DEVELOPMENT OF A RATIONAL AND PRACTICAL MIX DESIGN SYSTEM FOR FULL DEPTH RECLAIMED (FDR) MIXES

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SUMMARY

This report presents the findings of a research study carried out for the development of a rational and practical mix design system for Full Depth Reclaimed (FDR) mixes. This research project involved selecting project locations, obtaining samples from selected FDR sections, and detailed laboratory testing for evaluation. Planned work involved determination of effect of moisture content, compactive effort and additive content on volumetric and mechanical properties of FDR mixes. The overall work plan consisted of selection of test sections, sampling of materials from test sections, development of a mix design method using the Superpave gyratory compactor, construction of test section, evaluation of in-place materials, refinement of mix design and testing of in-place materials after construction of test sections. Work also included development of a rapid design procedure using the gyratory compactor only, and determination of resilient modulus of subgrade soils.

The criteria used for determination of optimum total fluid content are based on the determination of dry density and resilient modulus. Adequate resistance to moisture damage is a significant factor in obtaining good performance from stabilized base course mixes, and departments of transportation (DOT s) should consider any good test that they are comfortable with, to evaluate resistance of designed FDR mixes to moisture damage. Three different types of tests methods have been discussed.

Based on the research conducted in this study, it is concluded that the Superpave gyratory compactor can be used successfully for compacting full depth reclamation mixes. Use of a slotted mold is recommended to allow squeezing out of water during compaction of full depth reclamation mixes. Use of samples in sealed bags is recommended for determination of bulk specific gravity in the laboratory. A dry density versus total fluid content criteria can be used to

determine the optimum total fluid content. If an asphalt emulsion is used, then the total fluid consists of preexisting water in the material plus the emulsion. Any one of the additives considered in this study improves resistance of FDR against moisture damage. Cement and emulsion plus lime mixes show very high resistance to moisture damage compared to the other mixes. However, on the basis of wet tensile strength, emulsion plus lime is better than any other additive considered in this study. Therefore, use of emulsion and lime, and cement in low percentage, for full depth reclamation of materials similar to the materials studied in this project is recommended.

FDR samples for mix design should be compacted to 50 gyrations during mix design, and a minimum of 95 % of density of in-place loose mix samples, compacted to 50 gyration, is recommended to be achieved in a control strip in the field. Compaction in actual project must achieve at least 98 percent of the control strip density. Increase in structural numbers for FDR layers should be considered for designing binder and surface layers.

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SECTION 1: INTRODUCTION

Full depth reclamation (FDR) is a recycling technique in which the entire existing asphalt pavement, along with part of the underlying unbound base material, is recycled in-place to produce a stabilized base course. This technique has shown tremendous potential in saving material and money, providing a convenient way of restoring proper cross slope and grade to highway, and providing crack resistant base course. However, currently the selection of amount and type of additive used in FDR is based on experience or outdated techniques. To utilize its potential fully, there is a need to develop a rational and practical mix design system for selecting the correct amount of additive for FDR. There is also a need to evaluate the effectiveness of different types of additives on the basis of field performance.

The advantages of FDR make it an attractive option not only in the New England region, but also all over the United States. Many states are eager to adapt a rational and practical mix design system for FDR. The absence of such a system hinders the full cost-effective use of this technique, and hence prevents the savings, which can be attained through this procedure.

This project intends to address the problem of lack of a proper mix design procedure for selection of amount of additive for FDR, and the problem of determining a suitable type of additive for specific location in the state of Maine.

Objective

The objectives of this project were to develop a rational mix design system for FDR, and evaluate different additives used in FDR. Specifically, the objectives were:

1. Develop mix design method using the Superpave gyratory compactor
    a) Develop guidelines for the use of Superpave gyratory compactor for preparation of samples for mix design

b) Determine proper compactive effort in terms of gyration number for selection of optimum additive content.

2. Determine proper curing procedure

3. Evaluate the in-place performance of four different types of additive used in FDR.

4. Recommend proper structural numbers for full depth reclaimed base material.

The additional objectives were:

1. Validate the mix design procedure by designing and testing mixes from a different state.

2. Develop a procedure for selection of optimum fluid content for FDR mixes, using the gyratory compactor only.

3. Determine resilient modulus of subgrade soils from Maine

Scope

This research project involved selecting project locations, obtaining samples from selected FDR sections, and detailed laboratory testing for evaluation. Planned work involved determination of effect of moisture content, compactive effort and additive content on volumetric and mechanical properties of FDR mixes. These properties include density and resilient modulus. A mixture design procedure, specifically for determining the amount of curing and number of gyrations with the Superpave gyratory compactor, has been developed. Test sections were constructed with different additives, at contents determined from laboratory testing. In-place materials during and after construction were sampled and tested for refining the laboratory mix design procedure. Nondestructive testing of in-place material was conducted immediately after construction and one year after construction to evaluate the performance and structural strength of the sections with different additives. Samples were compacted with materials from the pavement using several different types of additives and contents. Resilient modulus and bulk specific gravity tests were conducted to determine the optimum content of each additive. Once each optimum additive content was determined, wet rutting tests were performed to compare the strength and durability of mixes with different types of additives. The scope of work also consisted of determination of resilient modulus of in-place cores and analyzing the data for determination of improvement in life of the pavement and structural numbers. A FDR mix design for reclaimed materials obtained from Nevada DOT was developed, and the density and stiffness of mixes with optimum, optimum minus and optimum plus additive content were determined. A method for rapid determination of optimum additive content using the Superpave gyratory compactor only was developed. Resilient modulus of subgrade materials obtained from three different counties (in Maine) were determined, and regression equations relating resilient modulus to bulk and deviator stress were developed.

SECTION 2: LITERATURE REVIEW

Roads are very important for our everyday life, economic prosperity, and defense of the nation. In the United States, more than 94 percent of the 2.3 million miles of roadways are paved with Hot Mix Asphalt (HMA). HMA is a mixture of mineral aggregates and asphalt binder, prepared and laid down at a high temperature in the range of 130-150^{o}C.

In the last few decades there have been tremendous developments in the field of HMA pavement recycling, specifically because of dwindling natural resources and landfill space and the simultaneous development of sophisticated plants and in-place recycling equipment. Full Depth Reclamation (FDR), even though recognized as a process with tremendous potential, has not been researched on the basis of any long-term study. While other cold recycling methods can alleviate problems related only to upper layers of a pavement, FDR is the only cold in-place recycling technique that can be used to treat a wide range of problems, particularly problems related to deeper layers, such as problems associated with weak base courses or pavements with insufficient structural capacity. FDR is capable of rectifying deep rutting problems, reflective fatigue and thermal cracking, deterioration of pavements due to maintenance patching and deterioration of ride quality caused by depressions and heaving (*1*). This technique, if performed properly, can save as much as 50 percent of the cost compared with conventional reconstruction methods (*2*). Additionally, since it is a cold recycling technique, it uses significantly less energy, results in less pollution, and helps avoid filling up landfill spaces.

Known by several names, such as deep cold recycling in Europe where the process was first used, and full depth reclamation when it was first adopted in United States, this energy saving and economical process has become generally known by its initials FDR. FDR was developed as a process for solving pavement problems that are associated with layers below the surface that form the base and subgrade. Very common problems are caused because of structurally weak base, poor base or subgrade material, and deterioration of base through the effect of environment. If a pavement shows distress due to deterioration of layers below the surface layer, such as base layer materials, the most common option is to mill the entire pavement structure and reconstruct the pavement by building it up from the base. This process involves a significant amount of expense because of the need to mill off the existing pavement, transport and deposit the old material in landfills, bring in new materials, and construct the different pavement layers. FDR provides the significantly better option of reusing existing materials to obtain a better performing base, on which a relatively thin and, hence, less costly surface layer can be used to obtain an equivalent pavement structure. The process of FDR consists of in-place cold grinding of the existing asphalt mix layer as well as the use of a predetermined amount of unbound granular base material, stabilizing the material with an additive, and compacting the layer to a proper density level. The mixing of asphalt mix and the additive with the base material provides a far superior base than the original unbound base material, avoids the problem of transporting existing material and bringing in new materials, saves energy by not using high temperature for heating asphalt mixes, and reduces the need for virgin natural resources such as mineral aggregates and asphalt binder (*3, 4*).

Since, in most cases, no new material (except stabilizer) is added during FDR, the challenges include determining the optimum thickness of base material that is to be recycled and the correct (optimum) amount of stabilizer that is to be added, to ensure that the recycled materials are properly coated with the additive (stabilizer), and compacting the mix sufficiently. The mix must then be given enough time for curing before the surface layer is applied. Currently, the process of FDR is more of an art than it is a science. In most cases, a specific percentage – a percentage that has been used before in the region for a commonly used additive – is used for recycling. The coating is checked by scooping some material by hand, making a ball out of the material, releasing the material, and looking at the uniformity of the marks on the palm of the hand (*5*). In many cases, the compaction is checked by a procedure in which the sample is taken after application of certain amount of fluid in a mold, compacting the mix with a hammer, and noting if any fluid is squeezed out of the mold. The curing time, in most cases, is based on an arbitrary number of days for which the recycled base should be left open before surfacing and is not related to any criteria or test that measures the development of strength with curing (*6*).

Needless to say, all of these techniques are based on empirical methods and experience. In most cases, contractors rely heavily on guidelines from equipment manufacturers. Hence, there is always an unknown element in the design and construction process with different contractors having their own methods of design and construction. Some contractors and states have developed their own specifications. However, contractors from different states and different state departments of transportation (DOT) will not necessarily tell the designer what tests need to be done or how to complete the mix design. Good results are not necessarily guaranteed when different materials at different climatic zones are used and when some of the criteria developed somewhere else are sacrificed for economy or convenience of construction or for a different test procedure. Still, there is a remarkably good record of FDR in the United States and it is regarded as a very economical and environmentally friendly process that can produce a good quality pavement if done properly. It has been discussed as one of the four major types of recycling in the Federal Highway Administration (FHWA) pavement recycling reference book for state and local departments of transportation (*7*).

A review of existing information on mix design and performance of FDR mixes indicate the following: 1. Coating of additives such as asphalt emulsion has a significant effect on durability (*8*), 2. Gradation of mixes, particularly percentage passing the 0.075 mm sieve has the most significant effect on the stiffness of the mix (*9*), 3. The total fluid content has a significant effect on the stiffness (*8*) of the mix, 4. Long-term performance of mixes should be studied to determine the relationship between short-term and long-term performance (*8*), 5. The effectiveness of additives for FDR is affected significantly by the plasticity of soil (*10*), 6. Maximum aggregate size has a significant effect on compactibility of mixes (*9*, *11*), 7. FDR mixes constructed in different climates need different curing periods to develop sufficient strength (*12, 13*).

The major conclusions from the literature review are:

1. The full depth reclamation process provides an attractive option in rehabilitation of pavements, particularly those with base related problems.
2. Asphalt emulsions, alone or in combination with other additives such as lime and/or cement are commonly used for FDR.
3. Coating of recycled materials is an important concern for proper construction of FDR mixes
4. Currently, there is no widely accepted mix design system, specially one using the Superpave gyratory compactor, for FDR
5. Several key issue such as curing time and temperature and structural strength of FDR mixes, need to be investigated.

SECTION 3: TEST PLAN

The overall work plan consisted of selection of test sections, sampling of materials from test sections, development of a mix design method using the Superpave gyratory compactor, construction of test section, evaluation of in-place materials, refinement of mix design and testing of in-place materials after construction of test sections. Work also included development of a rapid design procedure using the gyratory compactor only, and determination of resilient modulus of subgrade soils. The overall work plan is shown in Figure 3.1.

First, a location for test sections was selected in the state of Maine. Four half-mile long test sections (consisting of both lanes) were selected on a stretch of Route 201 (Annual Average Daily Traffic, AADT = 1900, percentage of trucks, 23) in western Maine. The existing road was investigated and samples of materials were obtained from the test section locations. Next step was to select additives for the mix that promised to be suitable for achieving adequate strength and durability. Five different additives were selected from a literature review. These are asphalt emulsion, water, cement, emulsion plus cement, and emulsion plus lime. Of these five, water and emulsion were selected for determination of optimum fluid content. The amounts of the other additives were selected on the basis of Reference *4*. The trial contents for the water and emulsion and the contents for the other additives are shown in Table 3.1.

Once additives were selected, it was then necessary to decide an optimum amount of each additive that would provide the maximum strength for a mix with that specific additive. To start this, 2,000-gram samples were prepared, using 666.6 grams of unbound base material, 1333.3 grams of recycled asphalt pavement (RAP) material, and 40.8 grams of water.

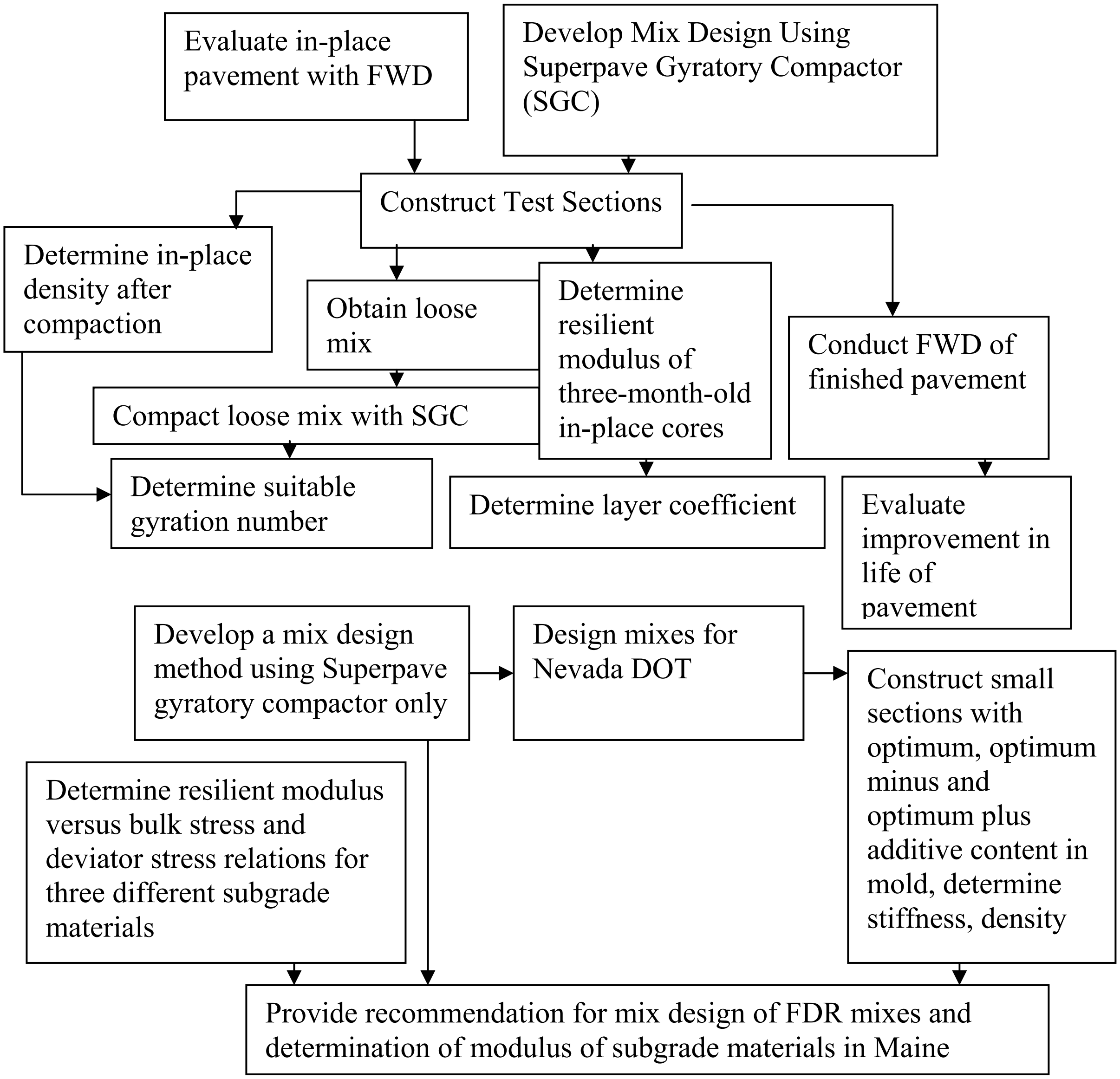


FIGURE 3.1 Overall work plan

TABLE 3.1 Amounts of additives used

Additive	Contents
Water	2%, 4%, 6%, 8%, and 10%
Emulsion	1%, 3%, 5%, and 7%
Cement	5%
Emulsion and Cement	3% Emulsion and 2% Cement
Emulsion and Lime	3% Emulsion and 2% Lime

Note: 2% pre-mix water was added to each mix

The amounts were determined on the basis of the 2:1 proportion used in the FDR mixture for the candidate pavement, and water was added to obtain the same water content as the in-place water content of the soil. Once these batch amounts were prepared in canisters and allowed to sit for 24 hours, the additives were then added in varying amounts, and for each content six batches were prepared. Each batch was then compacted using the Superpave gyratory compactor (SGC), with 75 gyrations. The compacted samples were then tested for bulk specific gravity, tensile strength and resilient modulus. From plots of dry density, indirect tensile strength and resilient modulus versus total fluid content, the optimum emulsion and water content were determined. These contents were then recommended for construction of the test sections.

Next, four sections were reclaimed at the selected location - each section with a different additive: MS-2 emulsion, water (some agencies use only water), cement (Type II), and a combination of MS-2 emulsion and lime. A visual examination of the existing pavement showed minor rutting but extensive fatigue cracking along wheel path. Immediately prior to recycling, FWD testing was conducted on the existing pavement. The decision to use lime and cement, in addition to the originally planned water and emulsion, was taken to evaluate their effect on early gain in strength and water resistance. In the emulsion section, two different contents were used in two different lanes – 2.2 % in the north-bound lane and 3.4 % in the south bound lane. In the emulsion plus lime sections (north and south bound) 3.4 % emulsion was used. Water and cement were added at 7 and 5 %, respectively, in the water and cement sections.

