the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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# Test for Efficiency of Mixing of Recycled Asphalt Paving Mixtures

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**The increasing costs of construction materials, along with environmental conditions, have given great impetus to current interests in recycling. In recent years, reuse or recycling of existing pavement materials has emerged as a workable rehabilitation and maintenance alternative because it offers several advantages over the use of conventional materials and techniques. Although the equipment and technology of recycling have been developed, there still is no standardized or widely accepted method for testing recycled mixtures. The practice of using a small amount of recycling agent is coupled with the problem of quality control. There is no suitable method of detecting how well the recycling agent mixes with the aged pavement materials. A study is described whose primary objective was to develop a test method that could be conducted in the field with a minimum of equipment and training. As a result, the dye chemistry technique was found to be the most practical method of measuring the extent of mixing during a recycling operation. Ten field projects involving various plant types were conducted to demonstrate the application of such a technique to full-scale construction conditions. The overall mixing efficiency of a specific operation can be evaluated by statistically analyzing the resulting dye distributions. Consequently, the mixing process or plant design can be optimized by obtaining such information.**

The need for efforts to conserve natural materials and improve methods and processes in the highway construction industry has greatly intensified since the realization of an imminent energy shortage. The problem of finding suitable virgin materials for pavements exists concurrently with the problem of disposing of spoils or solid wastes. One solution is to reuse or recycle existing materials for construction, rehabilitation, and maintenance purposes (1-4). The world has some 9 million miles of paved roads containing large quantities of quality aggregate and bitumen that in the past could not be reused. The economic value stored in the raw materials in existing roadways presents a new opportunity for the highway construction industry. FHWA indicates that there are more than 2 million miles of paved roads and streets in the United States, all of which are candidates for eventual recycling (5,6).

The term recycling is defined by the Asphalt Institute as "the reuse, usually after some processing, of a material that has already served its first-intended purpose in a roadway." The recycling or reuse of existing pavement materials for pavement rehabilitation, reconstruction, and maintenance is not a new concept. A wide variety of recycling approaches has emerged since 1915 (7,8). Asphalt as well as concrete pavements have been recycled, and quality improvement has often been accomplished by adding aggregate, asphalt, portland cement concrete, or a rejuvenating agent. In recent years the recycling of pavement materials has proved to be economically feasible and functionally successful. The state of the art of designing and constructing pavements composed of recycled materials has now advanced to a point where recycling is considered to be a workable rehabilitation and maintenance alternative.

The increase in recycling operations has created an awareness that the characteristics of the recycled material must ensure a quality pavement. One of the major concerns of engineers with regard to

Table 1. Additive or tracer techniques.

| Group | Type of Technique | Techniques |
|---|---|---|
| 1 | Detection techniques susceptible to scanning methods (large samples that can be scanned to determine individual distributions) | Phosphorescence salts (add to modifier and/or new binder), temperature differentials (which may exist between the old and new), fluorescence (add to modifier and/or new binder), X-ray (using pipe inspection techniques), ultrasonics, polarized light, and UV/IR detection techniques |
| 2 | Detection techniques that would require a large number of discrete samples (small asphalt samples selected from various locations) | Chromatography, including fingerprinting of molecular weight distribution, specific compound identifier and density, and extraction of the different parts; chemical tracers detected by image spectrophotometry, IR or UV detection techniques, spectroscopy, and end group analysis; radioactive tracers (Geiger counter detection); image spectrophotometry; comparison of viscosity at two temperatures; and carbon-14 tracers (very compatible with hydrocarbons in oils) |
| 3 | Measuring techniques | Solid-state light-sensitive matrix (or array) scanning, infrared microimaging (microscanning), photographic, and visual |

the use of recycled materials is construction control. Because of the high variability of salvaged materials and handling techniques, uniformity may be more of a problem in recycling than it would be in the use of conventional materials. Additional attention therefore needs to be given to monitoring recycling operations to ensure uniformity. In this regard, the following appear to be two of the most important criteria for recycling asphalt pavement: (a) the reclaiming agent must be uniformly wet and penetrate the crushed asphalt pavement to be recycled, and (b) the reclaiming agent and the material to be salvaged must be thoroughly mixed (9,10).

It has generally been recognized that the effectiveness of an asphalt modifier, or recycling agent, is a function of its uniform dispersion throughout the pavement binder. The performance of the recycled mixtures also depends on how well the virgin aggregate (if any) and asphalt is mixed with the old pavement materials and on how well the virgin asphalt (if any) coats the aggregate (11). Nonetheless, it is difficult to imagine how a small amount of recycling agent can have intimate contact with all of the old binder. There is certainly no assurance that the small amount of recycling agent will be well dispersed in a mixture under field conditions.

The primary objective of this study was to develop a technique and necessary test equipment to establish the ability of a mixing operation to produce an intimate mixture consisting of reclaimed bituminous materials, modifying agent, new asphalt, and new reclaimed aggregates. The primary goal was to produce a quality control-type test. Thus, the technique and associated test equipment were to be based on a macroscale; i.e., the dispersion of recycling agents was to be measured throughout the recycled mixture, not by the distribution on an individual aggregate particle.

MEASURING AND DETECTION TECHNIQUES

The actual detection and measurement of the additive, including average density and dispersion within the sample area and throughout the final asphalt mix, could be done in many ways. Table 1 gives some of the different options that were considered. Group 1 includes the primary methods that lend themselves to scanning-type techniques. The assumption was that the tracer elements could be detected by light-sensing devices or by varying thermal properties between the original and new binder and the modifier. This could also be done by using infrared scanning devices. The main advantage in this case is that the dispersion could be measured on a scale approaching a resolution (scale size) limited only by the size of the larger aggregate.

