1. The amount of asphalt in the old bituminous pavement by the extraction method or by using 80 percent of the actual asphalt used when the pavement was constructed;

2. The cost of new asphalt;

3. The cost of aggregate (BA-2) for bituminous mixture;

4. The cost of salvaging, loading, hauling, and stockpiling existing aggregate base;

5. The cost of scarifying, loading, hauling, stockpiling, and crushing salvaged bituminous pavement; and

6. The cost or profit of disposing of the existing gravel base and bituminous pavement [this should include scarifying, loading, hauling, leveling, landscaping, and the cost of dumping (royalty) or may include payment for the material being dumped].

Hauling costs are a major factor in determining the cost of a project. A preferred method for determining hauling costs is the cycle time method. The following information is needed: (a) rental rate of hauling unit per hour, (b) capacity of hauling unit, (c) cycle time of hauling unit. This can be expressed as (rental rate × cycle time) ÷ (capacity × 60) = cost per megagram. For example, if rental rate = \$26/h operated, capacity = 15.5 Mg, and cycle time = 45 min, then (26 × 45)/(15.5 × 60) = \$1.25/Mg.

Hauling costs can be reduced significantly on recycling projects by backhauling salvaged bituminous material and salvaged gravel base.

CONCLUSIONS

The Minnesota heat-transfer concept has wide application for cost-effectively recycling old bituminous pavements and aggregate bases. The modification to conventional batch, drum-mixer, and continuous-mix plants is minimal. This method requires clean aggregate for heat transfer, which in turn requires additional new asphalt. By using additional asphalt with higher than normal penetration, the effective penetration of the recycled asphalt binder is improved without the use of rejuvenators. The production rate of the plant is not seriously reduced. No smoke is emitted from the modified batch plant operation. There are some smoke emissions from the modified drum-mixer operation, but this can be held within present pollution standards. Although no continuous-mix plants have actually been modified, it is felt that they would work much like a modified batch plant.

Practical proportions for the design of future recycling projects would appear to be 50/50 for batch and continuous-mix plants. Since there appears to be some additional heat in the modified drum-mixer plants, the practical proportion limit would appear to be 60/40.

Many roadways, streets, and airports have been constructed with several centimeters of bituminous surfacing and several centimeters of gravel base. In many cases, no new aggregates would be required to produce a recycled mix that would result in a higher strength structure. Only the addition of new asphalt would be required, and this would be less than that required for a new conventional mixture.

Although there is some question as to the durability of recycled mix versus new conventional mix, all conventional testing shows recycled mix to be comparable to new mixes.

If the salvaged bituminous material and the salvaged aggregate are uniform and well graded, the gradation of the recycled bituminous mixture will also be uniform and well graded provided the contractor uses reasonable care in handling the stockpiled materials. The only change in gradation is the slight increase in the amount of materials passing the 0.075-mm (no. 200) sieve.

The savings attributed to recycling seem to be positive in all cases. Even if recycling were equal in cost to conventional construction, there are environmental and social benefits of extending and preserving the nonrenewable asphalt and aggregate resources. The biggest challenge left is to make recycling work for us by looking at every project to determine if the benefits of recycling are positive.

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Determination of Moisture Contents in Bituminous Mixtures by a Nuclear Method

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A study undertaken to evaluate the effect of moisture on nuclear-gauge data and to explore whether the nuclear gauge can be used to determine moisture content when asphalt content is held constant in a paving mixture is reported. A Troxler model 2226 gauge was used in the study. Four wearing-course mixtures that contained slag, gravel, and limestone aggregates were studied, and moisture content was varied from 0 to 3.47 percent. Statistical analysis of the

data indicates that the nuclear gauge has the potential to read moisture content within ±0.3 percent of actual value (at a 95 percent level of confidence). The nuclear gauge would provide a rapid means of testing and monitoring moisture content in the mixtures produced by the drum-dryer process. Tests run on emulsified asphalt-aggregate mixtures indicate that the nuclear gauge can be used effectively to monitor total liquid content (emulsified asphalt plus water) in a mixture to facilitate compaction at the optimum liquid content.