During FDR, samples of loose mix were obtained from the sections and transported to the laboratory in sealed bags. These mixes were compacted with a Superpave gyratory compactor (SGC) to 150 gyrations, and the densities of the compacted samples were determined using the vacuum seal method (*4*). Immediately after compaction rolling, the densities of the in-place mixes were determined using a nuclear density gauge. Densities of cores obtained after curing were compared to densities obtained at different gyrations during laboratory compaction of loose mix. This comparison was used for determination of appropriate gyration numbers.

A binder and a surface layer were constructed on the FDR base after ten days of curing. FWD test was conducted on the finished pavement after three months of construction. Full-depth in-place cores were also obtained at this time. These cores were tested for resilient modulus in the laboratory. The FWD data from before and after construction and the resilient modulus values were used for determination of improvement in pavement life and determination of structural numbers (respectively).

In the second phase, samples with different additives were compacted in the laboratory, using 50 gyrations with the Superpave gyratory compactor. This compactive effort was selected on the basis of comparison of densities of laboratory compacted samples and in-place cores obtained after curing. Immediately after each sample was compacted resilient modulus testing was conducted. Each sample's resilient modulus was recorded at time zero (that is immediately after compaction) and their bulk specific gravity (BSG) was determined using the vacuum seal (*6*) method.

Once this was done, the bulk specific gravity was recorded for time zero (that is immediately after compaction), and placed in the oven at 40° C for curing. This curing was done to imitate the curing of the FDR mix in the field. During the curing period the samples were tested again for resilient modulus at two hours, four hours, six hours, eight hours, and 24 hours. This was done to evaluate the gain in strength with time for different mixes. Once the samples were tested for the last time at 24 hours, their bulk specific gravity was again found. One exception to this procedure was samples where additional water was the only additive. It was found that these samples lacked the strength necessary for testing at an early age. Due to this problem water samples were only tested for resilient modulus and bulk specific gravity after being cured for a full 24 hours.

In the next step, mixes with different additives at the selected content were tested for durability. For this task, samples were prepared from 2,700-gram samples (one-third unbound base material and two thirds RAP, including 2% water). Once the water was added the samples were mixed and allowed to set for 24 hours as before. The additives were then added at the selected contents and the samples were compacted. Six samples were compacted for each additive. Upon being compacted the samples were cured for 24 hours in the oven at 40° C. Once the samples were cured, all the samples were tested in the Asphalt Pavement Analyzer (APA). The test consists of running loaded wheels over the mix samples under water and determining the damage to the mixes.

Next, samples of FDR mixes with water, emulsion, emulsion and lime, cement and emulsion and cement were tested for indirect tensile strength, under dry and wet conditions, and tensile strength ratios (between wet and dry) were determined.

The conditioning process was done in accordance with AASHTO T283. The samples were vacuum saturated to 50-80% saturation. They were then wrapped and placed in a self-sealing bag with 10 ml of water, and put into a -18°C freezer. After approximately 16 hours in the freezer, the samples were placed in a 60°C water bath. They were then transferred into a 25°C water bath and kept for a period of 2 hours before testing.

Next, a mix design was conducted for reclaimed materials obtained from Nevada DOT. The reclaimed materials were first tested for gradation and asphalt content. An optimum emulsion content was determined from the mix design. In the next step, three sections were constructed in an accelerated loading and testing facility mold. Each section was approximately 450 mm in length and 900 mm in width (150 mm thick). The first section was made at minus one percent of the optimum emulsion content, the second sections was at the optimum emulsion content and the third section was at plus one percent of the optimum emulsion content. The sections were compacted with a roller (vibratory) to refusal density and then left to cure for ten days. At the end of ten days, attempts were made to take cores for testing, but the material was not stiff enough to allow proper coring. In-place stiffness of the threes sections were determined, using a Humboldt Stiffness Gauge, an equipment that uses deflection under a dynamic load to measure stiffness of geo-materials. The stiffness data were analyzed.

The Nevada DOT material was used for development of a rapid mix design procedure for determination of optimum emulsion content. Mixes were prepared with different emulsion content and compacted in an instrumented mold in the Superpave gyratory compactor. The data from the instrumented mold were analyzed and a procedure for determination of optimum emulsion content as developed.

Subgrade soils from three counties in Maine were characterized (according to AASHTO classification system) and then tested for resilient modulus, using a range of deviator stress. The test results were analyzed and regression equations were developed for relating resilient modulus to deviator stress and bulk stress.

SECTION 4: SELECTION OF TEST SECTIONS IN WESTERN MAINE

Test sections for full depth reclamation (FDR) were selected and marked on U.S. Route 201, in the town of Caratunk in western Maine. The project begins at Station 2+115 metric, which is at the Caratunk-The Forks Twp. Town line and extends south ending at Station 8+019. Total length of the project was 5.9 km. Full depth reclamation for this research project was done at two locations. Stationing for FDR locations were from Station 2+650 to 3+800 and from 4+800 to 7+720. There was one 800 m test section in the first location, and three 800 m test sections in the second location. These sections were selected on the basis of the criteria that were set forth in the original test plan, and the additional criteria recommended by Expert Task Group (ETG) for the project.

The selected sections had general distress conditions of longitudinal, fatigue and thermal cracking, and maintenance patches. Photos of typical sections are shown in Figure 4.1 and 4.2. Rutting appeared to be minimal throughout the two-mile section (no actual measurements were taken), although fatigue cracking was quite evident.

FIGURE 4.1 Photo of typical section

FIGURE 4.2 Photo of typical section

SECTION 5: SAMPLING AND INVESTIGATION

Sampling of material from test sections was conducted in April 2000. The plan for taking pavement samples was discussed with Maine DOT personnel. Saw cutting a large portion of pavement at each test section was discussed. This would have been ideal, as it would have given the largest amount of material in a short time. However, as provisions had not been made to have compaction equipment at the site, the loose cold mix could not be adequately compacted after the sample was taken, leaving large section of unstable pavement. Since this was not acceptable, the option of saw cutting was not pursued.

The next option discussed was drilling cores at various locations in each of the eight test sections. Using this method, the crew would work their way south from the northern town line across four test sections, then change lanes and reverse directions. Plans were made to get at least ten cores from each section and a test pit excavated somewhere on the shoulder, close to the pavement edge, in each test section. From this pit base material would be sampled in sufficient quantity. The first coring site was selected approximately 90 m south of the Caratunk town line (northern). At approximately 9 am the first core was taken. At this point it was decided that it would be easier to drill the cores in a circle and take out the center section so that we could sample the base material directly under the pavement. The crew proceeded with this pattern through the first 4 test sections. More base material was sampled from the test pits that were excavated in Sections 2 and 3. The end of the fourth test section was reached at approximately 1:30 pm. Due to time limitation it was decided to take cores from the northbound lane of Route 201 just opposite the sampling site in Test Section 4. Since the old pavement was the same mix throughout the 3 kms of roadway, the pavement should be the same in both lanes of the road. It was also reasoned that, since the cores taken along the 3 kms stretch did not vary much in height (most of the samples were approximately 110-115 mm tall, and the top 25mm or so being a layer of “maintenance mix”) that it would make sense to take the remaining samples from one location.

In order to evaluate the pavement condition across the mat, cores were taken in a line from the centerline to the shoulder in two rows, and after removing the remaining pavement to make a crude trench in the lane. No test pit was excavated at this site. The sampling plan is shown in Figure 5.1

A search of records for the existing pavement indicated that prior to 1964 there was approximately 300 mm of gravel with 25-50 mm surface treatment (tar). In 1964 the section of roadway was rebuilt using 625 inches gravel base and 75 mm HMA. In 1991 a 19 mm maintenance mulch was applied.

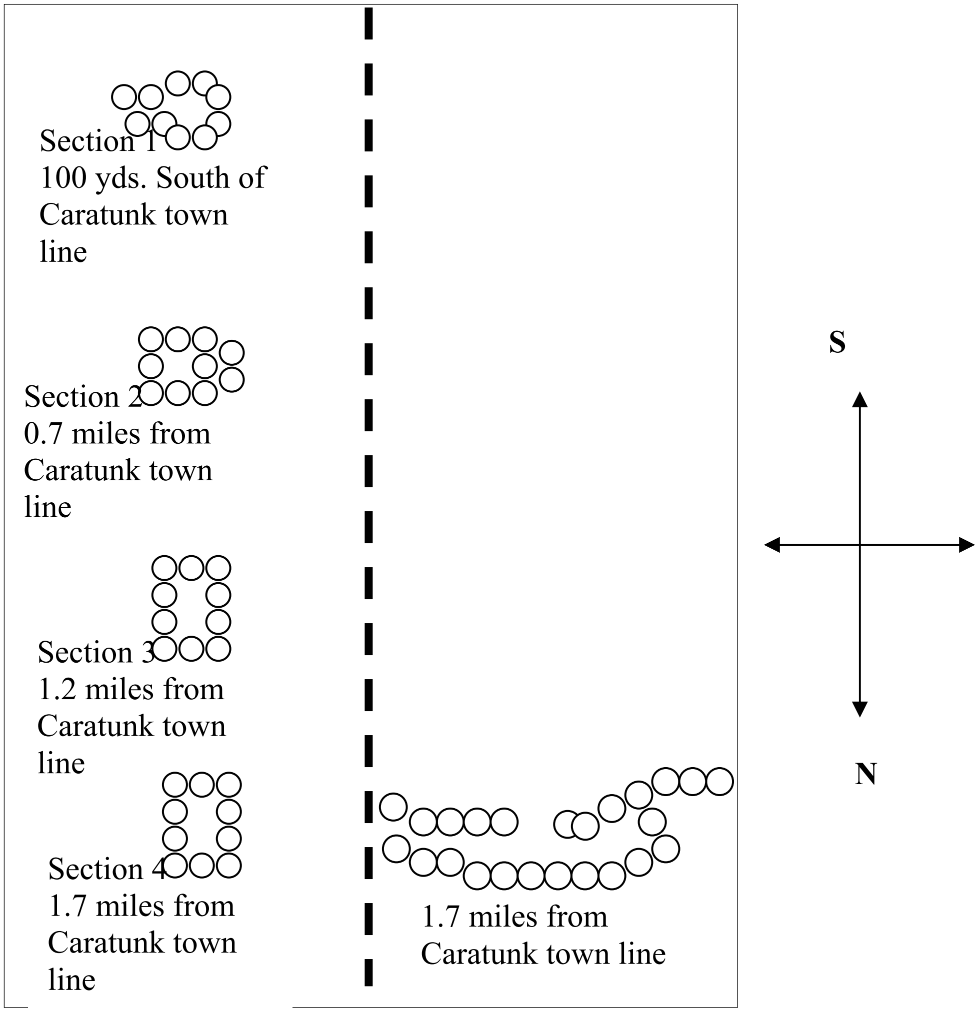


FIGURE 5.1 Sampling

TESTING OF SAMPLES FROM EXISTING PAVEMENT

Material from existing pavement and base layer were tested for composition and the results are shown in Table 5.1. The project was planned for reclaiming all 100 mm of asphalt pavement and 50 mm of the 600 mm underlying granular base course. The asphalt content (6.4 %) was noted to be fairly high, specifically because of the presence of 25 mm thick maintenance mix in the asphalt bound material.

TABLE 5.1 Results of tests of existing material

TEST	RESULTS
For Asphalt Bound Materials	
Quantitative extraction of asphalt binder	6.4 %
Penetration of extracted binder, 0.1 mm	33
Viscosity of extracted binder, Poise	11,393
Sieve analysis of fine and coarse aggregates	Sieve % Passing 19 mm 100 12.5 mm 87 9.5 mm 76 4.75 mm 58 2.36 mm 47 1.18 mm 35 0.6 mm 22 0.3 mm 12 0.15 mm 6 0.075 mm 3.5 (Note: All of 3.5 % passing 0.075 mm may not be present during cold recycling. Most probably, some of this material has resulted as a result of ignition testing).
For base course material	
Plasticity	Non plastic
Materials finer than 75 um sieve in base course material	8.1 %

The amount of material passing the 0.075 mm sieve (8.1 %) in the base course was not found to be excessive. Two samples were tested for each properties, from each of the four core locations.

The material from both asphalt bound material as well as the base course from the different sections was found to be essentially identical in composition.

Falling weight deflectometer (FWD) results showed that the structural strength of the pavement in different existing sections did not differ significantly.

SECTION 6: INITIAL MIX DESIGN

Selection of additives

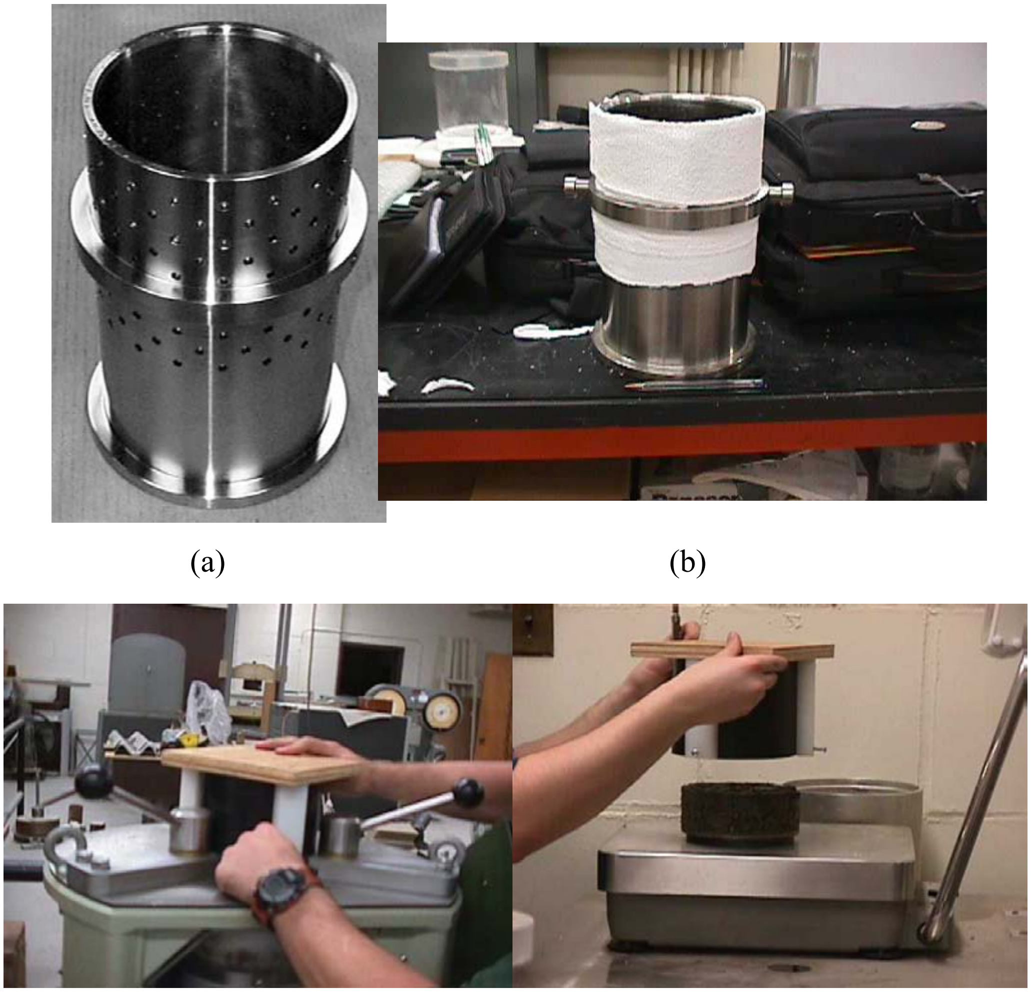
Based on the evaluation of existing materials, specifically, the percentage of material passing the 0.075 mm sieve, a MS2 emulsion was recommended.

Fabrication of modified gyratory mold

The researchers felt that compacting the recycled mix in a mold and letting it cure in the mold would result in a process, which is not representative of FDR construction methods. When the mix is compacted with a roller in the field, water is allowed to escape, and therefore the mix loses moisture (significant pore pressure does not build up) as and when it is compacted. However, in a closed mold this would not be the case, simply because there is no way for the water to escape. To solve this problem, a modified mold, with holes around it, was designed and procured from Pine Instruments. The mold is shown in Figure 6.1. Basically, it consists of several holes around the mold, through which water can escape during compaction. An band made of absorbing cloth was put around the mold to absorb the water and fine particles during compaction. It was observed that fine mortar can sometime clog the slots, and the slots should be cleaned before each compaction.

Fabrication of extrusion device for gyratory compactor

In the pine AFG1 model gyratory compactor (used in this study), the sample is extruded from the top, and then the mold is taken out, at the end of compaction. However, samples made with recycled material, with emulsion, may not be sufficiently stable to allow extrusion immediately after compaction. To solve this problem, a sample extrusion device was designed and fabricated (Figure 6.1). This device allows quick and efficient removal of



(a) (b)

(c) (d)

FIGURE 6.1 a) Slotted mold, b) cloth around slotted mold, c) extrusion device used for taking samples out, d) transferring sample with extrusion device.

specimen from the compactor immediately after compaction. However, such a device is not needed for gyratory compactors, which allows removal of the sample inside the mold.