Group 2 in Table 1 includes the major detection techniques that lend themselves more readily to analysis by taking a larger number of smaller samples over a larger area. These can be broken down chemically, as in the case of chromatographic or chemical tracer methods, or the average density of the tracer in the complete sample can be estimated by using radioactive measurements.

The techniques presented in groups 1 and 2 have been ranked in order of their expected importance.

The first step in examining potential test methods was to develop criteria by which numerous techniques could be properly evaluated. These criteria are summarized here because of their influence over the techniques selected.

1. The technique should address the question of mixing efficiency on a macroscale--i.e., how well the recycling agent is being dispersed throughout the mix immediately after mixing in a plant.
2. The ideal detection and measuring technique should not further mix or alter the original specimen.
3. The final detection and measuring equipment should be lightweight and cost less than $10,000 (assuming commercial availability). The test results should be available within 24 hr after a sample is obtained and much sooner if possible.
4. The maximum technician training time should be less than 4 days.
5. The technique should use a systematic scanning method (manual or electronic) for a final measurement and analysis procedure.

In short, the development and equipment costs should be low, the measurement capability should be high, and the equipment should be easy to operate, portable, easy to maintain, and somewhat versatile with respect to applications of the resulting data.

The results obtained can best be summarized in two categories: classical and nonclassical civil engineering techniques. The most workable techniques are the following:

1. Nonclassical--(a) Dye chemistry, (b) fluorescent, (c) UV and IR detection techniques, (d) phosphorescent, (e) microscope (light, electron, scanning), and (f) polarized light;
2. Classical--(a) Resilient modulus, (b) viscosity at 140° and 275°F, (c) penetration, (d) smoke point, flash point, fire point, and volatility, and (e) extraction-recovery.

One of the concerns within this task was a trade-off between a relatively simple but subjective approach to identifying the presence of asphalt modifiers in a mixture and a somewhat sophisticated but more objective method. The primary emphasis was placed on the evaluation of resilient modulus ($M_R$) and the application of dye chemistry techniques (12).

Resilient Modulus Test

It is generally known that recycled mixes from field projects exhibit significant variations in mixture properties due to many variables. Therefore, for this study, a standard mixture was prepared in the laboratory by artificially aging it to reduce the variation expected from mixtures obtained in the field. This mixture was then used in the study for comparison with the variables being investigated.

The final experimental design is given below:

| Factor | Low Level | High Level |
|---|---|---|
| Mixing time (min) | 1 | 5 |
| Mixing temperature (°F) | 250 | 300 |
| Recycling agent (%) | 0.25 | 1.00 |

This design uses the primary factors of mixing time and temperature and includes the use of a recycling agent (Witco Cyclogen L) at various levels.

Regression analysis was performed to evaluate the influence of these variables. The resilient modulus of a recycled mixture can be expressed as follows:

$$M_R = 378 - 0.370\,T + 25.4\,t + 130\,RA \qquad (1)$$

where

$M_R$ = resilient modulus (psi 000s),
$T$ = mixing temperature (°F),
$t$ = mixing time (min), and
$RA$ = percentage of Cyclogen L by weight of total mix.

However, it should be noted that the relation has been tested only for the materials and conditions involved in this study.

It is apparent that the amount of recycling agent added is the dominant factor with respect to the resilient modulus. Yet, in a given mixing operation, the distribution of a recycling agent throughout a mix is a function of mixing time. Therefore, it was important to investigate the time of mixing as it relates to dispersion of the recycling agent and its effect on the strength characteristics of the mixture. It should be recognized, however, that mixing actions are quite different with laboratory, pugmill, or drum mixers. Mixing time in the laboratory is not equivalent to field conditions. In addition, whereas mixing time in the laboratory can readily be changed, this may not be so feasible in the field, especially with drum mixers.

Mixing or distribution of the recycling agent appears to occur very rapidly provided sufficient recycling agent is available. It is difficult, if not impossible, to distribute a small amount of fluid evenly throughout a large amount of dry solid ingredients. A crumbled, aged asphalt tends to quickly absorb any hydrocarbon type of liquid at the spot where it is added before it can be distributed uniformly throughout the mixture (13). For example, based on general rejuvenating qualities, a recycling agent (such as Cyclogen L) content of 0.75 percent by weight of total mixture was considered to be adequate if thoroughly mixed. In the laboratory, it was observed that a good random distribution was achieved after 30 sec of mixing time. It appears that the effectiveness of mixing is high for about the first 10 sec but drops off rapidly thereafter.

To characterize the structural effect of mixing patterns, the resilient modulus test was conducted on specimens that had been mixed for varying lengths of time, from 0 to 60 sec. A mixing time of 60 sec was considered sufficient (based on laboratory observations) in that the recycling agent was uniformly distributed and the reclaimed materials were completely coated. Figure 1 shows a sketch of the deliberately patterned (or biased) mixture for a mixing time essentially of 0 sec (types A and B). Resilient modulus tests were performed at seven locations around the circumference of the test specimens. These locations are designated points 1-7 in Figure 1. The possible nonhomogeneity of various mixing patterns, and hence mixing times, can be checked by repeating the test across different diameters and comparing the variation in the results. Mixtures that have not been mixed adequately can have softened areas that contain high concentrations of recycling agent and thus can contribute to deformation under load.

Results of laboratory tests (see Figure 2) and use of these materials indicated, as expected, more variation in $M_R$ in aged samples containing recycling agent that was insufficiently mixed into the mixture. In addition, the loss in $M_R$ after vacuum saturation and application of the freeze-thaw cycles

**Figure 1. Test locations of patterned 0-sec mix.**

was generally greater for the poorly mixed test specimens. Furthermore, it was observed that the aggregate contained in the aged specimens that had no recycling agent stripped easily. The severity of water damage was estimated by the total area of breaking of the specimen. The specimen with a 60-sec mixing time, which was considered adequate, had the least water damage, and the specimen with 0-sec mixing time, which was considered inadequate, suffered most. Thus, adequate mixing is essential to ensure quality recycled mixtures.