Studies undertaken to determine asphalt content in bituminous mixtures by using a nuclear gauge have been very promising. However, the presence of absorbed moisture in the aggregate can pose problems since the hydrogen in the water will affect the nuclear gauge counts and the moisture will thus be read as an additional asphalt content in the mix. Absorptive aggregates such as slags can contain significant amounts of moisture (more than 1 percent) without any apparent visual signs of steaming or slumping in the bituminous concrete.

Moisture content in the hot aggregate after drying operations varies from day to day according to the condition of the aggregate stockpiles and the prevailing weather. Even if the gauge is calibrated with the aggregate from the hot bins to allow for retained moisture, some of the moisture might be lost in the mixing operation. There is a need, therefore, to investigate the extent to which moisture in bituminous mixtures affects nuclear gauge counts and to explore the possibility of determining moisture content in bituminous mixtures when asphalt content is considered to be constant. Since mixtures produced by the drum-dryer process at relatively lower mixing temperatures contain a significant amount of moisture to aid in compaction, it is believed that such investigations would have useful field applications. The current standard method of determining water content by distillation (AASHTO T 55 or ASTM D 95) is very time consuming and can take up to 4 h if the moisture content is very high. Use of the nuclear gauge could reduce the testing time to 15 min.

Bituminous mixtures that contain emulsified asphalt are normally mixed with a liquid content (emulsified asphalt plus water) that is higher than the optimum liquid content needed to achieve optimum density. Such mixtures are allowed to cure after spreading until the optimum liquid content is obtained, and then the rolling is begun. Curing time depends on the characteristics of the mix and the prevailing weather conditions. There is a need to continuously monitor total liquid content in the mixture so that rolling can be started when the optimum liquid content is reached.

LITERATURE REVIEW

The principle of using nuclear radiation to measure the asphalt content of bituminous mixtures was established several years ago by Lamb and Zoller (1). Subsequent studies by Varma and Reid (2), Howard and Covault (3), Walters (4), Qureshi (5), Hughes (6), and Grey (7, 8) have contributed to modifications of the nuclear gauge. Further studies to evaluate the effect of gradation, type of aggregate, and asphalt source on asphalt content have been reported by Klotz (9) and Hughes (10).

However, most of the research has been conducted on bituminous mixtures that contain relatively dry aggregate even though, in actual field conditions, some moisture is usually encountered in aggregates. Finding moisture is even more likely if absorptive aggregates are used in the mix or if the mix is produced by the drum-dryer process.

THE NUCLEAR GAUGE

The 40.6- by 40.6- by 40.6-cm (16- by 16- by 16-in) Troxler model 2226 gauge (Figure 1) consists of a one-piece unit that weighs about 56.7 kg (125 lb). All components are enclosed within the single unit, and a sliding-drawer arrangement is provided so that the stainless steel pans that contain the bituminous test sample can be inserted into the gauge. Three He_3 neutron detector tubes are used to monitor the thermal neutrons from the test specimen; two of the tubes are sample detector tubes positioned beneath the test specimen pan in the sliding drawer. The other tube sits near the top of the gauge and acts as a reference detector.

The counts monitored by the reference detector are used as a continuous, internal standard count and are electronically compared with the sample count. Thus, any electronic drift caused by variation in ambient temperature or aging of components can be accounted for during the actual test count. Because the system is continuously standardized, no auxiliary standard was provided.

The operation of a nuclear asphalt-content gauge of this type is based on neutron thermalization. The 11.1-GBq (300-mc) americium-241 source produces neutrons in the 0.4-pJ (2.5-MeV) range. Elastic and inelastic scattering collisions occur between the neutrons and the material under investigation. After a series of collisions, the "fast neutrons" [energies from 0.08 to 1.6 pJ (0.5 to 10 MeV)] are slowed to the "thermal" level [0.004 aJ (0.025 eV)], at which they can be counted by the gauge detector tubes. The scattering collisions that occur over a timed counting period are a function of the nuclei of the test material. In a typical bituminous mixture, it is the added hydrogen atoms present with increased asphalt that produce a higher count. Therefore, any increase in the number of hydrogen atoms, from either asphalt or the addition of moisture (H_2O, two hydrogen atoms per molecule), would produce more scattered thermal neutrons and yield a higher count rate on the gauge.

If the count obtained on a mixture of bituminous material can be separated into two portions—that attributable only to the materials that compose the mix (aggregate and asphalt) and that attributable to residual moisture in the aggregate—the gauge could be successfully used to determine the moisture content of a typical bituminous mixture.