Mix design using the Superpave Gyratory Compactor

Mix design for water and emulsion samples were conducted in the laboratory using a Superpave gyratory compactor. Since the mix design was intended to follow current construction practice as closely as possible, and currently in FDR projects in Maine no water is added separately before reclamation, it was decided that no additional water would be added other than that contained in the emulsion. However, it was decided that sufficient water must be added to bring the moisture content up to a level of natural moisture content. The existing moisture content of the base course material was found to be 6 %. Since base course and asphalt bound materials were used at 1:2 ratio, 2 % water (of the base course-asphalt mix combination) was added to the base course material, and covered with the asphalt material in gallon cans.

Design of water mixes

For water mix samples, water was added at 4, 6, 8, 10 and 12 percent. At 12 percent level water was found to be draining out from the mold, and the sample lost a significant amount of water during compaction. Hence, the 12 percent water mixes were not considered for further testing. The samples were mixed with hand for two minutes. No precompaction curing was done for water mix samples. The samples were compacted to 75 gyrations. The compacted samples were tested for bulk specific gravity and transferred to ovens maintained at 40^{o}C for post compaction curing.

Samples were taken out after every 24 hours for 6 days and tested for mass and resilient modulus. At the end of 6 days the mass was found to level off. The samples were kept in the oven for another day to ensure complete removal of moisture, and then taken out on the 7th day for testing for resilient modulus and indirect tensile strength. Figure 6.2 shows the plot of dry density and resilient modulus of mixes with different percentage of water. It can be observed that the dry density shows a peak at 2047.7 kg/m^3 for approximately 6 % of water. The resilient modulus values at 7 days peak at 2000 MPa at a water content of approximately 7 %, which is very close to the optimum water content obtained for dry density.

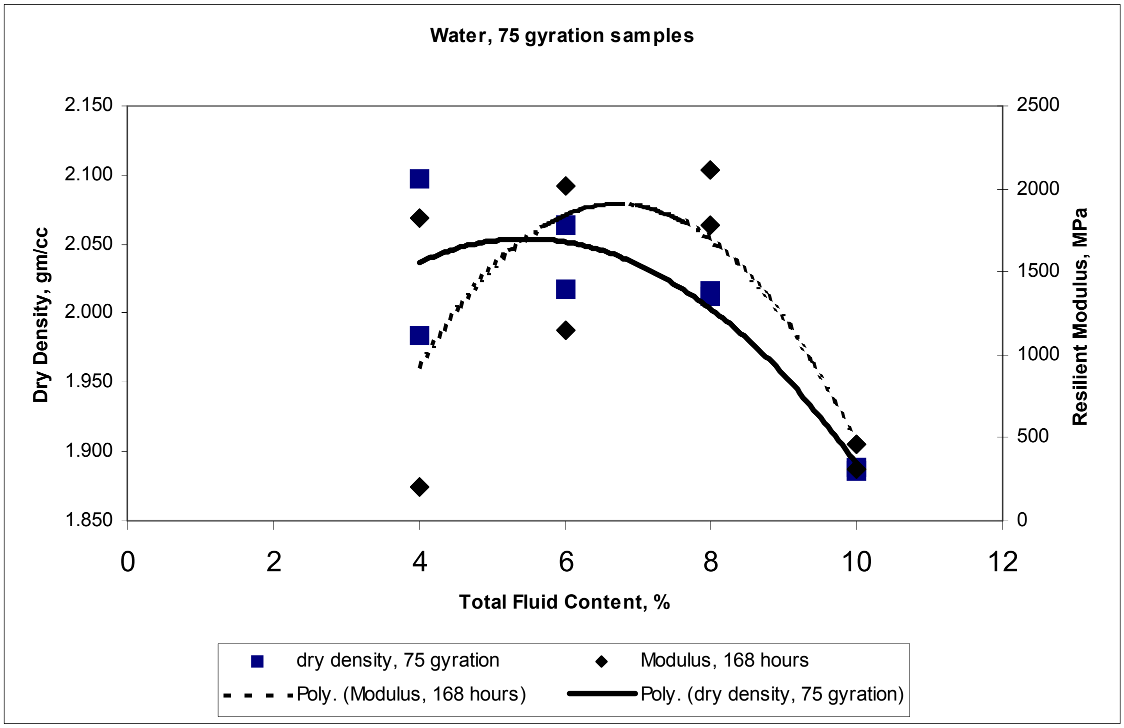


FIGURE 6.2 Plot of dry density and resilient modulus versus total fluid content (water mixes)
Note: Multiply densities by 1000 to get densities in Kg/m^3

Based on the results of this initial mix design, water content of 7 % was recommended. This percentage was close to what is typically used for reclaiming similar mixes by Maine DOT.

Emulsion mixes

As in the case of the water mix samples, the mix batches were mixed with 2 % water, before adding emulsion, and then mixes were prepared with 1, 3, 5 and 7 % of a MS-2 emulsion (with 70 percent residual asphalt content). The samples were mixed with hand for two minutes and visual evaluation of coating was made after every mixing. It was determined during mixing that with the level of water used in this study, 1 % emulsion was too low, 3 % was on the lower side, and 5 % gave good coating. The samples were tested for bulk specific gravity and then transferred to an oven maintained at 40^{o}C for post compaction curing. The samples were taken out at every 24 hours and tested for mass and resilient modulus. At the end of 10-day curing period the samples were tested for resilient modulus and indirect tensile strength.

Figure 6.3 shows the results of dry density versus total fluid content. The dry density versus total fluid content curve indicates that the emulsion and the prewet water actually work together as a fluid, which affects the compaction procedure significantly. Figure 6.3 shows that the dry density peaks at 2036.8 kg/m^3 at an optimum total fluid content of about 6 %. The peak of the resilient modulus at 1000 MPa is also very near to the optimum fluid content, at 6 %. In this case the resilient modulus was found to level off at 240 hours, and hence the values from tests conducted after 240 hours of curing are shown. Figure 6.4 shows the results of indirect tensile strength. The figure shows that the strength drops off at or near 3 % total fluid content.

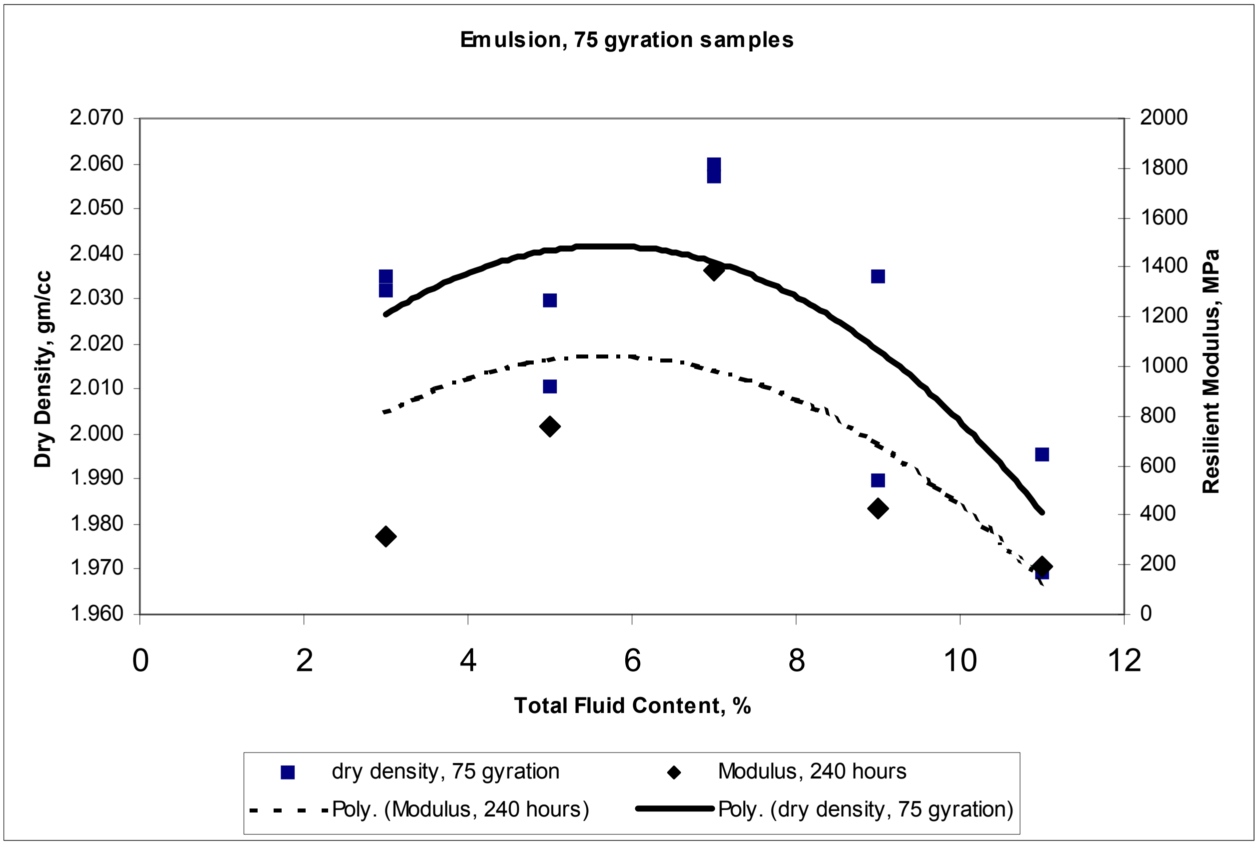


FIGURE 6.3 Plot of dry density and resilient modulus versus total fluid content

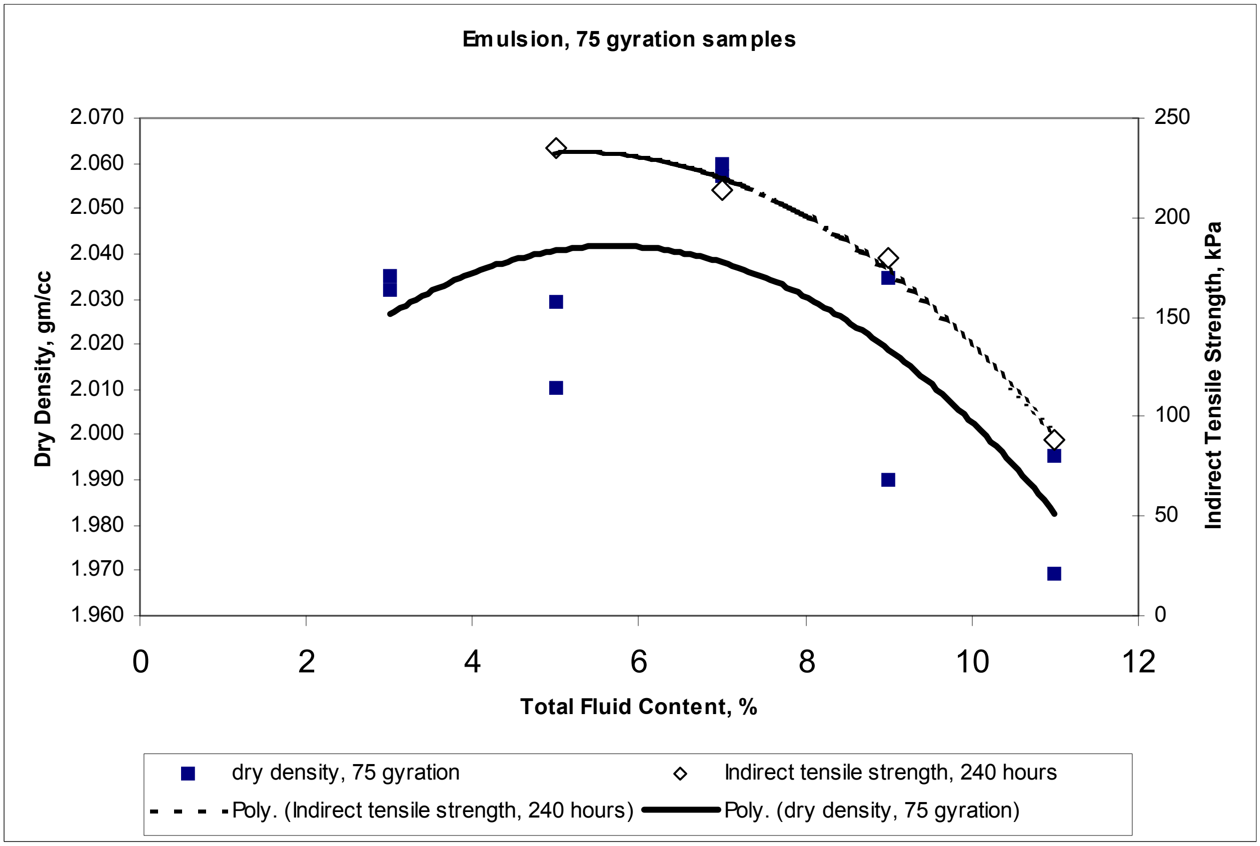


FIGURE 6.4 Plot of dry density and indirect tensile strength versus total fluid content (emulsion mixes) Note: Multiply densities by 1000 to get densities in Kg/m^3

An attempt was also made to define the properties of the mixes with respect to air voids. This necessitated the determination of theoretical maximum density (TMD). A comparison of gradation of samples compacted to 75 gyrations and uncompacted samples (Figure 6.5) indicated that the compaction procedure results in significant breakdown of aggregates (percentage passing for coarse aggregates increased by about 5 % after compaction). Hence instead of using uncompacted samples for determination of TMD, it was decided that samples compacted to 75 gyration be loosened and tested for TMD. The TMD at 3 % emulsion was determined from two samples, and then the TMD at the other emulsion contents were calculated. Voids in total mix values were calculated from bulk specific gravity values obtained after curing and the TMD, and the results are plotted against total fluid content in Figure 6.6. The figure shows that the air voids keep on decreasing with an increase in water content, and that the resilient modulus values peak at 6 % air voids.

On comparison of the air voids and dry density results it was decided to follow and recommend the dry density criteria as it is easier to determine, it shows good relationship with strength and fluid content. Hence, the dry density versus total fluid content was considered to be more practical and was used to recommend an emulsion content of 3 % with pre existing water content of 2 %. The total fluid content was selected below the optimum fluid content (6 %) that was obtained from this mix design in order to keep the mix on the dry side of the dry density versus fluid content curve. However, it was noted that if the existing water content is lower, then the emulsion content should be increased to bring the total fluid content to 5 %, and the consistency of the material should be checked during construction. If it was found that the material lacked cohesion then some additional emulsion should be used. It was strongly cautioned the emulsion