Resilient modulus tests were then performed to determine whether the recycling agent disperses as the mixture ages. Because the results show that variations of $M_R$ for inadequately mixed specimens were still greater than those for well-mixed specimens after 30 days, it is concluded that dispersion does not improve with time (12). Mixing pattern A (recycling agent off-center) shows higher $M_R$ and lower variation with time than mixing pattern B (recycling agent centered). This would be caused by the fact that the diametral modulus test is biased toward the properties of the material in the inner part of the specimen. For example, 80 percent of the diametral extension occurs within the inner 2.5 in. of a 4-in.-diameter specimen (14). It is apparent that the inner half of mixing pattern A is stiffer than that of mixing pattern B.

**Figure 2. Resilient modulus versus mixing times.**

| Mixing Time (sec) | Test Conditions | Test Days or Cycles* | $M_R$ ($\times 10^3$ psi) 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean | C.V. (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 (A) | Dry | 1 | 506 | 433 | 433 | 276 | 337 | 506 | 433 | 417 | 20.2 |
| | | 3 | 433 | 433 | 506 | 320 | 406 | 607 | 506 | 458 | 19.9 |
| | | 5 | 556 | 469 | 433 | 265 | 304 | 607 | 506 | 449 | 28.1 |
| | Wet | | 469 | 433 | 379 | 276 | 433 | 469 | 469 | 418 | 16.9 |
| | Freeze-Thaw | 9 | 357 | 404 | 264 | 217 | 337 | 433 | 379 | 342 | 22.5 |
| | | 18 | 289 | 202 | 248 | 276 | 337 | 404 | 253 | 286 | 23.3 |
| 0 (B) | Dry | 1 | 102 | 88 | 62 | 91 | 81 | 119 | 88 | 90 | 19.6 |
| | | 3 | 106 | 91 | 83 | 100 | 87 | 83 | 95 | 91 | 9.9 |
| | | 5 | 104 | 102 | 89 | 95 | 83 | 97 | 99 | 96 | 7.7 |
| | Wet | | 81 | 76 | 62 | 87 | 76 | 87 | 81 | 79 | 10.9 |
| | Freeze-Thaw | 9 | 55 | 59 | 68 | 59 | 53 | 55 | 65 | 59 | 9.4 |
| | | 18 | 42 | 48 | 51 | 38 | 45 | 51 | 49 | 45 | 10.6 |
| 5 | Dry | 1 | 113 | 205 | 144 | 159 | 144 | 129 | 124 | 145 | 21.0 |
| | | 3 | 117 | 220 | 159 | 155 | 155 | 164 | 144 | 159 | 19.5 |
| | | 5 | 124 | 114 | 144 | 136 | 144 | 117 | 130 | 130 | 8.3 |
| | Wet | | 95 | 124 | 191 | 146 | 159 | 204 | 130 | 150 | 25.5 |
| | Freeze-Thaw | 9 | 84 | 114 | 119 | 106 | 106 | 125 | 102 | 108 | 12.2 |
| | | 18 | 95 | 81 | 98 | 79 | 95 | 106 | 89 | 92 | 10.4 |
| 60 | Dry | 1 | 186 | 145 | 158 | 125 | 162 | 192 | 139 | 158 | 15.4 |
| | | 3 | 199 | 181 | 162 | 171 | 192 | 171 | 147 | 175 | 10.1 |
| | | 5 | 162 | 153 | 147 | 171 | 192 | 162 | 153 | 163 | 9.3 |
| | Wet | | 162 | 199 | 171 | 192 | 153 | 171 | 147 | 171 | 11.2 |
| | Freeze-Thaw | 9 | 123 | 128 | 147 | 118 | 118 | 128 | 114 | 125 | 8.8 |
| | | 18 | 106 | 128 | 128 | 110 | 128 | 102 | 96 | 114 | 12.1 |
| Control** | Dry | 1 | 454 | 492 | 538 | 492 | 474 | 474 | 422 | 478 | 7.5 |
| | | 3 | 538 | 590 | 538 | 492 | 538 | 656 | 492 | 550 | 10.5 |
| | | 5 | 590 | 492 | 590 | 492 | 656 | 656 | 492 | 566 | 13.2 |
| | Wet | | 492 | 538 | 538 | 438 | 538 | 492 | 454 | 498 | 8.4 |
| | Freeze-Thaw | 9 | 328 | 370 | 348 | 328 | 296 | 310 | 296 | 326 | 8.3 |
| | | 18 | 256 | 246 | 269 | 256 | 256 | 236 | 256 | 254 | 4.1 |

*Test sequence: $M_R$ (dry) @ 1, 3, 5 days (after compaction).— Vacuum saturated (wet) — freeze-thaw @ 9, 18 cycles.