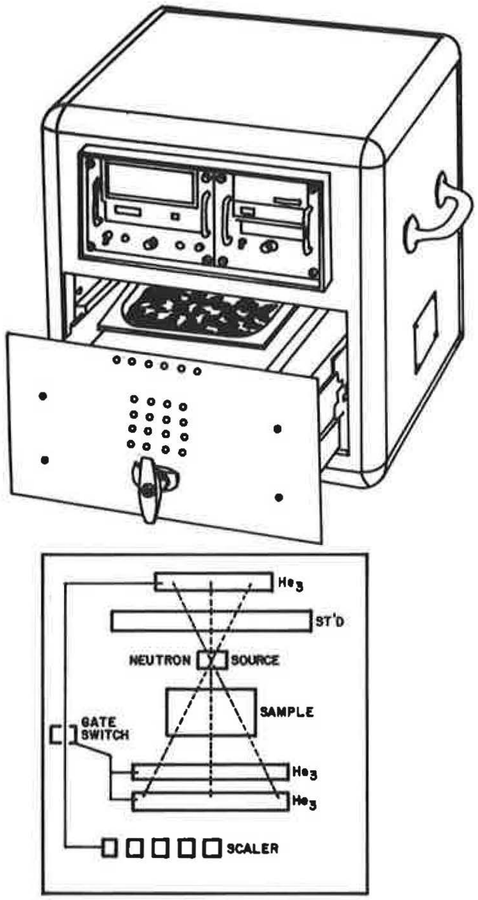
EXPERIMENTAL PROCEDURE

This study consisted of producing pans of bituminous mixtures that contained essentially the same asphalt content for a particular type of aggregate but various percentages of moisture. Three types of aggregate (slag, gravel, and limestone) were used. Slag aggregates from two different sources were investigated. The pores in the slag aggregates were more easily filled with water and aided in getting higher percentages of moisture.

The following general procedure was used:

1. An accurately weighed sample pan of aggregate material only (no asphalt added) was thoroughly dried (0 percent moisture) until a constant weight was achieved, and a count was made on it in the nuclear gauge.
2. Asphalt was then added to the above pan to obtain a precise mix with a known asphalt content, and a count was made again. A straight-line plot of count versus asphalt content (no moisture present) was made for the two data points so that the slope of the line would indicate the counts

Figure 1. Troxler model 2226 asphalt-content gauge.



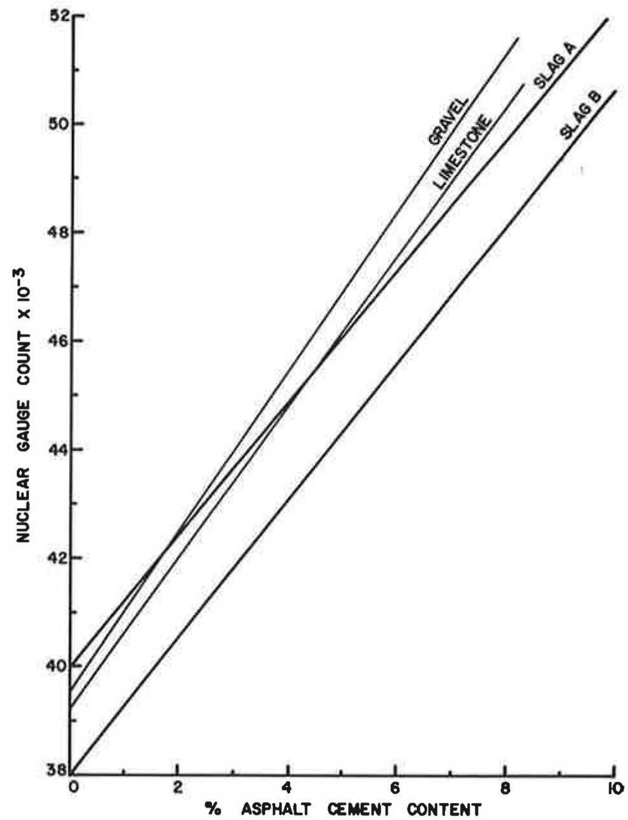
per percentage of asphalt content (Figure 2).