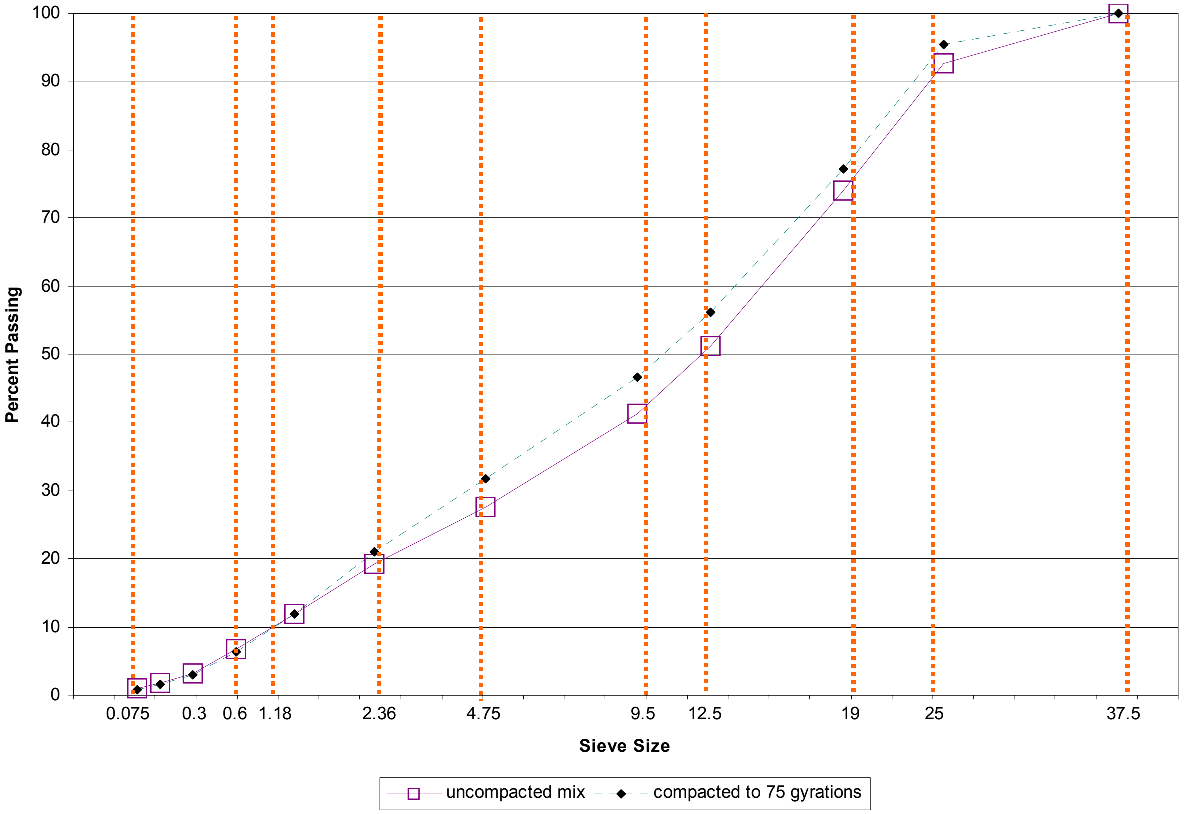


FIGURE 6.5 Gradation of compacted and uncompacted mix

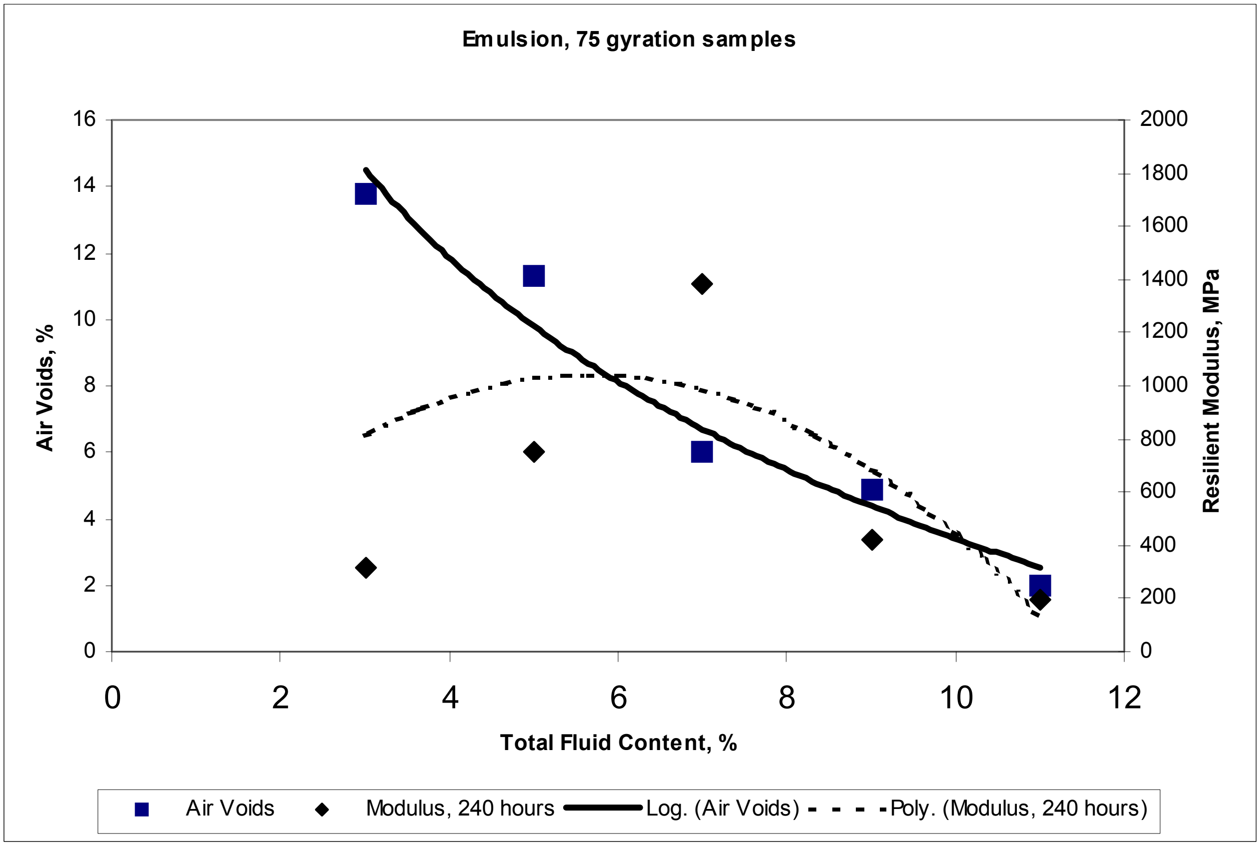
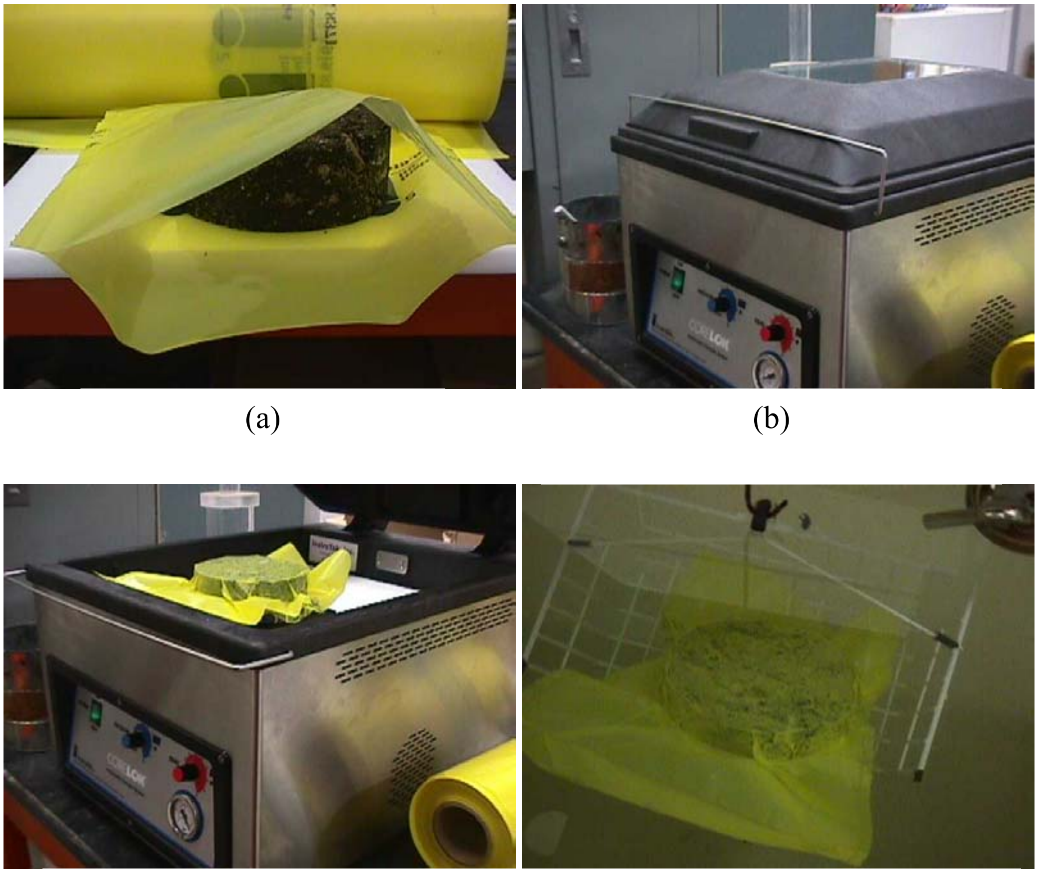


FIGURE 6.6 Plot of air voids and resilient modulus versus total fluid content (emulsion mixes)

be added carefully and too much emulsion should be avoided, since a higher than needed emulsion can cause problems during compaction and may result in low mix strength.

Use of Vacuum Seal Method

The samples were handled very carefully after compaction. However, it was suspected that the samples would fall apart if they are submerged in water for bulk specific gravity testing. The use of the newly developed CoreLok^{TM} system (*14*) provided the best solution. In this method, samples are sealed inside a plastic bag, and the samples are never in contact with water (Figure 6.7). All the bulk specific gravity determinations were done using the CoreLok^{TM} device. Since the samples remain dry and undisturbed, this process also allows the samples to be reused. The same samples were kept in oven and re-tested at regular intervals for bulk specific gravity, as well as for resilient modulus.



(a) (b)

(c) (d)

FIGURE 6.7 Use of CoreLok^{TM} (a) sample in bag, (b) CoreLok^{TM} device, (c) sample in sealed bag, (d) sample in water inside the sealed bag

SECTION 7: CONSTRUCTION

Construction of the four two-lane test sections was completed in the second week of June 2000. The sequence of construction for the emulsion sections consisted of reclaiming, application of emulsion, mixing, grading and compaction. In the case of the emulsion plus lime sections, lime was applied from bags manually on the surface before the initial reclaiming process. The same sequence was also followed for the sections with cement. The recycling equipment consisted of a reclaimer, water or emulsion tanker, a grader, a sheep foot roller and a vibratory roller (Figure 7.1). No pre-compaction curing was done. However, the time delay between the operation of different pieces of equipment resulted in some curing. In the case of water section, a field Proctor equipment was used to determine the optimum water content. The material was compacted with a field Proctor equipment and water was allowed to be added until it squeezed out from the Proctor mold. Nuclear density readings (direct transmission, AASHTO T238 & T239) were taken after every pass, and compaction was continued until a less than 1 lb/ft^3 increase in density was obtained in four successive passes. No specific problem was noted during construction, except some difficulty in compaction in the case of the cement sections. Even though the surface of the cement sections appeared to be hard, nuclear density gauge results indicated densities much lower than those obtained at the other sections. Rolling was continued for a significantly longer time than the time used for rolling the other sections.

For the water, cement and emulsion plus lime sections both lanes had identical amounts of additive. For the emulsion sections, two different percentages were used in northbound and southbound sections. In the northbound section, emulsion was added at the rate of 4.5 liter/m^2 (2.2 %), whereas in the southbound section it was applied at the rate of 6.2 liter/m^2 (3.4 %).

FIGURE 7 (a) Reclaimer, (b) Padfoot and (c) Vibratory roller

Since, Maine DOT generally uses an application rate of 4.5 liter/m^2 (2.2 %) in similar reclaiming projects, the northbound section can be considered as a control section. In the Southbound section, the material was visually evaluated (coating test) after application of emulsion at the rate of 4.5 liter/m^2. On examination it was found that the material lacked sufficient coating and cohesion. Another liter per square meter was then applied to bring the total percentage up to 3.4 %, which is very close to the recommended percentage of 3 % (*3*). On examining the material after the second application, it was found that the material had good coating and cohesion.

At the end of construction, the four test sections were left open to traffic for a period of 7 days before the application of binder (60 mm thick 19 mm nominal maximum aggregate size Superpave Hot Mix Asphalt) and surface (40 mm thick 12.5 mm nominal maximum aggregate size Superpave Hot Mix Asphalt) courses.

Before conducting FDR operation, the pavement was tested with a Falling Weight Deflectometer (FWD) equipment. A JILS 20 Falling Weight Deflectometer equipment was used. The raw data was used in DarWin 3.01 software to determine subgrade modulus, effective pavement modulus, and structural number.

SECTION 8: COST OF CONSTRUCTION

In addition to the results obtained from the different sections, it seems that a cost comparison for using different additives would be justified for this study. Table 8.1 shows the cost of constructions of the different test sections, as reported by the contractor. The numbers are based on costs that would be incurred in a regular job, assuming the use of the different additive as common practice. In order of increasing cost, the additives can be grouped as water, cement, emulsion and emulsion plus lime. However, for a rational cost approach, the initial cost must be considered in relation to performance, to obtain an estimation of the cost in relation to performance or a life cycle cost.

TABLE 8.1 Costs of construction of different sections

Material/Section	Cost ($)/square meter
Emulsion (MS-2) plus 2 % lime	$3.75 - $3.85
Emulsion (MS-2)	$3.50
Cement 5 %	$3.25 – 3.35
Water	$2.00 - $2.10

SECTION 9: RESULTS OBTAINED IMMEDIATELY AFTER CONSTRUCTION

During construction of the test sections, a nuclear density gauge was used to record bulk density of the mat and monitor the increase in density with every pass of the padfoot and the vibratory roller. A decision to stop compaction was taken when the bulk density leveled off. The level off densities were noted as the final densities for each test section, at the end of rolling, and are shown in Table 9.1. The values provide a basis for ranking the different sections according to the degree of compaction. In order of decreasing average density values, the sections can be ranked as 3.4 % emulsion, 3.4 % emulsion with lime, water, cement and 2.2 % emulsion. The standard deviation values ranged from 1.7 in the 3.4 % emulsion section to 3.5 in the 2.2 % emulsion section. Based on these results it can be concluded that the 3.4 % emulsion section showed a higher and more uniform density than the section with 2.2 % emulsion.

Following construction, cores were obtained from the test sections as soon as it was possible to obtain intact cores. The first set of cores from the emulsion sections were taken on the second day after construction, the samples from the emulsion plus lime and cement sections were taken on the first day, and the samples from the water sections were obtained on the fourth day. These cores were obtained by dry cutting with a handheld saw. No water was applied at the time of coring. The cores were kept in sealed plastic bags to prevent any moisture loss. A total of two cores were taken from each lane. The bulk densities of these cores were determined in the laboratory, and the average values are shown in Table 9.2. Table 9.2 shows that the emulsion (both 2.2 and 3.4 %) and the emulsion plus lime samples have similar densities (2275 Kg/m^3), the cement samples have the lowest density (2162 Kg/m^3), whereas the water samples have density in between (2245, Kg/m^3).

TABLE 9.1 Nuclear gage density readings taken at the end of rolling

SECTION	ADDITIVE	DENSITY READINGS (BULK, LB/FT^3)					AVERAGE (LB/FT^3)	STANDARD DEVIATION (LB/FT^3)
1NB	Emulsion, (2.2 %)	136.8	134.0	132.9	127.3	134.1	133.0	3.50
1SB	Emulsion, (3.4 %)	139.4	136.6	136.3			137.4	1.70
2NB	Emulsion (3.4 %) plus lime 2 %)	137.5	135.6	137.8	138.1		137.2	1.12
2SB	Emulsion (3.4 %) plus lime 2 %)	135.2	128.4	134.3	139.8	138.9	135.3	4.52
Average of two lanes of emulsion plus lime							136.3	
3NB	Cement	133.2	138.4	136.6			136.1	2.64
3SB	Cement	133.5	132.1	134.4	133.7		133.4	0.96
Average of two lanes of cement							134.8	
4NB	Water	132.1	135.0	135.2			134.1	1.73
4SB	Water	138.0	135.5	139.6			137.7	2.06
Average of two lanes of water							135.9	

Note: Multiply densities by 16.01 to get densities in Kg/m^3

TABLE 9.2 Bulk density of cores taken after construction

SECTION	ADDITIVE	DENSITY OF FIRST SET OF CORES TAKEN AFTER CONSTRUCTION (KG/M^3)	
		Density	Average of first set of cores
1NB	Emulsion, (2.2 %)	2275	2275
1SB	Emulsion, (3.4 %)	2274	2274
2NB	Emulsion (3.4 %) plus lime 2 %)	2240	2274
2SB	Emulsion (3.4 %) plus lime 2 %)	2307	
3NB	Cement (5 %)	2110	2162
3SB	Cement (5 %)	2211	
4NB	Water	2230	2245
4SB	Water	2258	

Note: First sets of all samples were taken on the 1st day after construction, except the emulsion samples, which were taken on the 2nd day after construction, and water samples which were taken on 4th day.

SECTION 10: DETERMINATION OF APPROPRIATE GYRATION NUMBER AND CONSTRUCTION DENSITY

Samples of recycled mix must be compacted in the laboratory, using appropriate number of gyrations (N_{design}) in the laboratory during mix design. In order to determine the appropriate $N_{design,}$ it is necessary to know the in-place density after sufficient construction and traffic compaction and how many gyrations produce a similar density. However, at the same time, it is necessary to fix a compactive effort (N_{comp}) in the laboratory - determine a density and then specify a certain percentage of the density as the required density after compaction. Since for base course material (for which the FDR is being used) most of the compaction takes place during compaction rolling and a negligible amount of densification occurs under traffic, the N_{design} and $N_{compaction}$ are the same.

To determine $N_{design/}$ $N_{compaction,}$ two approaches were used. First, mixes were compacted to 75 gyrations, and optimum fluid contents (for water and emulsion) were determined. Table 10.1 shows the results of this mix design. Dry density values (immediately after compaction) and resilient modulus (after curing) were evaluated for mixes with different total fluid content, and the total fluid content that produced the peak density and resilient modulus values were considered as optimum total fluid contents, as shown earlier (in Initial Mix Design section). The optimum total fluid content for water was noted to be 7 % and that for the emulsion, between 5 and 6.5 %. Based on these observations, a 7 % water content for water mixes and a 5 % total fluid content for emulsion mixes (with 3 % emulsion), was recommended for constructing the test sections.

TABLE 10.1 Density and resilient modulus of laboratory compacted samples

Additive	Gyration	Total Fluid Content (includes 2 % water)	Dry Density Kg/m^3	Average Density Kg/m^3	Resilient Modulus MPa	Average Resilient Modulus MPa
Water	75	4	1984	2041	1822.0	1822.0
			2097		destroyed	
		6	2018	2491	1143	1578.5
			2964		2014	
		8	2012	2014	1786	1952.5
			2016		2119	
		10	1886		458.4	386.2
			1889		313.9	
			2079		691.3	
			1893		153.5	
Emulsion	75	3	2032	2034	315.6	315.6
			2035		destroyed	
		5	2010	2020	1829	1829
			2030		destroyed	
		7	2057	2059	1207	1296.5
			2060		1386	
		9	1990	2012	558	490.8
			2035		423.6	
		11	1995	1982	213.7	205.3
			1969		196.9	
			2028		125.2	

After FDR was conducted using the recommended optimum fluid contents, in-place densities after compaction rolling was determined from in-place cores (Table 9.2 of RESULTS OBTAINED IMMEDIATELY AFTER CONSTRUCTION Section). Samples of loose mix were also obtained during recycling operations. These samples were compacted to 150 gyrations and the density at each gyration was back calculated from the density of samples obtained at the end of 150 gyration. The in-place densities (obtained from in-place cores at the end of FDR) were compared to densities obtained at different gyrations and the gyration that produced similar densities were noted (Figure 10.1 a). It was noted that in all the cases the in-place densities were closer to densities at 50 or lower gyration. For all cases except cement, the in-place densities were 96-98 % of densities at 50 gyrations. The in-place density for the cement section was at 92 % of the density at 50 gyrations (Figure 10.1b).