**Aged mix without recycling agent

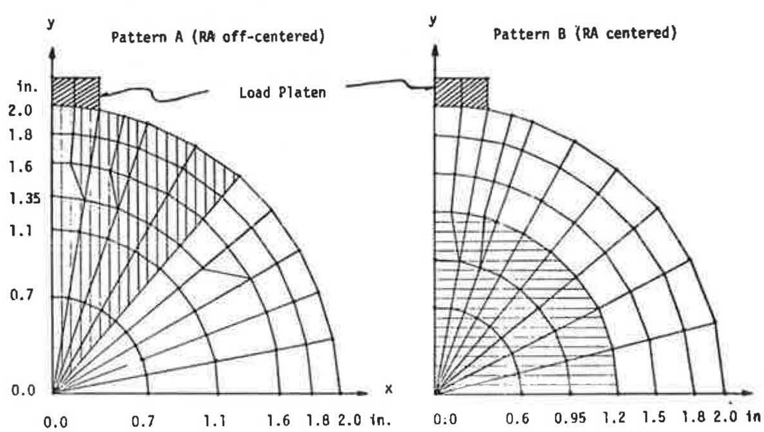
To analyze further the effects of various mixing patterns, a finite element program, SAP IV (15), was used for structure analysis. One-quarter of the specimens of centered and off-center mixing were idealized as an assemblage of plane stress finite elements, as shown in Figure 3. Figure 4 shows the variation of stress and displacement for various mixing patterns along the horizontal radius. The results are generally in agreement with previous findings (12). It appears that mixing pattern A exhibits less deformation, which may contribute to higher stiffness. It can also be seen that a large portion of the diametral extension arises from deformation of the inner part of a specimen. The resulting lower stresses may be due to the fact that the finite element solution underestimates the diametral tensile stress when close to the point of the line loading (14). Because the principal purpose of this analysis is to demonstrate the effect of mixing patterns, it has been simplified. For better results, stresses in such nonlinear material should be determined by iterative application of the linear finite element program.

In summary, the resilient modulus test appears to be sensitive to the recycling agent content but not sensitive enough to detect small changes in the mixture. The variation in $M_R$ for inadequately mixed samples is generally higher than that for the adequately mixed ones, but not significantly. Also performance of the test requires a long period of time. For these reasons, it is not recommended for use as an expedient mixing efficiency test.

## Dye Chemistry Technique

Among the nonclassical tests, the dye chemistry technique was determined to be the most acceptable method based on overall feasibility and associated costs. This recommended technique consists of a procedure for incorporating a small amount of dye chemical into the recycling agent and then detecting the developed dye in the mixture. A dye print technique was developed after a thorough investigation of the effect of dye print materials, dye concentrations, applied pressure, reaction time, coupling temperature, liquor ratio, and pH level of the

**Figure 3. Example of finite element mesh for plane stress analysis.**



diazonium solution. Optimum conditions were determined and satisfactory dye prints were obtained (12).

By placing a sawed face of an asphalt concrete briquet against a chemically treated piece of fabric, a dye print is developed that shows spots where the dye chemical (and hence the recycling agent) is located in the mixture. To evaluate this effect further, a dye print impression of the cut face was made for the asphalt binder after the dye print for the recycling agent had been obtained. Essentially, the asphalt binder was extracted from the face of the specimen to produce a second print, defined as a binder print. This second print is made simply by pressing the sawed (smooth) face of an asphalt concrete specimen against a piece of dye print material that has been saturated with cyclohexane. By superimposing the developed dye print on its corresponding binder print, the distribution of developed dye (and hence recycling agent) with respect to the other ingredients in the mix (asphalt and aggregate) can be observed.

The dye chemistry technique provided additional insight into how a recycling agent disperses with time. The possible dispersion of the recycling agent through a mixture over various time periods was investigated. This was particularly important because the dye test would be meaningless if the potential dispersion of recycling agent could mask the differences between degrees of initial mixing in a considerably short time period. [A mixture that was originally poorly mixed (inadequate) would be made equivalent to a well-mixed (adequate) one by the amount of dispersion of the recycling agent throughout the mixture.]

Standard laboratory samples were prepared and maintained at room temperature for 1, 5, 10, and 30 days and up to 6 months after compaction. Dye prints were made after each of these time periods by following the developed methods. Several representative dye prints are shown in Figures 5-7. Results indicate that little or no additional dispersion of the recycling agent appears to take place after compaction. In addition, the areas where the recycling agents were located remained soft even 2 years after mixing and compaction. This indicates that poorly mixed recycled mixtures stay poorly mixed with time and suggests that adequate mixing at the beginning is essential.

To examine further the recycling agent dispersion, thermal aging was conducted in an attempt to accelerate potential dispersion. Some poorly mixed specimens were maintained at 140°F for up to 8 months after compaction. Results indicate that little macrodispersion of the recycling agent takes place with time (see Figure 8). It was concluded that the potential dispersion (if any) might be restrained by the matrix of the asphalt binder and aggregate, particularly the mineral filler.

Although it was found that the recycling agent does not disperse with time on a macroscale, an attempt was made to examine microscale dispersion of the recycling agent by use of the scanning electron microscope (SEM). Asphalt cement (AR-4000) was artificially aged in an oven at 275°F for 24 hr. Trace element titanium was incorporated with the recycling agent (Cyclogen L) before coating an aged asphalt. It was expected that the energy dispersive X-ray detector (EDAX) would be able to detect the dispersion of titanium, which in turn would detect the dispersion of recycling agent. However, the