3. The same aggregate and asphalt were used in making up a series of pans of bituminous mixtures with accurately determined moisture contents by weight in the aggregates used. These were made by soaking aggregate of predetermined weight for several hours and then pouring off excess water and oven drying until the percentage weight of water reached a desired value. Asphalt was then quickly added and mixed to the same asphalt content as in step 2 above, and the mixed pan sample was read by the nuclear gauge, the count being a sum of asphalt and moisture. Weighing was done just after mixing to allow for any loss of moisture during the mixing operation. Counts were taken as quickly as possible after mixing to keep the loss of moisture during testing to a minimum. Tests of water distillation run on the bituminous mixtures immediately after the nuclear test indicated minimal loss of moisture during the nuclear testing operation.

4. Asphalt content was held as constant as possible in the series of mixtures, and only moisture content was varied. However, the actual asphalt contents incorporated in the mixtures varied ± 0.2 percent from the target asphalt content after the asphalt that stuck to the mixing bowl was taken into account. The data acquired in step 2 (asphalt content versus count) were used to correct all counts to a count value that corresponded to the target asphalt content. In most cases, slight corrections were needed.

5. A statistical analysis of the data was then made to

Figure 2. Percentage asphalt content versus gauge count.



show the relation between gauge count and moisture content of typical bituminous mixes.

TEST DATA AND INTERPRETATION OF RESULTS

The mixtures in test series 1 through 4 met the gradation requirements of 1973 Pennsylvania Department of Transportation specifications for ID-2 wearing course. The gradation is given below (corresponding U.S. sieve sizes are 2, 0.75, 0.5, and 0.375 in and nos. 4, 8, 16, 30, 50, 100, 200):

	Percentage Passing	
Sieve Size (mm)	ID-2 Wearing Course	Base Course
50	100	100
19	100	76
12.5	100	–
9.5	90	53
4.75	62	37
2.36	45	27
1.18	32	20
0.6	22	–
0.3	15	–
0.15	9	–
0.075	5	5

Test Series 1

Nineteen mixtures consisted of slag aggregate A supplied by Sheridan Slag Company and AC-20 asphalt cement supplied by United Refining Company. It was desired to incorporate 9 percent asphalt by weight of the mix, but the actual asphalt content ranged from 8.85 to 9.23. As men-

Figure 3. Percentage moisture versus gauge count for slag A.

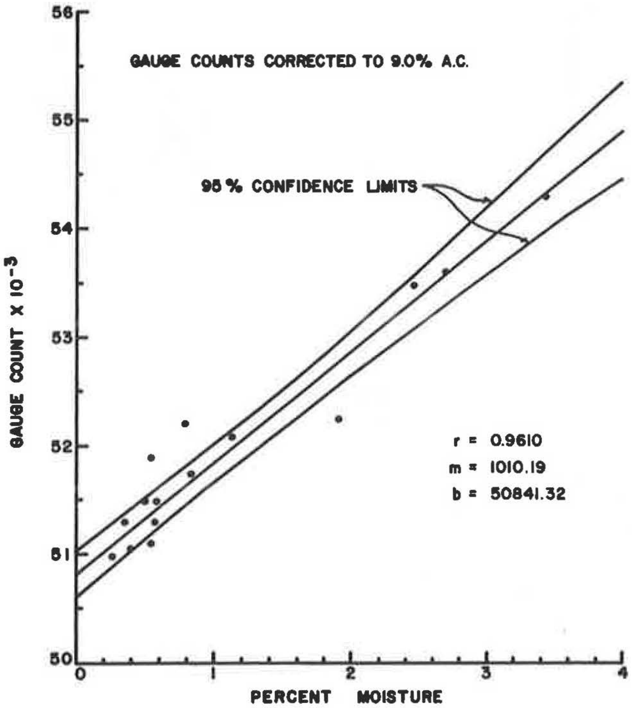


Figure 4. Percentage moisture versus gauge count for slag B.