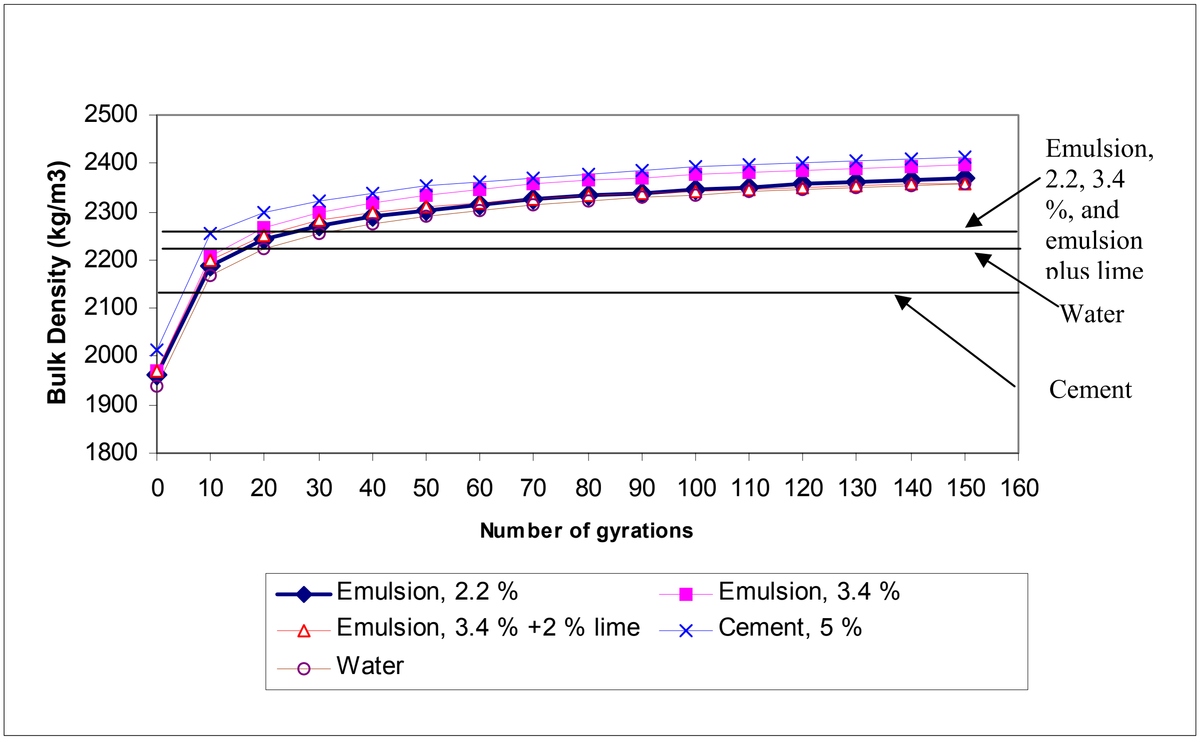


FIGURE 10.1a Density of Laboratory Compacted Loose Mixes and In-Place Density

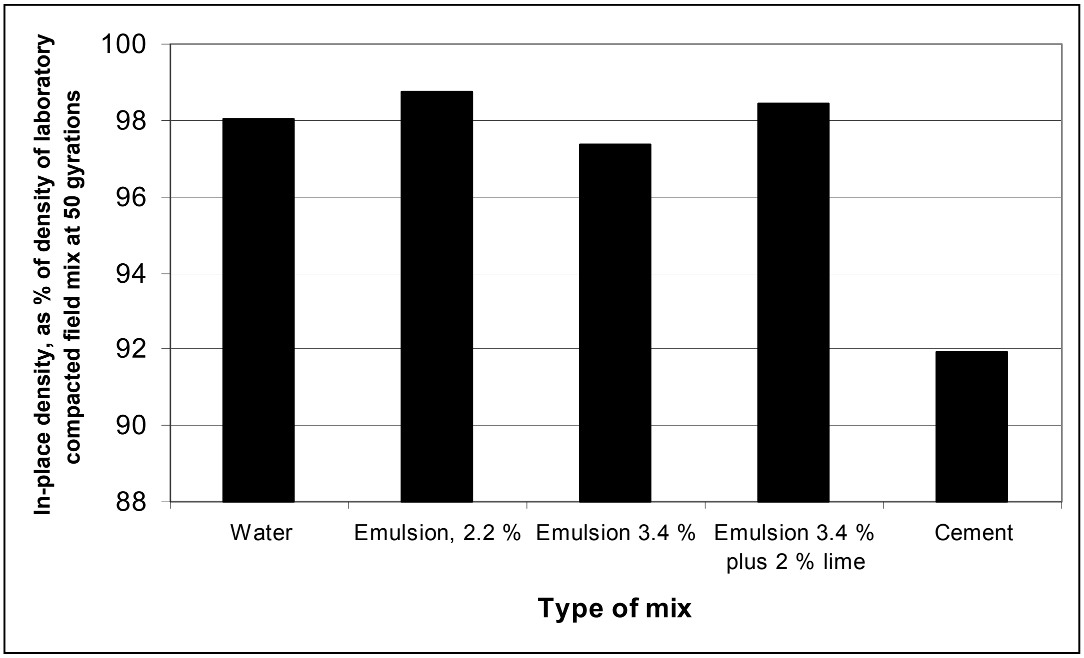


FIGURE 10.1b Comparison of In-Place Density with Density of Samples Compacted to 50 Gyrations

Next, samples were prepared and mix design was conducted (for water and emulsion) by compacting the mixes to 50 gyrations (Table 10.2). The mix design results (Figures 10.2a and 10.2b) were compared against results from the mix design conducted with samples compacted to 75 gyrations. The comparison showed that the optimum total fluid contents obtained for samples compacted to 75 gyrations (7 % for water and 5-6.5% for emulsion) were not significantly different from the optimum total fluid contents obtained for samples compacted to 50 gyrations (7 % for water and 5-6.5% for emulsion). Hence, from the results of comparison of in-place density and density of loose mix, and comparison of optimum fluid content and resilient modulus of laboratory samples compacted to 50 and 75 gyrations, it is concluded that samples be compacted to 50 gyrations during mix design.

Effect of large particles during compaction

It should be noted that the material was compacted in the SGC after discarding the plus 37.5 mm aggregate particles. However, during construction some plus 37.5 mm aggregates were noted. During compaction with loose mix obtained during compaction, approximately 8 % of material was found to be retained on plus 37.5 mm sieve. (These aggregates were discarded before compaction). Hence, it must be noted that the material that is used for mix design compaction and determination of N_{design} is not essentially the same exact material that is reclaimed. However, this difference must be recognized, and as long as the amount of plus 37.5 mm aggregates is not excessive (<10 %), and the plus 37.5 mm aggregates are discarded before compaction with the SGC, results obtained from mix design should be reasonably accurate.

TABLE 10.2 Density and resilient modulus of laboratory compacted samples (50 gyrations)

Additive	Gyration	Total Fluid Content (includes 2 % water)	Dry Density Kg/m^3	Average Density Kg/m^3	Resilient Modulus MPa	Average Resilient Modulus MPa
Water	50	4	2044	2041	194.1	392.5
			2026		211.3	
			2050		599.7	
			2044		564.8	
		6	2089	2073	203.5	601.3
			2115		260.7	
			2036		1306	
			2051		635	
		8	2130	2107	553.4	453.6
			2083		750	
			2143		327.5	
			2071		183.3	
		10	2090	2021	323.2	389.3
			2079		691.3	
			1893		153.5	
			1969		196.9	
Emulsion	50	3	1981	1996	140.9	171.2
			2011		201.5	
		5	2037	2052	135.4	171.2
			2066		206.9	
		7	1987	2005	124.1	123.3
			2023		122.5	
		9	2021	2025	74.6	99.9
			2028		125.2	

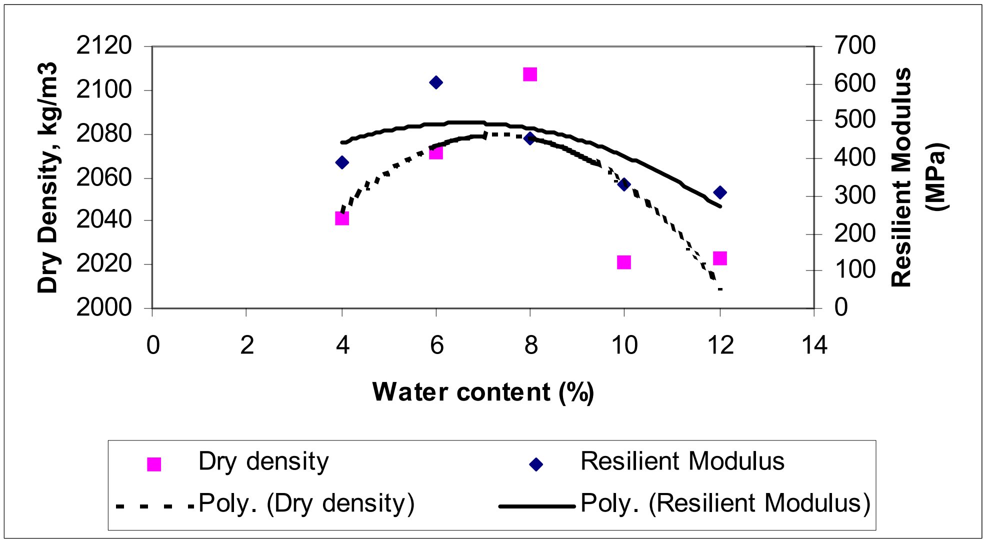


FIGURE 10.2a Plot of water content versus properties for water samples compacted at 50 gyrations

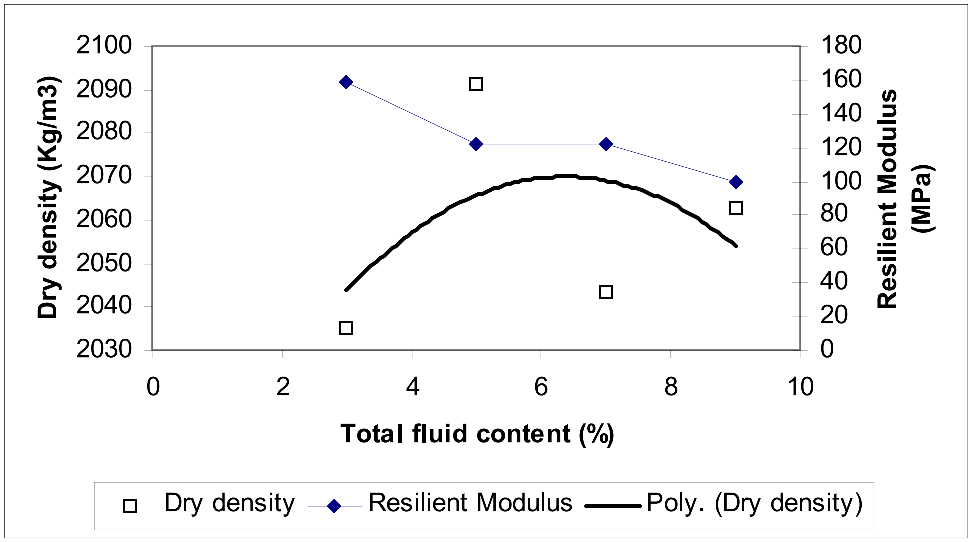


FIGURE 10.2 b Plot of water content versus properties for emulsion samples compacted at 50 gyrations

SECTION 11: MOISTURE CONTENT OF MIXES AND CURING

In order to determine proper curing periods in the laboratory and in the field, moisture contents were determined for mixes and samples obtained at different times during construction. Figure 11.1 shows the moisture contents for three sets of samples for each test section – for samples taken behind the reclaimer after the application of the additive, for samples taken immediately before rolling, and for cores obtained at the end of curing (or the last set of cores taken for a specific test section).

In all of the cases, except water section, the moisture content before rolling is higher than the moisture content at the end of application of additive. This is expected since according to current FDR practice in Maine, no precompaction curing was done. Therefore, in the laboratory, during mix design, it is suggested that no curing be done between mixing and compaction, to keep the moisture content of the samples at the time of compaction at least same as that at the end of mixing. Also, a curing period may be necessary to reduce the moisture content and facilitate compaction in the case of compaction in a Marshall mold. Since in this case compaction is recommended in a slotted gyratory mold (which allows squeezing out of water), and there seems to be no problem in achieving densification of mixes, no precompaction curing is recommended for design of FDR mixes.

A review of the moisture content at the end of the curing period (Figure 11.1) shows that all the moisture contents are between 2 and 3 %. The last set of cores for the sections other than the emulsion sections were taken before the end of the 7 day curing period, as noted in the figure. Taking this into consideration, the moisture content of all the mixes at the end of the 7 day curing period can be estimated to be less than 3 %.

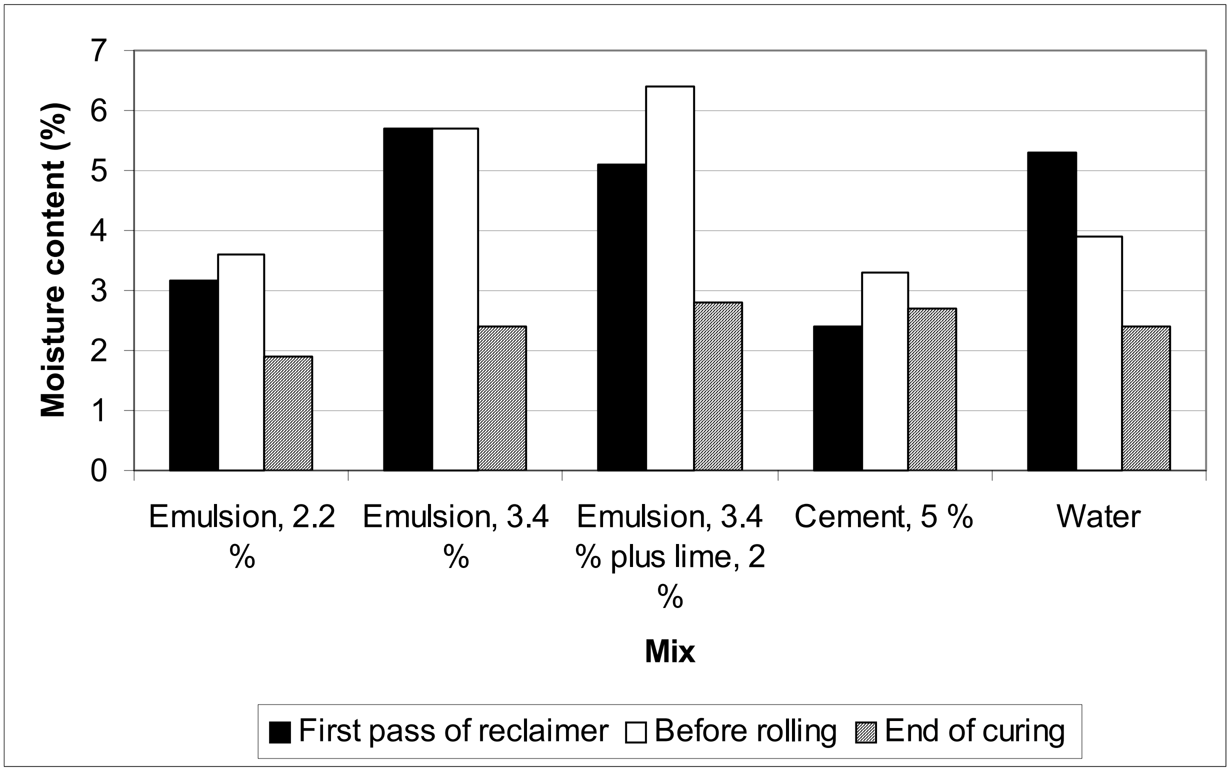


FIGURE 11.1 Moisture content of mixes

Note: The last set of cores for emulsion samples were taken on the 7th day after construction, 6th day for the emulsion plus lime samples, 5th day for the cement samples and 4th day after construction for the water samples

Therefore, maximum water content of 3 %, rather than a number of days, can be specified as criteria for curing in the field prior to placement of overlay. However, for practical purposes, a minimum of 10 curing days or a moisture content less than or equal to 3 % moisture content is recommended for field curing.

Similarly, in the laboratory, post compaction curing should be continued until the samples have water content equal to or less than 3 %. If a number of days for curing, which can reduce the moisture content to 3 %, can be determined, then the samples can be cured for that many days, during mix design. During the initial mix deign conducted as part of this study, loss in moisture content was noted for the different mixes, through the 6 day curing periods. From the dry mass, the moisture content at different times was back-calculated. Figure 11.2 shows the moisture content of two different mixes, one with initial moisture content of 7 % and the other with initial moisture content of 10 %. In both cases it can be seen that the moisture content is reduced significantly less than 3 % within a day of curing at $40^{o}C$. Based on this observation, it seems to be justified to recommend that postcompaction curing be conducted in the laboratory for one day at $40^{o}C$. However, it should be noted that this is a general recommendation and may not be strictly valid for mixes with a wide range in material composition, particularly gradation, since finer mixes should take more time to cure than coarser mixes.