**Figure 4. Variation of stresses and displacement along the horizontal axis.**

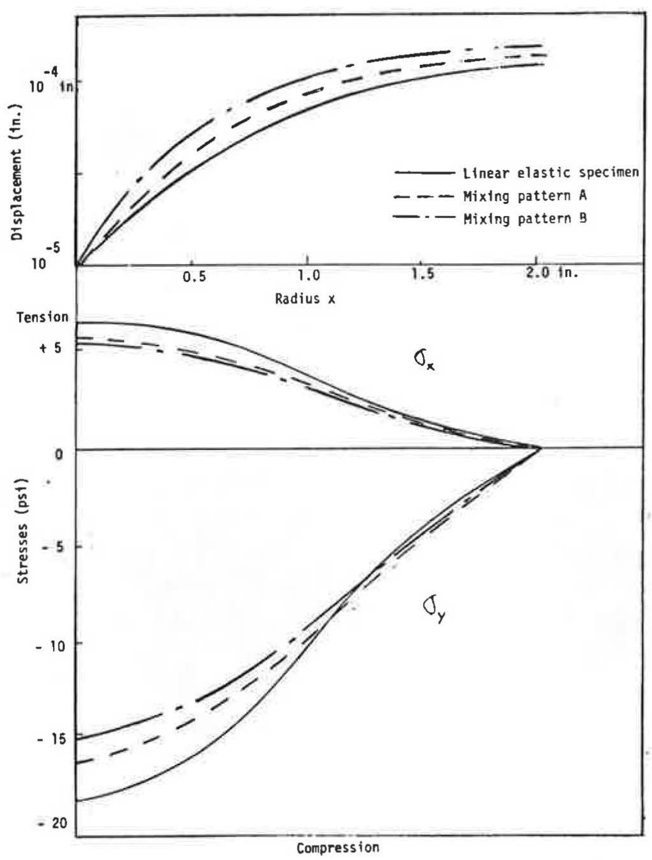
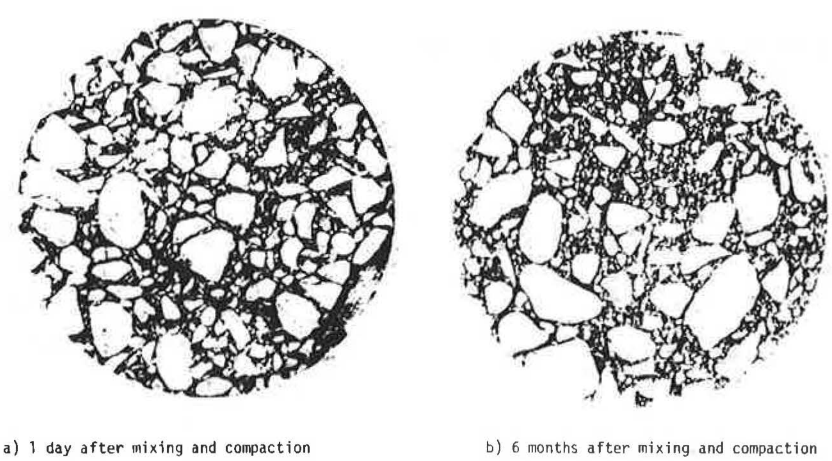



**Figure 5. Dye prints of β-naphthol: 60-sec mixing time.**



a) 1 day after mixing and compaction b) 6 months after mixing and compaction specimen could not be palladinized under vacuum because of the low melting point and vapor pressure of Cyclogen L. This method will not be valid unless the problem of interference at the interface between recycling agent and aged asphalt during the palladinizing process can be solved.

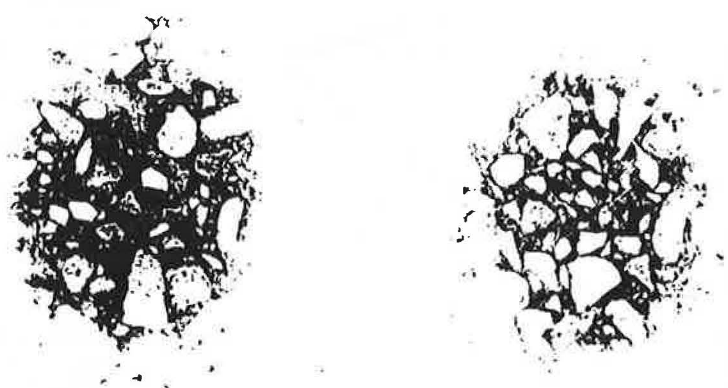
In a similar approach, AR-2000, a paving grade asphalt cement that is harder than Cyclogen L was used instead. The resulting SEM and the corresponding EDAX scan are shown in Figures 9 and 10. The interlayers of virgin asphalt (outer) and aged asphalt (inner) can be identified clearly. The dot pattern depicts the distribution of the trace element and hence the virgin asphalt. This method appears to have significant potential for verifying the microscale dispersion of a recycling agent.

Overall, the technique developed appears to be a straightforward, simple, and rapid test method. The reasonably low cost of the β-naphthol dye permits large-scale operations. Superimposing the developed dye print and its corresponding binder print makes visible the distribution of developed dye (and hence recycling agent) with respect to the other ingredients in the mix (asphalt and aggregate). The re-

**Figure 6. Dye prints of β-naphthol: 5-sec mixing time.**

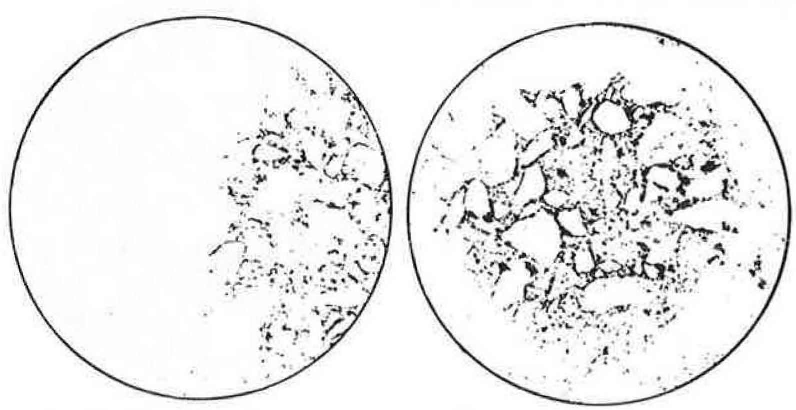
a) 1 day after mixing and compaction b) 6 months after mixing and compaction

**Figure 7. Dye prints of β-naphthol: 0-sec mixing time (recycling agent centered).**



a) 1 day after mixing and compaction b) 6 months after mixing and compaction

**Figure 8. Dye prints of β-naphthol for specimens under thermal aging.**



a) 4 months after mixing and compaction b) 8 months after mixing and compaction

Figure 9. SEM view of virgin asphalt coating on aged asphalt (200X).