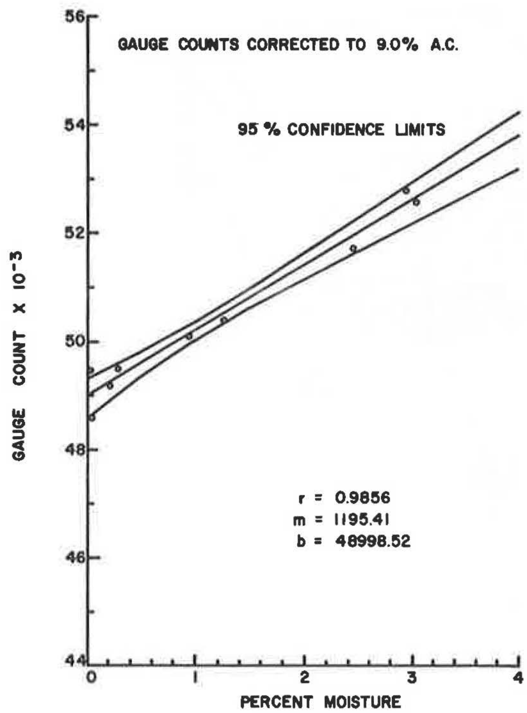


Figure 5. Percentage moisture versus gauge count for gravel.

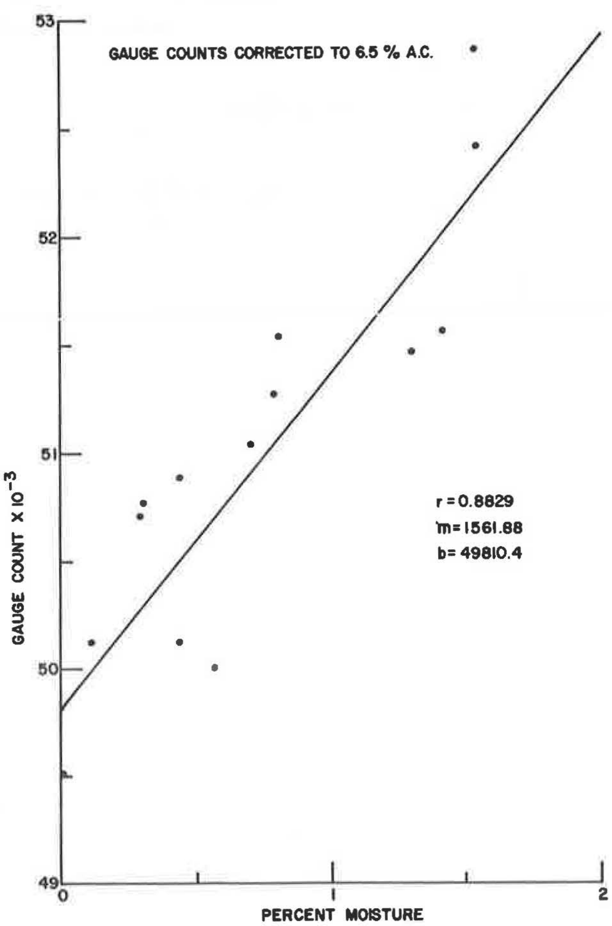
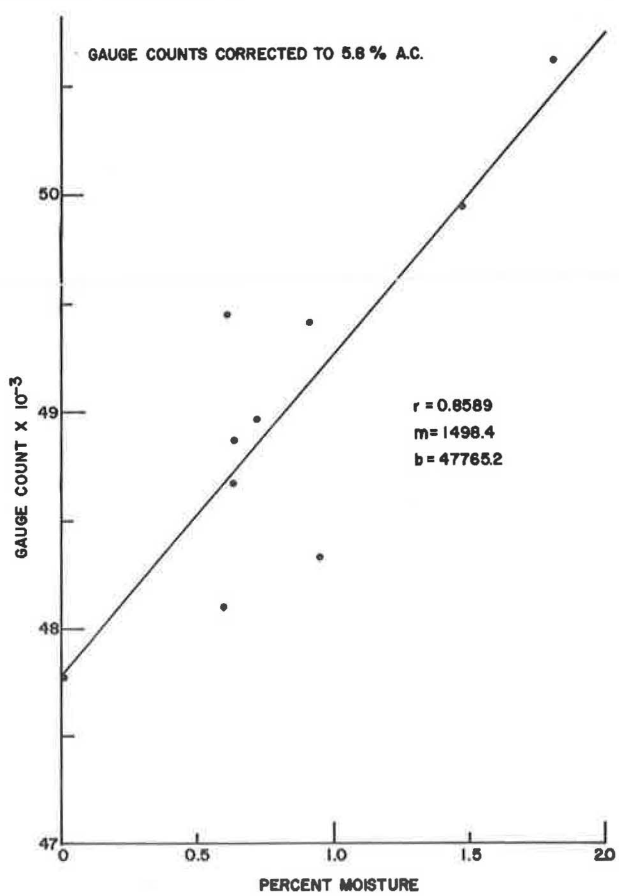


Figure 6. Percentage moisture versus gauge count for limestone.



tioned earlier, the nuclear gauge counts were corrected to 9 percent asphalt content by using Figure 2. Moisture in the mix just after mixing ranged from 0.07 to 3.47 percent by weight in 19 test runs.