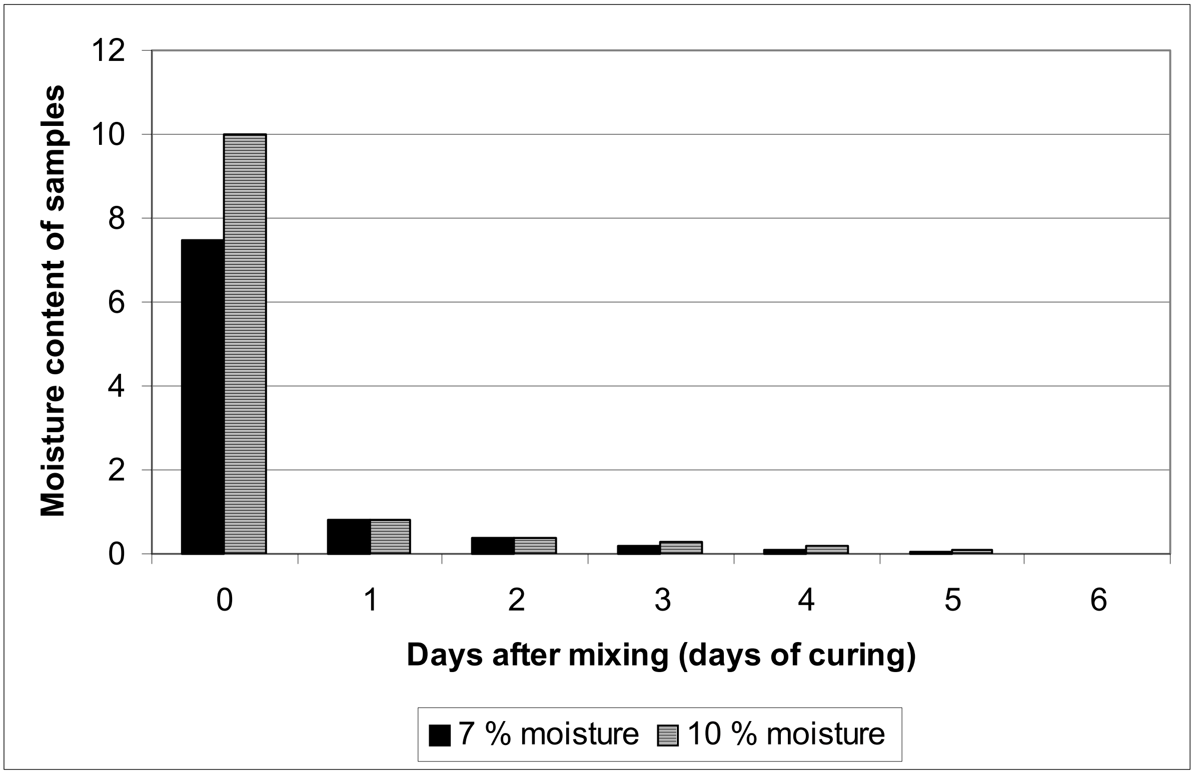


FIGURE 11.2 Moisture content of water mix samples from initial mix design

SECTION 12: EVALUATION OF MOISTURE SUSCEPTIBILITY OF FDR MIXES WITH DIFFERENT ADDITIVES

Moisture induced damage is a significant factor in deterioration of base mixes. Hence, any additive that is recommended for use in FDR, must be evaluated in terms of its effect on moisture susceptibility of the resultant FDR mix. In this study, samples of FDR mixes with water, emulsion, emulsion and lime, cement and emulsion and cement were tested for indirect tensile strength, under dry and wet conditions, and tensile strength ratios (between wet and dry) were determined.

The conditioning process was done in accordance with AASHTO T283. The samples were vacuum saturated to 50-80% saturation. They were then wrapped and placed in a self sealing bag with 10 ml of water, and put into a -18°C freezer. After approximately 16 hours in the freezer, the samples were placed in a 60°C water bath. They were then transferred into a 25°C water bath and kept for a period of 2 hours before testing.

The results of the strength tests are shown in Table 12.1. It is noted that the cement samples show the highest tensile strength ratio (0.9), followed by the emulsion plus lime samples (0.7), emulsion plus cement (0.4) and emulsion (0.2). The water samples crumbled during vacuum saturation. A consideration of wet strength only, however, shows that the cement samples have very low wet tensile strength (62 kPa), compared to the emulsion, emulsion plus lime or emulsion plus cement samples. The emulsion plus lime samples actually show the highest wet tensile strength (189 kPa).

The samples of water only mixes were not suitable for testing for indirect tensile strength in wet as well as dry condition. Compared to the water mixes, samples of all other mixes were better, since they could be tested in the wet and dry conditions, even though the wet conditions strengths were much lower than the dry condition strength.

Based on the results, it can be concluded that any one of the additives considered in this study improves resistance of FDR against moisture damage. Cement and emulsion plus lime mixes show very high resistance to moisture damage compared to the other mixes. On the basis of wet tensile strength, emulsion plus lime is the most desirable additive.

TABLE 12.1 Results of moisture susceptibility test

Specimen ID	Condition	Diameter (mm)	Height (mm)	Tensile Strength (kPa)	Average Tensile Strength (kPa)	TSR
Water #1	Wet	100	59.8	NA	NA	NA
Water #2		100	61	NA		
Water #3		100	60.4	NA		
Water #4	Dry	100	61.3	NA	NA	
Water #5		100	59.1	NA		
Water #6		100	61.2	NA		
Emulsion #1	Wet	100	63	55.3	56.2	0.20
Emulsion #2		100	62.1	52.0		
Emulsion #3		100	63.5	61.3		
Emulsion #4	Dry	100	62.4	296.9	274.3	
Emulsion #5		100	62.6	283.2		
Emulsion #6		100	63.6	242.9		
E + L #1	Wet	100	64.3	171.0	189.1	0.72
E + L #2		100	64.9	203.4		
E + L #3		100	63.1	192.9		
E + L #4	Dry	100	62.2	232.7	263.0	
E + L #5		100	63.1	240.8		
E + L #6		100	63.3	315.5		
E + C #1	Wet	100	62.9	99.0	79.9	0.39
E + C #2		100	62.1	50.2		
E + C #3		100	62.5	90.6		
E + C #4	Dry	100	62.5	226.5	199.9	
E + C #5		100	62.7	234.9		
E + C #6		100	61.4	138.3		
C #1	Wet	100	63.6	53.5	61.7	0.97
C #2		100	63.5	57.9		
C #3		100	65.4	73.6		
C #4	Dry	100	63.9	34.7	63.3	
C #5		100	65.7	51.8		
C #6		100	63.2	58.2		

Note: E – Emulsion, L – Lime, C- Cement, TSR – tensile strength ratio

SECTION 13: MOISTURE AGGRAVATED DEFORMATION

In the next phase, water and emulsion mixes were prepared and samples were compacted at the optimum total fluid content. Samples were also compacted with mixes prepared with cement (5 %) plus 2 % premixed water (cement samples) and emulsion (3 %) plus lime (2 %) (emulsion plus lime samples), emulsion (3 %) plus cement (2 %) (emulsion plus cement samples) and emulsion (3 %) plus cement (2 %) plus lime (2 %) (emulsion plus cement plus lime samples). All of these samples, except the emulsion plus cement plus lime samples were then tested with the Asphalt Pavement Analyzer (APA). The testing was done by running loaded wheels under 690kPa pressure over the samples. The entire testing was done under water. At the end of 8,000 cycles of loading, the rut depths of the samples were compared. Also, the automatic data acquisition system in the APA obtained rut depths at 500 cycle and at every 1,000 cycles thereafter, and as a result the rut depth versus cycles data was obtained for each group of samples. These results are shown in Figure 13.1. Each plot indicates the average values from six samples. A comparison of the final rut depth (at 8,000 cycles) clearly shows the beneficial effect of additive in the mixes – the mixes with no additives, that is with water only, shows the highest amount of rutting. In terms of the final rutting, the mixes can be ranked as (from best to worst) – emulsion plus cement, emulsion plus lime, cement, emulsion and water.

An Analysis of Variance (ANOVA) was conducted with the rut depths obtained at 8,000 cycles for the different mixes. The results are shown in Table 13.1. As indicated by a low p value (0.001) there is significant difference between the rut depths of the different mixes. This indicates that the additives used in this study have a significant effect on rutting potential of these mixes. Studen-Newman-Keuls (SNK) test conducted to rank the mixes showed that (Table 13.1) there is a significant difference between rutting potential of mixes with cement and emulsion,

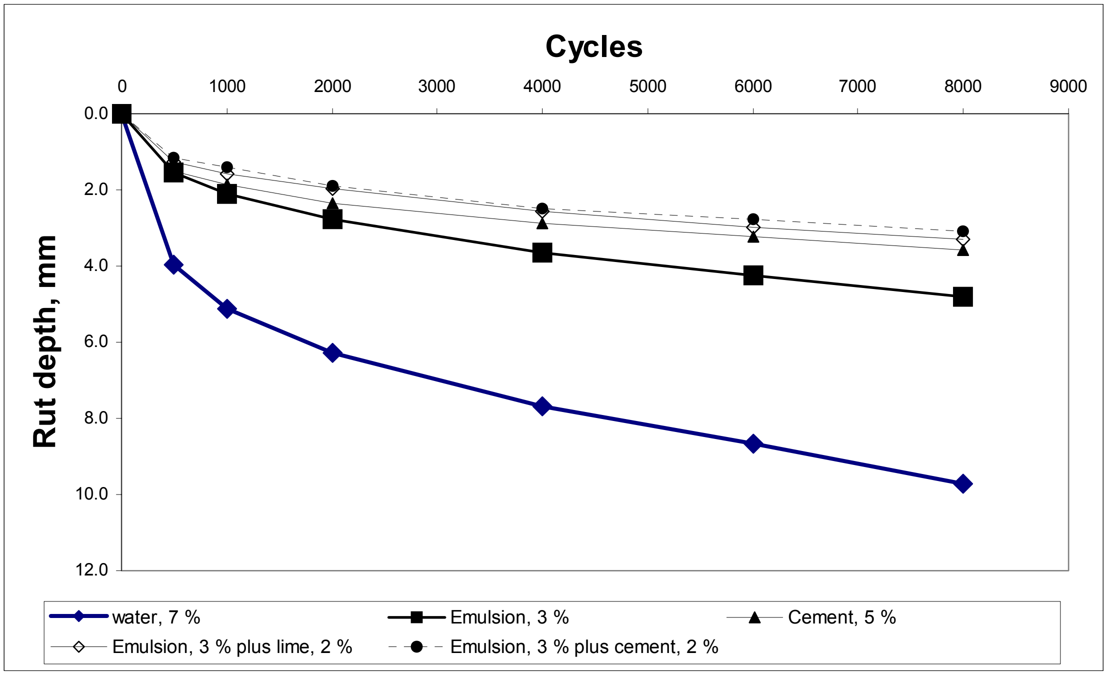


FIGURE 13.1 Plot of rutting versus cycles for different mixes

TABLE 13.1 Results of statistical analysis with rut depths at 8,000 cycles

ANOVA Table for Rut Depth_8000

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Additive	4	92.847	23.212	18.432	.0001	73.727	1.000
Residual	10	12.593	1.259				

Student-Newman-Keuls for Rut Depth_8000
Effect: Additive
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	
Cement 5 %, Emulsion 3 %	-1.233	2.041	
Cement 5 %, Emulsion 3 % plus cement 2 %	.467	2.514	
Cement 5 %, Emulsion 3 % plus lime 2 %	.267	2.041	
Cement 5 %, Water 7 %	-6.167	2.514	S
Emulsion 3 %, Emulsion 3 % plus cement 2 %	1.700	2.805	
Emulsion 3 %, Emulsion 3 % plus lime 2 %	1.500	2.514	
Emulsion 3 %, Water 7 %	-4.933	2.041	S
Emulsion 3 % plus cement 2 %, Emulsion 3 % plus lime 2 %	-.200	2.041	
Emulsion 3 % plus cement 2 %, Water 7 %	-6.633	3.013	S
Emulsion 3 % plus lime 2 %, Water 7 %	-6.433	2.805	S

Note: S denotes significant difference (when the difference exceeds the critical difference) cement and water, emulsion plus lime and emulsion plus cement and water, and emulsion and water mixes.

Photos of typical rutted samples of different mixes are shown in Figure 13.2. A close observation showed that initially, with the start of loading, the asphalt and the asphalt rich fine particles on the surface began to strip off (commonly referred to as stripping) and then the bigger particles started raveling or pushing out, resulting in ruts (depressions). Hence, the initial stripping seems to have affected the rut depths significantly – higher the amount of stripping deeper is the rut. An examination of the plots in Figure 13.1 shows that the slope of the plots, between 0 and 500 cycles can be used as indicators of final rut depths. The data clearly shows that the water samples show the highest slope of rutting versus cycles, indicating a high degree of stripping. In terms of stripping resistance, the mixes can be ranked as (from best to worst) – emulsion plus lime, cement, emulsion and water. Hence from strength and durability consideration, an addition of 2 % cement or 2 % lime with 3 % emulsion seems to result in the best mix.

ANOVA and SNK tests were also conducted with the rut depth at 500 cycles to evaluate the mixes in terms of their stripping potential. The results are shown in Table 13.2. Again, the rut depths at 500 cycles are significantly different for the different mixes, and the SNK test shows essentially the same results as the results shown by the analysis of the rut depth at 8,000 cycles (as shown in Table 13.1). Hence, the rut depth at 500 cycles can be considered to be an indicator of rutting and stripping potential in rut tests with the APA.

Water sample Emulsion sample Emulsion plus cement

Emulsion plus lime sample

FIGURE 13.2. Photos of rutted samples of different mixes

TABLE 13.2 Results of statistical analysis with rut depths at 500 cycles

ANOVA Table for Rut Depth_500

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Additive	4	16.511	4.128	25.375	<.0001	101.500	1.000
Residual	10	1.627	.163				

Student-Newman-Keuls for Rut Depth_500
Effect: Additive
Significance Level: 5 %

	Mean Diff.	Crit. Diff.	
Cement 5 %, Emulsion 3 %	-.033	.733	
Cement 5 %, Emulsion 3 % plus cement 2 %	.333	.903	
Cement 5 %, Emulsion 3 % plus lime 2 %	.233	.733	
Cement 5 %, Water 7 %	-2.467	.903	S
Emulsion 3 %, Emulsion 3 % plus cement 2 %	.367	1.008	
Emulsion 3 %, Emulsion 3 % plus lime 2 %	.267	.903	
Emulsion 3 %, Water 7 %	-2.433	.733	S
Emulsion 3 % plus cement 2 %, Emulsion 3 % plus lime 2 %	-.100	.733	
Emulsion 3 % plus cement 2 %, Water 7 %	-2.800	1.083	S
Emulsion 3 % plus lime 2 %, Water 7 %	-2.700	1.008	S

Note: S denotes significant difference (when the difference exceeds the critical difference)

SECTION 14: EVALUATION OF RATE OF CURING

One important consideration in selection of an additive for full depth reclamation is the rate of gain of strength with time- how quickly the mix “cures” or gains strength after construction. Obviously, the shorter the “curing” time, shorter is the time needed to wait before the surface course (of hot mix asphalt, HMA) can be applied, and hence shorter is the total construction time. To compare the time needed to gain strength for the different mixes, resilient modulus of the different mixes, as prepared in the second phase, were tested immediately after compaction and at several intervals of time, such as 6, 8, 12, for 24 hours after construction. The results are shown in Figure 14.1. The results indicate the rate of gain in strength for each type of mix. For the water samples, there is only one data point – average of resilient modulus of three samples conducted after 24 hours of testing. The water samples were very soft and could not be tested before 24 hours of curing. Compared to that, the samples from all other mixes were tested at several times before the end of the 24-hour curing period. The emulsion samples show a lower rate of gain in strength, whereas (in decreasing order of rate of increase in strength) the emulsion plus cement plus lime, emulsion plus cement, emulsion plus lime and cement samples show higher rate of gain in strength with time. The emulsion plus lime and the cement samples show comparable (and higher than emulsion only) rate of gain in strength, whereas the emulsion plus lime plus cement samples show a distinctively higher rate of gain in strength. Although initially the rate of gain is comparable to that of the other mixes (except water), the cement samples show significant higher modulus values at 24 hours, indicating a very high stiffness. It must be noted that materials with excessively high stiffness are susceptible to cracking and should be used with caution. Therefore, from overall consideration, it seems that the emulsion plus lime mixes provide adequately high rate of gain in strength for use in full depth reclamation.

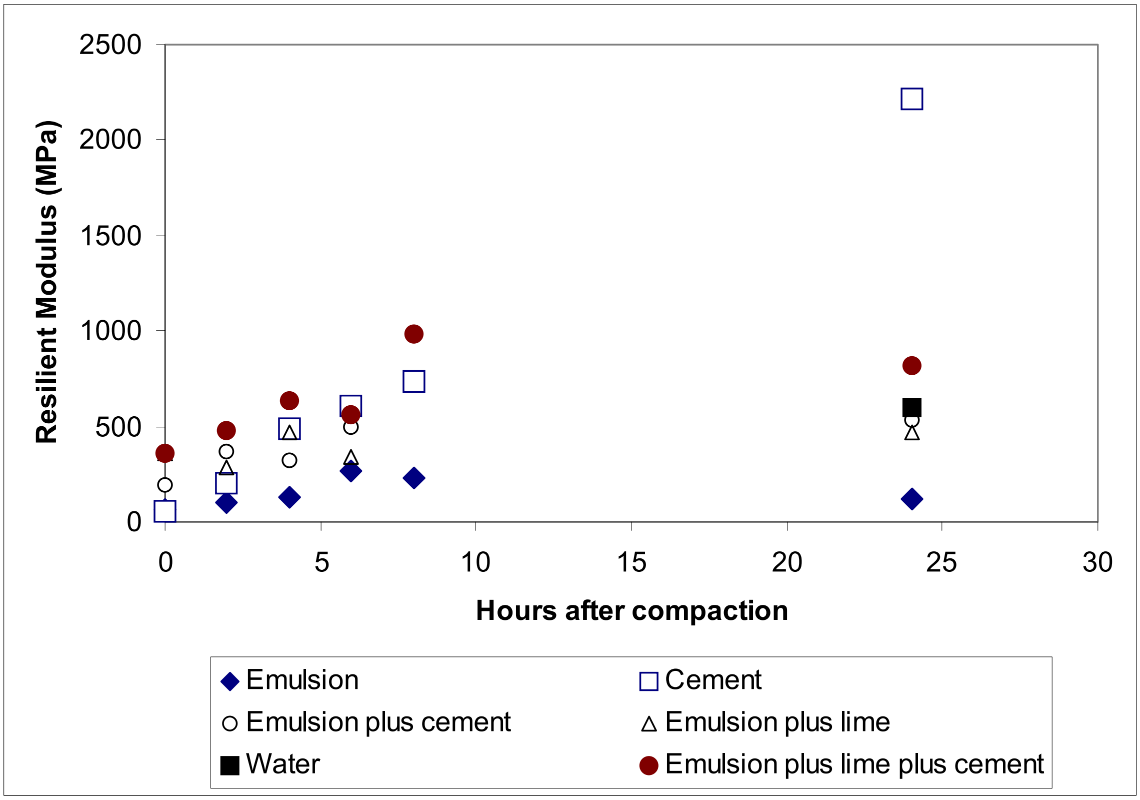


FIGURE 14.1 Plot of resilient modulus versus time after compaction for different mixes

SECTION 15: DETERMINATION OF STRUCTURAL STRENGTH

Falling Weight Deflectometer (FWD) tests are widely used for structural evaluation of pavements. For the FDR study, FWD tests were conducted on the existing pavement prior to reclamation, and again on the reclaimed base material immediately after construction and before the application of binder and wearing courses. The initial FWD results, in terms of pavement modulus, are shown in Table 15.1. These results will be compared to results obtained from FWD that was conducted on the pavement after three months of traffic. However, the data can be analyzed to determine whether any significant different in strength existed in the different parts of the pavement, which were treated with different materials during reclamation (and hence labeled as different sections). An Analysis of Variance (ANOVA) conducted with the data indicated (Table 15.1) no significant difference in the strength of the existing sections.

