower temperature because obviously there was a little water in the mix. I am kind of rambling a little bit, but I am trying to answer your original question.

QUESTION: H. Schweyer
I would like to ask any of the past speakers -- does the asphalt harden more, or less; drum-mixer vs. conventional?

ANSWER: R. Terrel
I believe I may have skipped over this earlier. Very definitely the asphalt hardens less in a drum-mixer. This fact has been confirmed through many tests and projects. Quantitatively, the reduction in penetration loss over conventional pugmill mixes is about 30 percent or so.

QUESTION: R. Lottman - to R. Schmidt
The question I have is about Mr. Galloway's question earlier in this session about putting a plant-mix seal over an old pavement that supposedly was all right. However, once it was covered with the plant-mix seal, possibly open and porous, the pavement below began to deteriorate. I could have answered this question by saying much of the trouble could be due to deep stripping action that starts at the bottom and works up. In this case, the old surface now is closer to the bottom and more susceptible to stripping. But, going back to Mr. Schmidt's relative humidity observations -- could he help me answer Mr. Galloway's questions.

What happens in overlays where we have a moderately moisture susceptible paving surface but it has been going through what Bob calls the yo-yo effect, alternately picking up moisture and drying fast enough so that it performs fairly well. However, putting on an overlay, it could possibly increase the humidity of the old surfacing. Would this then increase the tendency of the old pavement to retain a higher moisture over a longer period of time - causing the problems it had a potential to have?

ANSWER: R. Schmidt
I would think that any change in the structure should be suspected as possible cause for a change in the average moisture content in the original asphalt-treated mix. It is hard to speculate on the direction of change. For example, a new tightly sealed surface can reduce the amount of rainfall that penetrates into the structure but at the same time it can reduce the evaporation rate. If there is considerable ground moisture, the seal can increase the moisture in the base because it slows evaporation.

COMMENT: Warren Warden
I cannot agree with Ron and Bob on the asphalt absorbing moisture concept. I visualize the mechanism a bit differently. Namely: that in the hot mass of paving mixture we have a combination of fluids -- air, moisture and liquid asphalt-filler mortar -- encased within the aggregate voids. If the expanding air and moisture cannot escape rapidly enough, the whole fluid portion acts as lubricant, which in some cases may yield improved compaction by assisting particle orientation, but in others results in over-filling of the voids which causes slumping in the truck and tearing behind the screed. I visualize the silicone as having a surface active effect which facilitates release of both air and moisture from the hot mass, thereby reducing the volume of the total fluid enough to permit point-to-point contact within the aggregate portion of the mix.

Conference Session -- Moisture Restrictions

L. C. Krchma -- Meeting Closure:

Our panelists on the subject, "Second Look at Moisture Restrictions in Plant Operations and Construction", have discussed 'Moisture Monitoring', 'Laboratory Measurement' or Workability and Performance', 'Conventional Plant Operations', 'Drum-Mixer Operations', Hauling, Spreading and Rolling Operations', and 'Pavement Performance'.

Lottman, discussing Moisture Monitoring pointed out that the two areas of interest are control of workability, and durability. He briefly reviewed the drying process and the balance sought between heating and drying of coarse and fine aggregates, between surface moisture and absorbed moisture.

In all of this, there was sufficient variability that agencies found it necessary to set a maximum moisture but that there were problems in setting such maximums because of differences in the pore and moisture volumes and the rates of the moisture loss, or rate at which the moisture is driven off. He finds the latter particularly significant though difficult to measure.

He concludes latitude in hot-mix moisture maximums are possible to obtain workability, but in so doing, the durability trade-off needs to be known. Fortunately moisture damage information found in the literature could be useful.

Schmidt, studying laboratory workability, in the area of 'Rolling', found it necessary to resort to rolling under controlled conditions that very closely duplicated actual field conditions. By this process, a good deal was learned about compaction. It is obvious that Mr. Schmidt had to go to a good deal of trouble to measure workability. From this it is evident measurement of workability of mixes is a most important feature that our present mix design and moisture tests measure, indirectly, if at all. We need to give this more attention. This would be workability at all levels--certainly laying and compacting workability -- conceivably at some later time, mixing workability.

Schmidt made the point moisture can be a workability aid or a hinderance but up to now, we have gone only in one direction, towards less moisture. So this looks like a fruitful area of study.

The point was made that we would not have many pavements if moisture and its effects were not reversible.

The cycling in moisture level and moisture effects explored by Mr. Schmidt proved to be reversible. Thus the moisture level in a pavement is not dependent on the initial degree of drying but on an equilibrium set by the pavement and its environment. This state of affairs was used to explain the failure of a pavement once it was

overlaid. While it was not brought out in the discussion of this type of failure, it seems there was no basis in believing more complete original drying would have altered the results.