Figure 3 shows a plot made for percentage moisture in the aggregate (or mix) versus the nuclear gauge reading. Statistical analysis of the data was performed to establish the 95 percent confidence belt on the plot (11). The results are very encouraging. As expected in statistical analyses, the belt is narrowest at the mean value of the independent variable (approximately 1 percent moisture content). At this level, the nuclear gauge can read moisture content within ±0.15 percent of actual value at a 95 percent confidence level. The divergence of the belt at higher moisture contents is probably attributable to the following:

1. At higher moisture contents, the mix might have been losing moisture while it was being tested in the nuclear gauge so that the exact moisture content is difficult to determine.
2. Fewer tests are performed at higher moisture contents than are performed below 1 percent.

However, the gauge can read moisture content within ± 0.3 percent in the 0 to 3.5 percent moisture range, which appears acceptable.

Test Series 2

Eight mixtures consisted of slag B supplied by Duquesne Slag Products Company and AC-20 asphalt cement supplied by Chevron Asphalt Company. The asphalt content was held constant at 7.93 percent in all mixtures. However, the gauge counts were corrected to 9 percent by using the slag B line from Figure 2 so that a comparison could be made with the data from test series 1. Moisture content was varied from 0 to 3.05 percent.

Figure 4 shows the plot for percentage moisture versus gauge count. Again, the correlation is very good. For the entire moisture content range of 0 to 3 percent, the gauge would give results within ±0.3 percent of the actual value, which appears acceptable.

Test Series 3

Thirteen mix samples consisted of gravel aggregate from Oil City Sand and Gravel Company and AC-20 asphalt cement. It was desired to incorporate 6.5 percent asphalt by weight of the mix, but the actual asphalt content ranged from 6.46 to 6.60 percent. The gauge counts were corrected to 6.5 percent. Moisture in the mix just after mixing ranged from 0.11 to 1.54 percent by weight.

The plot for percentage moisture in the aggregate (or mix) versus the nuclear gauge reading is shown in Figure 5. Statistical analysis of the data indicates that the nuclear gauge can read moisture content within ±0.3 percent of actual value at the 95 percent confidence level.

Test Series 4

Ten mixtures consisted of limestone aggregate and AC-20 asphalt cement. It was desired to incorporate 5.8 percent asphalt by weight of the mix, but the actual asphalt content ranged from 5.74 to 5.95 percent. The gauge counts

Figure 7. Comparison of percentage moisture versus gauge count for slags A and B, gravel, and limestone.