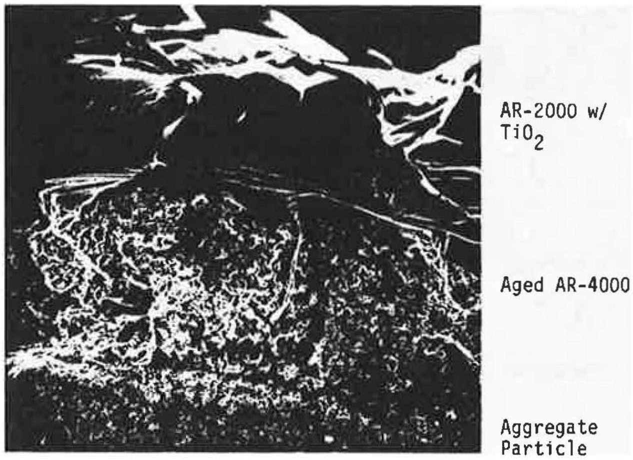



Figure 10. EDAX X-ray scan of AR-2000 containing trace element $TiO_2$ (200X).

sulting dye prints can be evaluated simply by visual examination or by using more sophisticated detection and measuring methods (12).

FIELD EVALUATION OF DYE CHEMISTRY TECHNIQUE

The application of the dye chemistry technique has been found to be a useful laboratory method of detecting the dispersion of recycling agent in a recycled mixture. However, the real value of the method will be demonstrated only if it can be applied to actual field paving operations. In general, the reclaimed asphalt pavements are milled or removed and crushed, screened, and converted to a recycled asphalt mixture by either cold-mix or hot-mix methods. The hot-mix method is currently used because it allows better control and a wider range of uses.

To date, however, a consistent system has not been developed for the process from scarification to repaving. Because plant type and layout vary from system to system, the methods of introducing the dye into the mixture differ. For example, a dye powder slurry can be pumped directly into the asphalt feed line through a positive displacement pump. Alternatively, the dye powder can be liquified by heating or by adding solvents and then pumped into the system. The best practice depends largely on the particular job encountered and the particular plant arrangement.

Ten studies of actual field projects were conducted to further evaluate the application of the dye chemistry techniques to large-scale paving operations. Various plant types, pumping systems, production rates, mixing temperatures, and asphalt modifiers were encountered in the field trials. The results of these trials indicate that the dye chemistry technique can be successfully applied to the construction process. These projects are discussed in more detail in a companion paper (16). Only two were selected for brief discussion in this paper.

Basically, the field method of the dye chemistry technique was to add some dye chemical into the new binder (recycling agent or asphalt cement). Then the dye-treated binder is put into a drum mixer or pugmill. After a normal mixing operation, the resulting mixture was sampled from the discharging outlet, from trucks, or from the grade behind the paving machine.

Most of the field projects were conducted in a similar way but the method for introducing the dye differed. The method of introducing dye mainly depends on the plant type, production rates, and mixing temperatures of the recycling jobs as well as the use of other admixtures. The dye-treated binder was pumped into a drum mixer or dumped directly into a pugmill. For a batch-type pugmill plant, the treated binder can be placed into the batch through the weigh hopper or any convenient openings. For a drum mixer plant, a metering system with a calibration tank would be ideal. Two typical examples are presented below to illustrate the field application of the dye chemistry technique. They were selected from the 10 field projects to include several variables: concentration of dye chemical, medium for dye chemistry, and relative amount of recycled asphalt mixture.

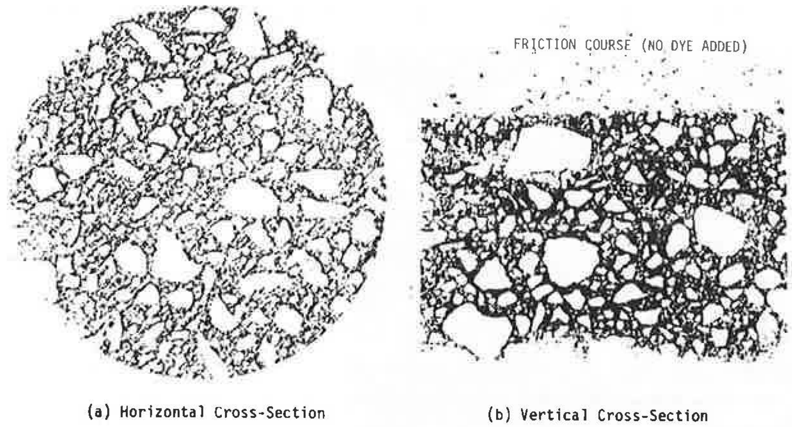
Phoenix, Arizona, Project

One project included surface recycling and milling along a 16-mile stretch of I-17 north of Phoenix. Millings were conveyed directly into bottom-dump trailer trucks and hauled to a dumping area near the contractor's hot-mix plant. A loader scooped the millings, which ranged from about 1 in. down in size, into a stockpile. Through a portable crusher, the crushings were separated by downstream screen at the 0.25-in. size. Virgin aggregates were produced from a nearby alluvial pit.

The reclaimed millings were processed in a CMI drum mixer as 30 percent of the aggregate, with the remaining 70 percent being virgin material. The reclaimed millings were fed into the center of the drum to eliminate emission problems. The virgin aggregates were preheated before mixing with the cold millings. Paving-grade asphalt (3.5 percent AR-4000 by weight of total mix) was sprayed into the mixed aggregates in the usual manner near the discharge end of the drum. The resulting hot mix was then hauled directly to the grade where it was spread and compacted by conventional equipment.