The data obtained from FWD tests conducted immediately at the end of curing period, before the application of binder and wearing courses, are shown in terms of deflections, in Table 15.2. These deflections obtained from the different sections were analyzed for significant difference, and the results are shown in Table 15.2. Since the deflections were found to be significantly different, a mean comparison technique (SNK) was used to group the different additives according to the deflection of the different sections. The results, shown in Table 15.2 show that the different sections can be divided into two groups on the basis of deflection. The cement and water sections have no significant difference in deflection, but both sections have significantly less deflection compared to the emulsion and emulsion plus lime sections. The two emulsion and the emulsion plus lime sections do not have any significant difference in deflection.

TABLE 15.1 Modulus of existing sections (from FWD tests conducted prior to FDR)

Means Table for Modulus (kPa)
Effect: Section

	Count	Mean	Std. Dev.	Std. Err.
Water	15	394831.067	52507.673	13557.423
Cement	15	379921.667	79112.356	20426.723
Emulsion plus lime	15	365268.267	50910.902	13145.138
Emulsion	15	417976.400	77684.044	20057.934

ANOVA Table for Modulus (kPa)

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Section	3	22773704952.850	7591234984.283	1.721	.1731	5.163	.416
Residual	56	246995717982.800	4410637821.121				

TABLE 15.2 Deflections from different sections (from FWD tests conducted after FDR)

Means Table for Deflection
Effect: Additive

	Count	Mean	Std. Dev.	Std. Err.
Water 7 percent NB	7	13.804	1.816	.686
Water 7 percent SB	15	15.107	2.468	.637
Cement 5 percent NB	8	14.160	3.075	1.087
Cement 5 percent SB	15	14.427	1.696	.438
Emulsion 3.4 percent plus lime 2 percent ...	8	15.505	2.705	.956
Emulsion 3.4 percent plus lime 2 percent ...	15	15.147	1.922	.496
Emulsion 2.2 percent	8	17.895	3.241	1.146
Emulsion 3.4 percent	15	17.285	2.849	.736

ANOVA Table for Deflection

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Additive	7	149.462	21.352	3.533	.0023	24.731	.964
Residual	83	501.603	6.043				

Section	Mean Deflection	Group
Cement 5 % NB	14.2	A
Cement 5 % SB	14.4	A
Water 7 % NB	13.8	A
Water 7 % SB	15.1	A
Emulsion 3.4 % plus lime NB	15.5	B
Emulsion 3.4 % plus lime SB	15.1	B
Emulsion 3.4 % (SB)	17.3	B
Emulsion 2.2 % (NB)	17.9	B

Determination of structural strength and improvement in life of pavements

In order to design a pavement with different layers, the layer coefficients of different layers must be known. The layer coefficients can be determined in different ways, such as from the resilient modulus of samples or from data obtained from non-destructive in-place testing, such as Falling Weight Deflectometer (FWD). Also, for evaluation of the use of different types of additives for recycling of pavements, it is necessary to know what kind of improvement in life of the pavement can be expected by using the different additives, and, if different additives are considered, the cost of increasing the life of the pavement by a specific amount, for each additive.

Two approaches were followed for answering these questions. The layer coefficients of the base layers, recycled with different additives, were determined from resilient modulus of three-month-old in-place cores from the different sections (recycled with different additives). The improvement in the life of the pavement was evaluated by comparing the structural numbers of the pavement sections (considering all three layers – base, binder and surface) before and after recycling. The cost of increasing the life of pavement for each additive was determined by considering the life (in terms of design traffic) of the existing pavement, the life of the new pavement, and the cost of recycling.

Table 15.3 shows the resilient modulus of three-month-old in-place cores from different sections (recycled with different additives). The mixes can be ranked as (in decreasing order of modulus) – Cement-5% (10,469.0 MPa), Emulsion-3.4 % plus 2 % lime (3,566.2 MPa), Emulsion-2.2% (1,317.5 MPa). (Note that the resilient modulus values of the water and emulsion-3.4 % could not be determined since sufficient number of samples was not available.)

TABLE 15.3 Resilient modulus of three-month-old in-place cores

Section/materials in base	Resilient Modulus (MPa)	Average Resilient Modulus (MPa)
Emulsion, 2.2 %	1526.4	1,317.5
	1108.5	
Emulsion, 3.4 % plus 2 % lime	3508.5	3,566.2
	3342.5	
	3847.5	
Cement, 5 %	4879.5	10,469.0
	14695.0	
	17476.0	
	9541.5.0	
	5753.0	
	2920.0	
	3174.5	

Based on the resilient modulus values, the layer coefficients were determined (*5*) to be as follows: Cement-5% - 0.28, Emulsion-3.4 % plus 2 % lime – 0.37, Emulsion-2.2% - 0.24. These layer coefficients were derived by determining the equivalent thicknesses of the FDR and AASHTO bitumen treated and cement treated material layers, based on structural response criteria. A multi layered elastic program, BISAR, was used to determine the thickness of the FDR layer required to produce the same surface deflection as a 6 inch thick AASHTO bitumen treated base layer (BTB, E = 400,000 psi, $a_2 = 0.34$, Page GG-11, *5*) under two standard 4,500 lb wheel loads. Then the ratio was used to determine the layer coefficient of the FDR material. For example, 5.5 inch of emulsion plus lime treated base course was found to produce the same surface deflection as a 6 inch thick AASHTO bitumen treated base, having a layer coefficient of 0.34. Therefore, the layer coefficient of the emulsion plus lime treated material is determined to be 0.34*6/5.5 = 0.37. For the cement treated base course, the equivalent layer thickness required to produce the same vertical strain as produced by a 6 inch thick AASHTO cement treated base layer (CTB, E = 850,000 psi, a_2 = 0.23, Page GG-11, *5*) was determined, and used for calculation of layer coefficient.

The cement mix showed very high resilient modulus values, which are indications of very high stiffness. However, it should be noted that the percentage of cement can be reduced, and research with a lower percentage of cement and possibly in conjunction with other additives should be considered. The beneficial effects (rapid curing and resistance against rutting and moisture damage) of adding cement (2 %) with an optimum emulsion content (3.4 % for the materials studied in this project) have been presented earlier. Maine DOT has planned to use emulsion plus cement mixes for their upcoming FDR jobs.

The Emulsion-3.4 % plus 2 % lime mix shows a significantly higher layer coefficient compared to the Emulsion-2.2% mix. A comparison of these layer coefficients with those used currently by Maine DOT (0.14 for untreated and 0.22 for treated), for FDR, shows a need for consideration of a significantly higher layer coefficient if an Emulsion-3.4 % plus 2 % lime is used. This will result in significant savings through reduced depth of HMA layers.

For the different sections, the FWD data showed the following pre and post construction modulus and structural numbers:

Section	Pre Construction Modulus, kPa	Post Construction Modulus, kPa	Pre construction SN, mm	Post construction SN, mm
Water	394831	552515	133.6	149.3
Cement	379921	567455	131.6	150.6
Emulsion plus lime	365268	656831	130.0	158.0
Emulsion	417976	535333	135.8	147.8

The structural numbers of the existing and the new pavements sections, as determined from the data obtained through FWD testing and subsequent analysis of the data, were compared. It can be seen that according to the improvements, the sections can be ranked as (from high to low):

Emulsion-3.4 % plus 2 % lime (20 % improvement), cement-5% (15 %), water (12 %), emulsion-3.4 % (8 %).

The life of the existing and new pavement sections were determined in terms of increase in traffic. Structural numbers as determined from FWD data was used for determination of total design traffic (W_{18}) for each section, before and after construction. A comparison of cost per mile per 1000 Equivalent Single Axle Load (ESAL) increase in life, shown in Table 15.4, shows that recycling with emulsion (3.4 %) and lime (2 %) is the most cost effective option.

TABLE 15.4 Cost of improving life of pavement

Section	Remaining life (Equivalent Single Axle Loads, ESAL) for existing section	Life (ESALs) for recycled section	Cost per mile ($)	Cost per mile per 1000 ESAL increase in life ($)
Water	8,128,305	18,365383	24,133	2.4
Emulsion, 3.4 %	9,332,543	18,365383	41,202	4.0
Emulsion, 3.4 % + 2 % lime	6,918,309	31,045595	44,734	1.8
Cement, 5 %	8,128,305	21,232,444	38,848	2.9

SECTION 16: PERFORMANCE EVALUATION

The different FDR sections were inspected in the week of June 4, 2001, approximately one year after construction. Photos of sections are shown in Figure 16.1. None of the sections showed any significant distress. However, a significant amount of edge cracking was noted in the water section. Also, a single crack, extending through both lanes was observed in the 800 m cement section. However, it must be noted that the cement section was not cured properly in this study, and that proper curing would have prevented cracking in the section reclaimed with cement.

Emulsion

Emulsion plus lime

Cement

Water

Crack in cement section

Crack in water section

FIGURE 16.1 Photos of recycled sections after one year of construction

SECTION 17: VERIFICATION OF MIX DESIGN WITH NEVADA FDR MATERIAL

In order to verify the mix design system developed in this project, materials from other states were requested. Nevada Department of Transportation (DOT) sent materials, (mix of RAP and unbound base materials), from a FDR project on I-80. Four sets of samples were then made to conduct a mix design. Before conducting the mix design, the materials were tested for relevant properties. Gradation was checked by sieve analysis and asphalt content was determined with the National Center for Asphalt Technology (NCAT) ignition oven. A review of these properties (Table 17.1) indicates that the FDR material was suitable for reclamation with emulsion.

Mix Design

Next, this material was used for designing a suitable FDR mix with asphalt emulsion. Figure 17.1 shows plots of total fluid content versus dry density and resilient modulus values. Corresponding to the maximum dry density and resilient modulus, an optimum total fluid content of 5.8 percent, and hence an optimum emulsion content of 2.6 percent (the difference between the total fluid content and the emulsion consisted of pre mixed water, required for bringing the moisture content to in-place moisture content) were obtained.

TABLE 17.1 Properties of Nevada DOT reclaimed materials

Gradation of unbound materials

Sieve Size, mm	% Passing
50	100
37.5	100
25.0	100
19.0	98.02
12.5	69.51
09.5	47.37
4.75	31.13
2.36	25.54
1.18	20.17
0.6	15.58
0.3	7.42
.15	90.25
.075	1.16

Gradation of RAP

Sieve, mm (in)	% Passing
50	100
37.5	100
25.0	100
19.0	96.97
12.5	88.70
9.5	79.90
4.75	57.87
2.36	39.61
1.18	27.60
0.6	19.83
0.3	12.98
.15	7.28
.075	4.07

Asphalt content: 5.0 %

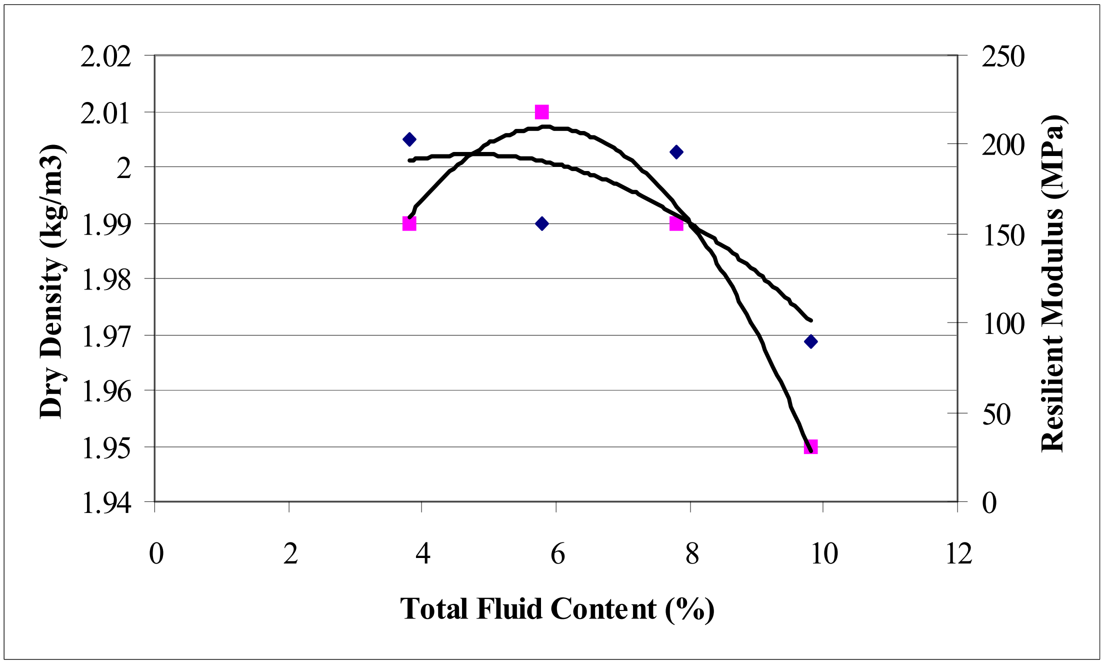


FIGURE 17.1 Mix design results for Nevada I-80 FDR mix

Determination of properties of in-place stiffness

The designed mix, along with mixes with plus 1 percent and minus 1 % (compared to optimum) emulsion content were put down in three sections in a mold (Figure 17.2). The mixes were compacted to refusal density with a vibratory roller (Figure 17.3), and left to cure for seven days. At the end of the curing period, attempts were made to obtain cores for subsequent testing (density and resilient modulus). However, the mix was not strong enough to allow coring, and an alternative method for determination of in-place (in-mold) properties was sought.

The Humboldt Stiffness Gauge was used for measuring in-place stiffness. This equipment operates on the principle of generating a force, measuring the resultant displacement and determining the stiffness as the ratio of force to displacement. The deflection, as a result of a small force at frequency of 100-200 Hz, is measured by a geophone. This equipment was selected because of relative simplicity of operation, non-destructive nature and experience of the research personnel at WPI. A small amount of sand was spread to even out the reclaimed mixes at the point of testing, in order to make the stiffness gauge have a flat and smooth contact with the testing surface.

The results of stiffness test are shown in Table 17.2. All of the readings are greater than 30 MN/m, and in general, all of the three mixes can be categorized as excellent base course (*15*). It can be noted that the stiffness of the mix decreases with an increase in emulsion content. However, in spite of having a high stiffness at optimum minus 1 % emulsion content, the standard deviation of the stiffness readings at optimum minus 1 % emulsion content (12.9 MN/m) is almost two times the standard deviation of the stiffness readings at the optimum emulsion content (6.6 MN/m). This indicates that minimum emulsion content is needed for uniform dispersion of the emulsion and compaction (and resulting density) of FDR mixes.

FIGURE 17.2 Mix in the mold

FIGURE 17.3 Compacting with vibratory roller

TABLE 17.2 Stiffness of mixes

Test Number	Location	Stiffness, MN/m	Average Stiffness, MN/m	Standard Deviation, MN/m
1	+1%	29.44	40.69	8.5
2	+1%	48.67		
3	+1%	45.45		
4	+1%	39.2		
5	Optimum	54.53	46.16	6.6
6	Optimum	45.36		
7	Optimum	46.28		
8	Optimum	38.45		
9	-1%	61.24	52.29	12.9
10	-1%	37.52		
11	-1%	58.12		

SECTION 18: APPLICATION OF LATERAL PRESSURE INDICATOR (LPI)

Researchers at WPI have developed a novel tool for creating an indicator of lateral pressure generated in a mix during laboratory compaction. It consists of a load cell attached to the cut out section of the mold, which is used for holding the mix during compaction with a Superpave gyratory compactor (Lateral Pressure Indicator, Figure 18.1). The load cell provides an indication of the lateral pressure in the mix during compaction. It is hypothesized that this tool can be used as an indicator optimum total fluid content and hence determination of design emulsion or foamed asphalt binder content during mix design.