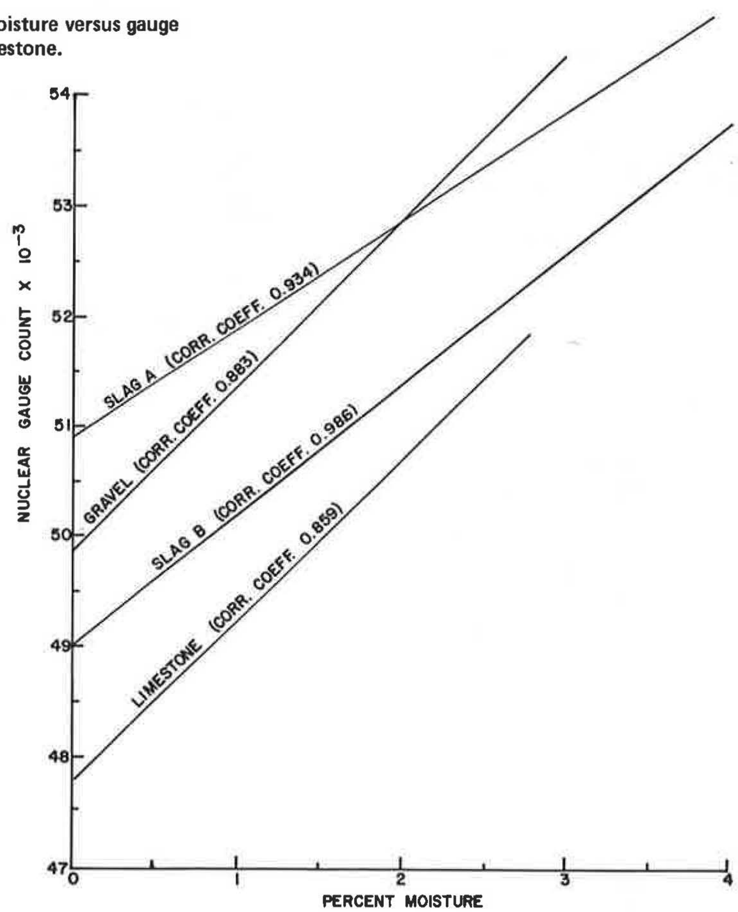
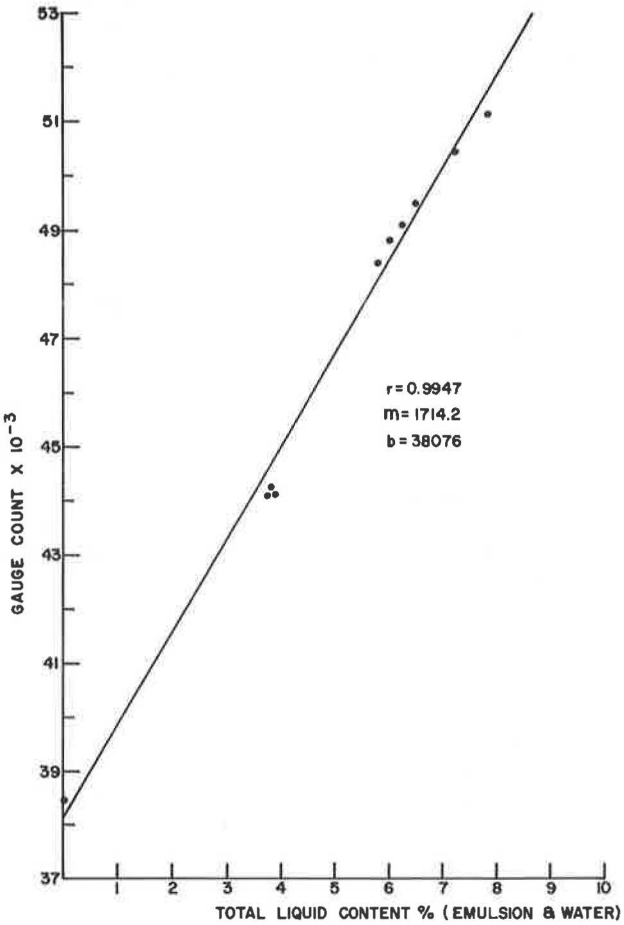


Figure 8. Total percentage liquid content versus gauge count for mix A.



were corrected to 5.8 percent asphalt content. Moisture in the mix just after mixing ranged from 0.60 to 1.81 percent of the weight.

The plot for percentage moisture in the aggregate (or mix) versus the nuclear gauge reading is shown in Figure 6. Statistical analysis of the data indicates that the nuclear gauge can read moisture content within ±0.3 percent of actual value at a 95 percent confidence level.

Comparison of Four Test Series

Figure 2 shows the plot of percentage asphalt versus gauge reading for all aggregates. The apparent shift between the straight lines can be attributed to the difference in aggregates, asphalts, and gauge backgrounds. The same shift can be seen in Figure 7 when percentage moisture versus gauge count is plotted. This indicates the need, also established by other researchers, for recalibration of the gauge for each type of aggregate and asphalt cement.

Relative gauge counts per 1 percent of asphalt cement and moisture are given below:

Material	Asphalt Cement	Moisture
Slag A	1226	1004
Slag B	1269	1195
Gravel	1503	1562
Limestone	1418	1499

Therefore, 1 percent moisture in the mix could be read as 0.82, 0.94, 1.04, and 1.06 percent asphalt content in test series 1, 2, 3, and 4 respectively. The average would be 0.96 percent.