This project called for no recycling agent; instead 1 percent Unichem 7175 antistrip (by weight of added AR-4000) was used. It was decided to take advantage of the existing calibration barrel used for antistrip so that the plant mixing operation was not substantially disrupted. In this case, 25 lb of β-naphthol was blended with 15 gal of antistrip agent (at 180°F) in a 55-gal barrel. This mixture

Figure 11. Dye prints of cored samples from Ajo project.




was heated to about 250°F with a propane torch in an attempt to melt the β-naphthol flakes. This process took as long as 30 min and was found to be inefficient and exhausting. The heated mixture was transferred to the calibration barrel and was then pumped through the antistrip metering system to the drum mixer. This resulted in the addition of 20 percent dye by weight of antistrip agent, which is equivalent to a dye concentration of 0.2 percent by weight of total added binder. Samples were taken at intervals of 3 min over a 30-min period at the drum discharge outlet.

The test results show that, in spite of the small addition of dye concentration (approximately $7 \times 10^{-5}$ by weight of total mix), the dye was still discernible in the mixture of a continuous large-scale mixing operation (12). In addition, based on this limited sample, the materials were well mixed. However, the dye concentration in this project was quite low and may be at the lower practical limit. For the Ajo project, described below, the dye concentration was 25 times greater.

Ajo, Arizona, Project

Another field trial was conducted for an unusual 100 percent recycling job by using 1.8 percent Chevron RA-25 recycling agent (by weight of total mix). The reclaimed millings from a highway through Ajo, Arizona, were produced in the same manner as discussed above and were processed in a Boeing drum mixer. Because the RA-25 was kept at a sufficiently high temperature (265°F), there was no need to preheat the β-naphthol. A 55-gal barrel was tapped into the suction line of the metering system. About 30 gal of the recycling agent was pumped into the 55-gal barrel, followed by 60 lb of β-naphthol. These were then mixed with a mechanical mixer to ensure uniformity. The blended mixture was then pumped into the drum mixer through the antistrip metering system. A three-way valve prevented any disruption of the mixing operation. This resulted in the addition of 5 percent dye by weight of the total added binder (RA-25).

Samples were taken from the discharging outlet, the trucks, and the grade. The resulting dye prints showed a strong indication of thorough mixing. In addition, dye prints of cored samples obtained 4 months after paving showed the same good result (see Figure 11), which indicated that the dye was still in the pavement and would be available for further evaluation.

DISCUSSION OF RESULTS

Dye prints of field samples were very informative. The mixing efficiency of a particular mixing operation could be evaluated by examining the distribution of the developed dye spots on the resulting dye prints. In general, most of the dye prints showed that there was thorough mixing (12). This implied that the mixing action of plants now being used was satisfactory; however, additional trials with respect to variables such as mixing time and production rate should have been conducted in order to examine whether there is overmixing in the mixing operation. Consequently, optimization of mixing operation or plant design can be achieved through such knowledge.

Overall, the dye print technique appears to be a simple and easy test method. It fulfills the selection criteria for field evaluation, and it is versatile, portable, reasonably rapid, and, above all, relatively inexpensive. These criteria can be restated as follows:

1. Ease of operation: The developed dye print technique is relatively simple and straightforward. A field technician who is not a chemist can be trained to perform the test in 2 or 3 days of training. As a quality-control test, the results can be obtained in a few hours or, at most, overnight, depending on the amount of dye added.
2. Versatility and portability: It has been found that the dye is compatible with various types of binder. It appears conclusively that the dye can be used with other additives such as antistrip and sulfur as well. Furthermore, the dye is detectable even when used at a considerably low concentration. This technique involves the use of only normal equipment in a chemistry laboratory and requires no sophisticated devices.
3. Development and equipment cost: Minor modification of the normal operation process may be necessary. For example, a small amount of plumbing at the asphalt plant may be needed. In addition, if the dye were to be used on a regular basis, a dispersing module would be required. With practice, however, this may become routine, as it is in Arizona, where antistrip additive is always required. Now all asphalt plants are equipped with metering systems. The total cost is reasonably low, as indicated in the following calculations.

The cost of a pugmill plant is calculated as follows:

Assumed sample size: 8,000 lb/batch.
Assumed 70/30 mix, for 1 percent recycling agent (by weight of reclaimed material): 224 lb.
For 5 percent dye (by weight of recycling agent): 12 lb.

Cost of dye: 12 lb at \$1.35 = \$16.20/test.
Assumed test frequency of six times.
Cost of testing: \$16.20 x 6 = \$100.00 (labor excluded).

The cost of a drum mixer plant is calculated as follows:

Assumed production rate: 300 tons/hr.
Assumed 70/30 mix, for 1 percent recycling agent (by weight of reclaimed material): 70 lb/min of recycling agent.
For 5 percent dye (by weight of recycling agent): 35 lb/min of dye required.
Dye required for 20-min sample: 70 lb.
Cost of dye: 70 lb at \$1.35 = \$95/test.
Cost of hardware, etc.: \$200 (variable).
Cost of metering system: \$1,200 (variable).
For a 30,000-ton job, cost of construction: 30,000 tons at \$25 = \$750,000.
Assumed test frequency of 6 times.
Cost of testing: (\$405 x 6) + \$200 + \$1,200 = \$1,970 (labor excluded), which constitutes only 0.25 percent of total cost.

The cost of such items as hardware and the metering system will depend largely on the existing pumping system. In most cases, the cost of a single test would be less than \$100.