From the above, some amounts of moisture are not automatically harmful. It would appear that with reversible moisture cycling, we are further faced with the rate phenomenon discussed by Mr. Lottman. Obviously, if we are to make the most of hot-mix pavements, this needs further study and better understanding.

Mr. Kellam, in covering the 'Conventional Plant Operations' pointed out the difficulties with restrictive moisture requirements for which there is not an indication such a restriction is associated with better field performance.

Obviously there is room in conventional hot-mix for some more meaningful control, probably workability again rather than percent moisture. In doing so, fuel could be conserved and emissions reduced.

Mr. Terrel, in dealing with 'Drum-Mixer Operations' covered the mixing involved in the 'drum-mixer' and showed in his slides that placing a moisture requirement obviously involved plugging in something about the aggregates. For example, if an aggregate was absorptive, there is no question that the equilibrium moisture is appreciably higher. This is nothing new to you gentlemen but, do the specifications relate the absorptive character of the aggregate and the permissible moisture?

Mr. McCrae, in covering "Hauling, Spreading, and Rolling" reported on his considerable experience with difficult aggregates. He reported again that the moisture levels measured and specified do not correlate with pavement performance. There is a challenge to control in some other way what we tried to do in the past by moisture control.

Mr. Beatty also dealing with "Hauling, Spreading, and Compaction" reaffirmed what can be expected when moisture and workability are examined in terms of the equilibrium moisture condition. He pointed out the distinctions between conventional mixing versus drum-mixing; how moisture can contribute to compaction at lower temperatures; and that the workability-temperature relationship is discontinuous, in that, around and below the boiling point of water, moisture can be an aid, but once the moisture is driven off, workability is more the function of the viscosity of the asphalt, i.e., higher temperature.

As related by Mr. Drake discussing 'Field Performance' Mr. Serafin reported that at one time Michigan had very restrictive moisture requirements. However, adjustments in the aggregate gradations and operations, permitted good construction with appreciably more moisture. What is more important, there was no evidence this additional moisture harmed pavement performance.

In all the above we have evidence some moisture is not detrimental. This suggests further study of what levels of moisture are permitted for workability and pavement performance. This suggests study of adjustments that can be made in other variables that would allow more moisture and the nature of the trade-offs.

Then too, considering the overall variety of situations, aggregates and asphalts, some have not been covered by the experience reported on at this conference. So we need to be alert to exceptions and learn of the reasons for this. Then too, laboratory studies involving moisture tend to be with mixes made with dry aggregates, just because of the nature of the laboratory conditions and operations. It would be of interest to check performance relative to moisture in the laboratory using mixes made with aggregates where the moisture level is maintained comparable to some of the moisture levels reported to us here.

This summary is only one man's view. We, however, have Mr. Drakes, Co-Chairman of this Conference, to broaden or perspective.....Mr. Drake.

Frank Drake

Listening to the remarks that are so pertinent to the subject of the conference, it seems to me workability is a term that should be used more than it is. Presently we have neither the scale nor the measurement of such a term. Yet is it a characteristic of the mixture we can ill afford to ignore when we think of compacting the mixture in the shortest period of time without causing lateral displacement in the mix.

Bob Schmidt has made reference to the term "optimum compactive effort" as the condition where the mixture is exposed to the maximum compactive pressure the mix will support without lateral displacement. This is unquestionably true. However, this condition of optimum very rarely happens because there is very little thought given to bringing into focus the three factors of workability, lift thickness, temperature, and compactive effort.

On the other hand optimum compaction can be achieved by adjusting the compactive effort to accommodate the following: (1) the thickness of lift and (2) the workability of the mixture. The above statement seems to be the most reasonable for efficient construction. However, if adjusting the weight of the roller is not feasible or possible the only alternative is to adjust the lift thickness. This seems to be a vicious circle. Yet, to practice good construction procedures workability is very much a part of the overall consideration.

L. C. Krchma

There is no need to add to Mr. Drake's observations. It is hoped this Conference will add to an improved technology, leading to better engineering, better operations, wider use of more economical aggregates, fewer emissions, and the improved conservation of fuel.

We owe a good deal to the Members of this Panel. We are indebted to the joint A2D02 and F02 Committee Members, who we named and who assisted us in the planning of this Conference, though limited time precluded introduction from the floor.

ERRATA

Transportation Research Circular 242

Page 1

Insert the following:

"The subcommittee responsible for preparing this circular consisted of David G. Tunnicliff, chairman, Donald E. Carey, and Charles S. Hughes."

Page 3, column 2, paragraph 5, line 2:

Change to "The difference between a static and a vibratory roller is that part of the total applied force of a vibratory roller is applied through vibration."