Test Series 5

A base course mixture (mix A) that met the gradation given in the first text table above was prepared by using a medium-setting cationic emulsified asphalt (CMS-2) and limestone aggregate. The total liquid content of 7.87 percent consisted of 3.52 percent residual asphalt in the emulsion, 1.96 percent water in the emulsion, and 2.39 percent free moisture or water. Nuclear gauge counts were taken just after mixing. A count was also made on thoroughly dried aggregate (0 percent liquid content) before the mixing operation. As the emulsified asphalt-aggregate mixture was allowed to cure, weight losses attributable to evaporation of water were accurately determined and gauge counts were taken at several intervals until the mixture was completely cured. The data from this initial run are plotted in Figure 8; the best fit straight line was obtained. The correlation between total liquid contents and gauge counts was excellent (r = 0.995).

To verify whether this relation could be used to determine total liquid content, another base-course mix (mix B) was prepared with a known liquid content of 9.07 percent, consisting of 3.49 percent residual asphalt in the emulsion, 1.95 percent water in the emulsion, and 3.63 percent free moisture or water. The mix was then allowed to cure. Total liquid contents were determined at several intervals from the gauge counts by using the mix A calibration straight line (extrapolated when necessary) and from actual weight losses by weighing. The following results were obtained:

Actual Liquid Content (%)	Gauge Liquid Content (%)	Difference
9.05	8.70	+0.35
8.00	8.05	–0.05
6.90	6.85	+0.05
5.90	6.20	–0.30
5.00	4.90	+0.10
3.50	3.30	+0.20

Statistical analysis of differences indicates that the difference is not significant at the 95 percent confidence level and that the gauge can read the total liquid content within ±0.3 percent in the 3.5 to 9.0 percent total liquid content range, which appears acceptable for use in the field.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations resulted from this study:

1. If asphalt content is held reasonably consistent, which is possible in contemporary automated asphalt plants, the nuclear asphalt-content gauge has the potential to read moisture content over the range from 0 to 3.5 percent.

2. The nuclear gauge must be recalibrated whenever there is a change in aggregate source, asphalt source, mix type, and test background.

3. Undetected moisture in the bituminous mix would be read by the gauge as asphalt content. According to this study, 1 percent moisture would be read as 0.82 to

1.06 percent asphalt by weight, depending on the aggregate composition.

4. Some moisture is required in the mixtures produced by the drum-dryer process to aid in compaction. However, it is necessary to regulate the moisture content within a working range. Conventional methods of determining moisture content are very time consuming. The nuclear asphalt-content gauge would provide a rapid means of testing and monitoring moisture content in mixtures produced by this process.

5. Tests run on mixtures that contain emulsified asphalt and aggregate indicate that the gauge can be used effectively to monitor total liquid content (emulsified asphalt plus water) in the mixture within ±0.3 percent. The gauge could thus be used to indicate when the optimum moisture content has been reached for proper compaction.

ACKNOWLEDGMENTS

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Abridgment

Recycling Asphaltic Concrete: Arizona's First Project

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Interest in Arizona in the possibility of recycling old asphaltic concrete pavement stemmed initially from a paper by Dunning, Mendenhall, and Tischer (1). In addition, the increase in the price of paving asphalt from approximately $44.20/Mg ($40/ton) in 1971 to $110.50/Mg ($100/ton) in 1975 caused us to realize the great potential savings represented by the approximately 4 percent residual asphalt in old asphaltic concrete. Consequently, Materials Services of District 3 of the Arizona Department of Transportation (DOT) began a testing program on old asphaltic concrete to determine if recycling of this material was feasible.

In the southeastern portion of Arizona, between Willcox and the New Mexico state line, part of the old asphaltic concrete being removed and disposed of on an $8.5 million Interstate highway project was salvaged, crushed, recycled, and used to overlay 8.53 km (5.3 miles) of US-666 from I-10 north to the Graham County line. The material was crushed, heated, and remixed and was checked by the Marshall method of determining asphaltic concrete mix designs. It was determined that adding 1.5 to 2 percent AR 2000 paving asphalt to the old asphaltic concrete resulted in a good mix.

On the basis of these preliminary tests, approximately 16 819 m^3 (22 000 yd^3) of old asphaltic concrete was salvaged from project I-10-6(50). This material was stock-