## SUMMARY

There has been a general increase in the amount of recycling done in the United States. Although some states have recycled far more projects than others, there is still a degree of uncertainty as to the effectiveness of recycling. This factor is emphasized by the wide range of types and amounts of recycling agent used (if any). This study provides some insight into the recycling agent and aged binder system. The dispersion of a recycling agent throughout a recycled mix can be qualitatively and quantitatively determined by the use of the dye chemistry technique. It was found that the dispersion of a recycling agent throughout the mixture after compaction was only local. Thus, this test can be beneficial in the development of an end-result type of specification. In addition, the observation that an inadequate mix behaved poorly in laboratory durability tests indicates that assurance of adequate quality from the standpoint of recycling agent dispersion can be attained from such knowledge.

While the long-term performance data on recycling are being collected, it is essential that the mixture being produced has the specified engineering properties necessary for a high-quality paving mixture. Without the tools to control the process, the engineer will not be able to estimate the performance of a given mixture. This study provides a simple test method by which to measure qualitatively and quantitatively the distribution of each component in the final bituminous mixture. As a result, there are several advantages in being able to determine the homogeneity of the mixing process:

1. The contractor can make appropriate adjustments to temperature and mixing times to optimize the plant operation and possibly reduce costs.
2. The equipment manufacturer is able to modify the design of mixing paddles and other features in a pugmill or drum mixer to provide more efficiency.
3. The owner agency is able to establish the mix design criteria of recycling materials.
4. The project engineer has a quality-control test to ensure that specification material is being produced.
5. The materials engineer is able to test specimens that are representative of material produced in the field.

## CONCLUSIONS

In summary, the primary conclusions based on the laboratory testing and findings of this study are as follows:

1. The dispersion of developed dye spots and hence of the recycling agent is readily observable. The distribution of a recycling agent can be qualitatively and quantitatively measured.
2. The distribution of a recycling agent throughout a mix is a function of mixing time. The potential of further dispersion of a recycling agent with time is only local.
3. The possible nonhomogeneity of various mixing patterns can be checked by repeating the resilient modulus test through different diametral planes and comparing the variations of the results. In general, an inadequate mix possesses more variation in the value of $M_R$ than an adequate mix.
4. An adequate mix appears to be less damaged by freeze-thaw conditioning.
5. The dye print technique is versatile, portable, rapid, and relatively inexpensive and has been applied successfully to large-scale paving operations for measuring the mixing efficiency of a recycling job.

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# Cold-Mix Recycling of Asphalt Materials: An Application to Low-Volume Roads

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**For several years now, rising asphalt prices and diminishing revenues have led many highway departments, especially local agencies, to experiment with alternative methods of rehabilitating their old asphalt pavements. One such method, which has received particular attention in Illinois, is the process of cold, in-place recycling. It has been found to be an economical alternative to other more conventional patching and overlay treatments. Cold, in-place recycling makes it possible to remove surface deficiencies and improve levels of safety and serviceability while minimizing the addition of new asphalt and aggregate materials. Furthermore, it has been found that this type of rehabilitation can be accomplished by using available equipment and basic road mix procedures. Recycling work performed by the Vermilion County, Illinois, Highway Department during the summer of 1982 is described, and details of the overall work sequence are discussed.**

In July 1982, the Vermilion County Highway Department began to recycle a 4.25-mile segment of IL-1 north of Henning, Illinois. The existing road was 18 ft wide and consisted of repeated A-3 seal coat treatments applied over about 3 to 4 in. of gravel base. An on-site pavement condition rating indicated that the road was in an advanced stage of deterioration with such deficiencies as potholes, alligator cracks, raveling, bleeding, and shoving (see Figure 1) (1). Average daily traffic totaled 350 vehicles/day, of which a large portion consisted of heavy farm machinery and tandem-axle trucks.

## SAMPLING AND TESTING

A consultant was hired to perform the necessary sampling and testing work. Field sampling involved the use of a Koehring (Bomag) rotary speed mixer that cut full-depth cross sections of the pavement at 500-ft intervals. Test material was then collected from these cuts at left, right, and centerline locations along the project, and a visual inspection was made of the thickness and composition of the existing pavement cross section. This cross section was later used to determine the tilling depth.

All field samples were laboratory tested as a means of evaluating both the quality and reusability of the existing in-place materials. Specific asphalt properties tested showed an average recovery penetration at 75°F of 17.2 and a residual asphalt content of 3.7 percent. These values were used as a basis for selecting new asphalts that could be added to replenish the old asphalt properties. Subsequent sieving of the extracted aggregate provided the in-place gradation given below:

| Sieve Size | Percentage Passing |
|---|---|
| 1.5 in. | 100.0 |
| 1 in. | 100.0 |
| 0.75 in. | 98.7 |
| 0.5 in. | 89.7 |
| 0.375 in. | 82.2 |
| No. 4 | 55.6 |
| No. 8 | 33.5 |
| No. 16 | 23.3 |
| No. 30 | 17.4 |
| No. 50 | 13.2 |
| No. 100 | 9.8 |
| No. 200 | 7.7 |

Several trial mixes, consisting of assorted combinations of old (reusable) and new materials, were then designed and tested to determine the optimum mix design. Low traffic volumes and economics led to mix designs within the following parameters: residual asphalt contents of 4 to 5 percent and aggregate gradations of CA-6 (No. 200 to 1 in. in size) or equivalent (2, p. 596). None of the mixes tested involved the use of a rejuvenator because of limited amounts of asphalt found in the test samples.

Test results indicated that the optimum mix design should provide a modified Marshall stability (Illinois method) (3) of 4,000 lb at 75°F. To reproduce this mix design in the field, an additional 3 in. of modified CA-7 aggregate (0.375 to 1 in. in size) and 2.5 gal/yd² of HFE-150 (high-float) emulsion were needed.

Actual quantities and specifications of virgin materials added to reproduce the optimum mix design are given in the following tables (the CA-6 gradation represents the design parameter, which was not used in the added materials):