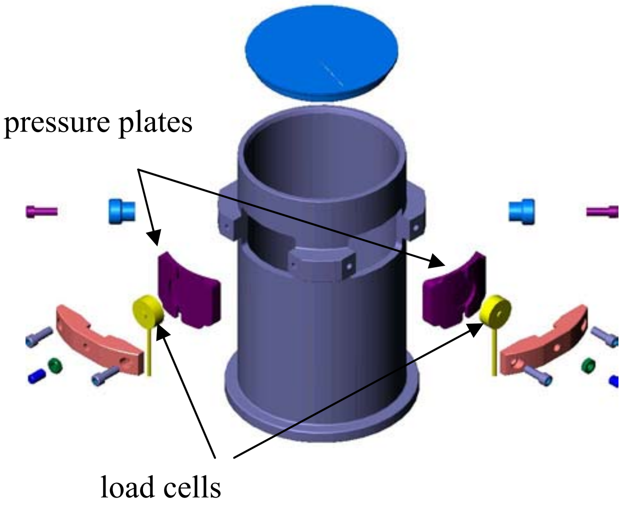


FIGURE 18.1 Exploded view of instrumented mold

In order to test its applicability, mixes with 3, 5 and 7 percent total fluid content were compacted with the LPI. During compaction, lateral load, as well as heights, were measured with a modified Superpave gyratory compactor. The data were analyzed to determine lateral pressure versus gyration plots for mixes with different total fluid content. Figure 18.2 shows that the lateral pressure generated in mixes with 1 and 3 percent emulsion content are quite similar, whereas the pressure generated in mixes with 5 percent emulsion is significantly higher. This indicates that the mixes with 1 and 3 percent emulsion content are compacted to a more stable state, as compared to the mix with 5 percent emulsion – since a higher lateral pressure is indicative of lower angle of internal friction (as shown in Figure 18.3, *16*). Therefore, in this example, it is obvious, that at least from a compaction point of view, the optimum emulsion content lies below 5 percent. In general, since the objective of design is to provide as much emulsion as possible (for obtaining good coating and durability) without decreasing the strength of the mix significantly, the results shown in Figure 18.2 would indicate an optimum emulsion content of 3 percent.

The advantage of the use of lateral pressure indicator is that an existing Superpave gyratory compactor can be used in screening out unstable mixes and getting an idea about optimum total fluid or emulsion content.

In order to develop guidelines for regular use of this procedure, research with a wide variety of materials and mixes should be conducted.

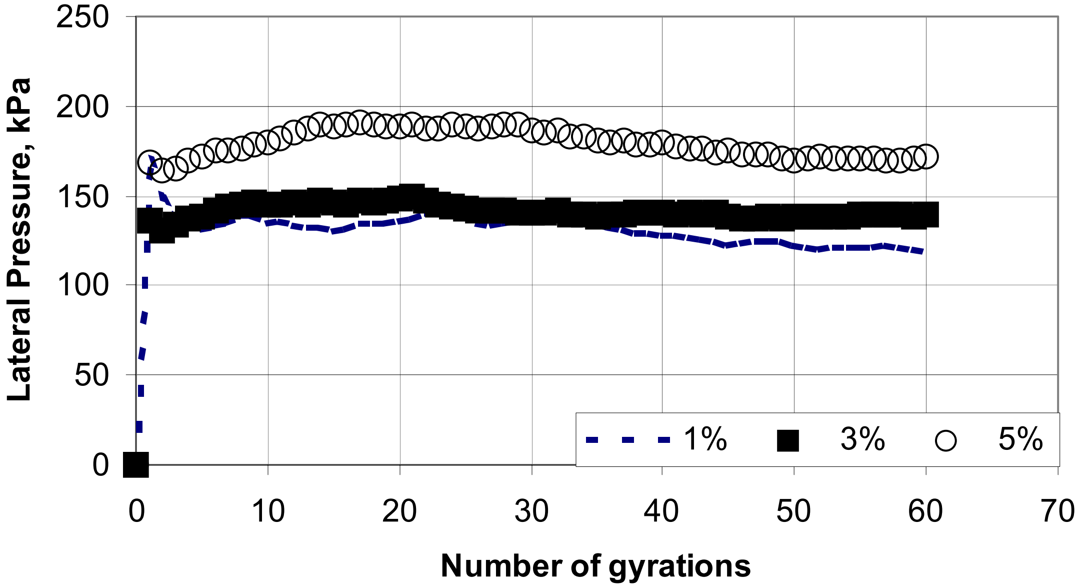


FIGURE 18.2 Gyration versus lateral pressure for mixes with different emulsion content (average from two samples)

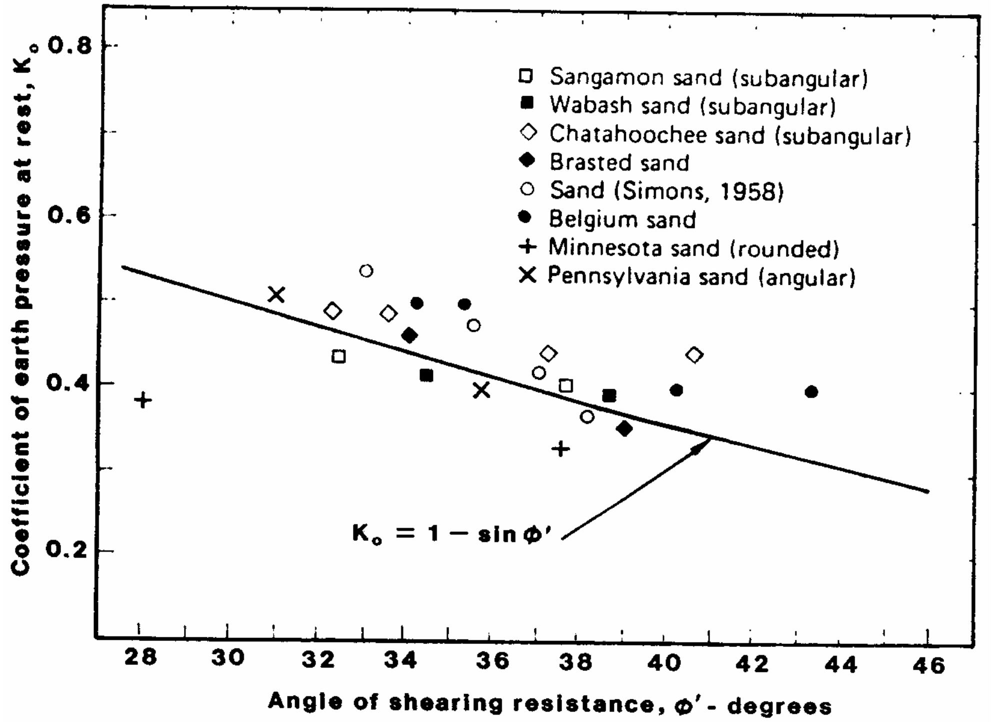


FIGURE 18.3 Relationship between K_o (coefficient of earth pressure) and φ. (*16*)

SECTION 19: DETERMINATION OF LABORATORY RESILIENT MODULUS OF SUBGRADE SOILS

Introduction

The elastic modulus based on the recoverable strain under repeated loads is called the resilient modulus; M_R. It is defined as the ratio of the amplitude of the repeated axial stress to the amplitude of the resultant recoverable axial strain.

$$M_R = \frac{\sigma_d}{\varepsilon_r}$$

where, σ_d – deviator stress, which is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in the triaxial compression test, and ε_r is the recoverable axial strain.

As the magnitude of the applied load is very small, the resilient modulus test is a nondestructive test and the same sample can be used for many tests under different loading and environmental conditions. A haversine or a triangular stress pulse is applied in order to simulate the traffic loading on pavements.

Subgrade soils are prepared and compacted before the placement of subbase and/or base layers. They are classified as Type 1 or Type 2 for the purpose of resilient modulus testing. Material Type 1 includes all untreated granular base and sub base material and all untreated subgrade soils which meet the criteria of less than 70% passing the 2.00 mm sieve and less than 20% passing the 75-µm sieve, and which has a plasticity index of 10 or less. Material Type 2 includes all untreated granular base/subbase and untreated subgrade soils not meeting the criteria for Material Type 1. Thin-walled tube samples of untreated subgrade soils fall in this category.

DESCRIPTION OF TEST SOILS

Three types of soils were obtained for this project. They are from three different counties in Maine namely, Cumberland, Hancock, and York. Table 19.1 shows the details of the sampling locations.

TABLE 19.1 Sampling locations

County	Cumberland	Hancock	York
Town(s)	Standish-Gorham	Hancock-Sullivan	Saco-Buxton
Route No	114	1	112
Station	3+398	0+951	10+120
Position	2.4 m Right	2.4 m Right	1.8 m Left
Date	06/19/2001	06/18/01	08/02/01
PIN	010213.00	9191.00	9493.00

Test Plan

The test plan for this study is shown in Figure 19.1.

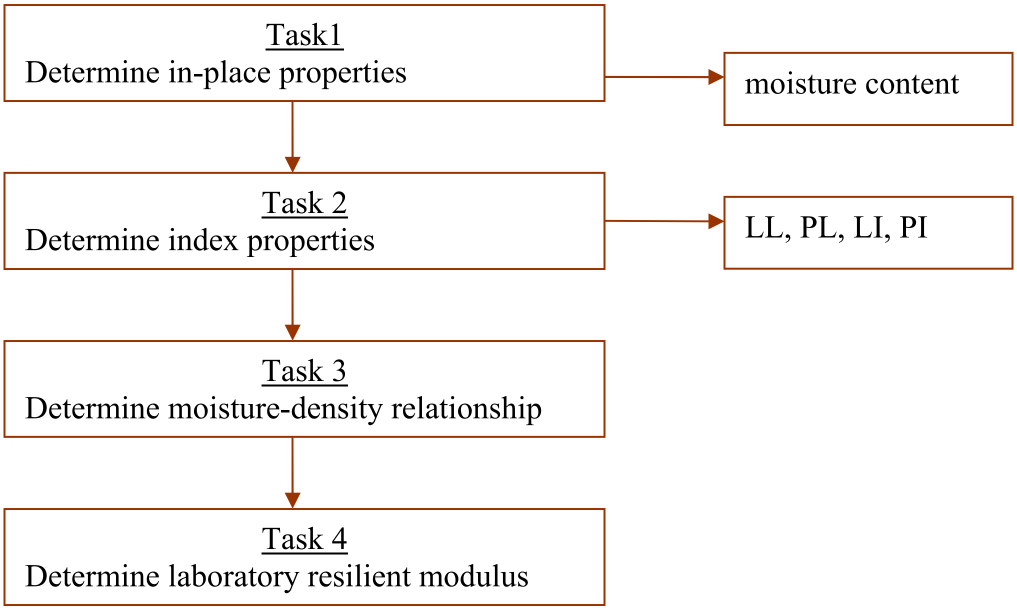


FIGURE 19.1 Test plan

Task I: In-place Properties

1. Moisture Content

AASHTO T265 (*17*) procedure was used for the determination of moisture content.

The moisture content w is given by

$$W_W = (W_C + W_S) - (W_C + W_d)$$

W_w in terms of its dry weight

$$w = \frac{W_W}{W_d} \times 100 \text{ percent}$$

where w - moisture content

W_w - weight of water present in soil mass

W_s - weight of soil (wet)

W_d - weight of dry soil

Task 2: Index Properties

1. Liquid Limit
2. Plastic Limit
3. Plasticity Index
4. Liquidity Index

1. Determination of Liquid Limit (LL)

Definition: Liquid limit is the moisture content below which the soil behaves as a plastic material.

Experimental definition: Liquid limit is defined as the water content at which a pat of soil placed in a brass cup, cut with a standard groove, and then dropped from a height of 1 cm will undergo a groove closure of 12.7 mm when dropped 25 times.

A nearly linear plot of the water content (%) vs. log of number of blows (N) is prepared. The moisture content corresponding to 25 blows is the liquid limit.

AASHTO T 89-96 (*18*) procedure was used for the determination of liquid limit.

2. Determination of Plastic Limit (PL)

Definition: Plastic limit is the moisture content below which the soil is nonplastic.

Experimental definition: Plastic limit is defined as the water content at which a soil thread just crumbles when it is rolled down to a diameter of 3 mm (approximately).

$$Plastic\ Limit = \left[\frac{(mass\ of\ water)}{(mass\ of\ oven\ dry\ soil)}\right] \times 100\ percent$$

AASHTO T 90-96 (*19*) procedure was used for the determination of the plastic limit of the soils.

3. Determination of Plasticity Index (PI)

$$PI = LL - PL$$

4. Determination of Liquidity Index (LI)

$$LL = \frac{(w\% - PL)}{PI}$$

The in-place properties and the index properties were used in the classification of soils by the AASHTO method. Table 19.2 summarizes the above mentioned properties and also their classification.

TABLE 19.2 Properties of soil samples

County	Cumberland	Hancock	York
Town(s)	Standish-Gorham	Hancock-Sullivan	Saco-Buxton
Moisture Content, %	7.79	11.26	9.96
Liquid Limit, LL	-	15.74	15.40
Plastic Limit, PL	-	-	-
AASHTO Classification	A-1-b	A-2-4	A-2-4

Task 3: Determine Moisture-Density Relationship

The target density for the specimens was obtained from CRREL special report on subgrade resilient modulus study in New Hampshire (*20*). The specimens could be molded at several moisture contents. Target dry density values were specified for various soils classified by the AASHTO method as shown in Table 19.3.

TABLE 19.3 Target dry densities (*20*)

AASHTO Classification	NHDOT Classification	Target Dry Density, kg/m^3
A-2-4	**Silty fine sand**	1712
A-7-5	Marine clay	1560
A-7-5	Marine clay	1610
A-7-5	Marine clay	1584
A-4	Silty glacial till	2048
A-1-b	Medium fine sand	1632
A-1-a	Coarse gravelly sand	1728

Table 19.4 shows the corresponding dry densities and moisture contents of the specimens.

TABLE 19.4 Densities and moisture contents of the subgrade specimens

County	Cumberland	Hancock	York
Town(s)	Standish-Gorham	Hancock-Sullivan	Saco-Buxton
Moisture Content, %	8.0	11.3	10.0
Target Dry Density, kg/m^3	1762	1712	1712

Task 4: Determine Laboratory Resilient Modulus:

The laboratory resilient modulus tests were conducted in accordance with AASHTO TP 46-94 (*21*).

The bulk density was calculated using the formula,

$$\gamma_b = \gamma_d (1 + w)$$

The amount of water used in the preparation of the specimens was in-place moisture content $\pm$ 1%. Table 19.5 shows the moisture contents of the specimens prepared for the laboratory M_R testing.

TABLE 19.5 Moisture contents of the specimens as calculated from bulk densities

County	Cumberland	Hancock	York
Town(s)	Standish-Gorham	Hancock-Sullivan	Saco-Buxton
Moisture Content, %	8.0	11.3	10.0

The specimens were compacted using the Gyratory Testing Machine. Then they were tested for the M_R using the UTM in the triaxial mode. UTM test number 42 i.e., 'Feed Back Controlled RATT Stress Stage Resilient Modulus Test (*22*) which is based on TP 46-94 was used for testing.

Results

Based on the results of the natural logarithm of M_R was expressed in terms of natural log of bulk stress using the linear regression method. Three equations were developed corresponding to the three samples. The equations are:

a. Standish-Gorham Soil

$$M_r = -73.232 + 23.216 \times \ln(\Theta)$$

b. Hancock Soil

$$M_r = -109.239 + 30.434 \times \ln(\Theta)$$

c. Saco Soil

$$M_r = -82.722 + 23.487 \times \ln(\Theta)$$

Units: M_r - MPa; θ - kPa;

where,

$$Bulk\ Stress = (3 \times Confining\ Stress) + (Deviator\ Stress)$$

Note: All the data having negative deviator stress were deleted, as the results were abnormal. With the above equations and appropriate bulk stress, in-place moduli of subgrade layers can be determined. These moduli can then be used for design of pavement structures.

SECTION 20: DISCUSSION

This research study was conducted primarily to develop a rational and practical mix design system for Full Depth Reclamation (FDR) using asphalt emulsion. The key findings from this research are related to the use of a slotted mold and determination of appropriate design number of gyrations (for using the Superpave gyratory compactor) for compacting design samples, establishment of a procedure for determination of optimum total fluid content, determination of post compaction curing time and temperature, and evaluation of different strength and durability of FDR mixes with different types of additives.

Criteria for mix design

The criteria used for determination of optimum total fluid content are based on the determination of dry density and resilient modulus. The dry density criterion was selected because of the experience of use of this parameter in determination of optimum fluid content in compaction of soils (such as for subgrade), and in general, a good relationship between dry density and strength. However, because of difference in densities of materials in base course, an increase in dry density does not necessarily mean a proportional change in stiffness. Therefore, it is important that in addition to checking dry density, one uses a stiffness criterion to select optimum fluid content. Hence, the second criterion of resilient modulus was selected.

Generally, both dry density and resilient modulus can be determined by using conventional testing equipment, commonly available in DOT laboratories. However, FDR mixes, which are essentially not as “bound” as say Hot Mix Asphalt (HMA), are susceptible to breakdown, when tested according to the commonly used saturated surface dry bulk specific gravity testing procedure (for determination of dry density). Quite often therefore, bulk specific gravities of samples of cold recycled mixes such as FDR mixes, are determined from their mass and volume. The volume is estimated from the dimension of the samples. It seems that a better procedure is needed to determine the bulk specific gravities more accurately. Hence, the use of vacuum sealed method has been suggested. The equipment for this procedure is now commercially available, and an ASTM procedure for using this procedure is also available.

Moisture damage

The philosophy used in the development of the mix design procedure is that one should use as much additive, such as asphalt emulsion, as it is possible, without causing a significant decrease in stiffness of the mix. The logic behind this approach is that an optimum emulsion content would provide adequate coating around the particles and hence provide adequate durability to the mix. If the criterion of a high stiffness (as measured by resilient modulus test) is followed, then one also ensures that the mix has adequate stiffness – for adequate structural strength. The researchers felt that at this time, although several candidate tests are available, a single simple and adequate test for determination of moisture susceptibility of stabilized mixes is not available. However, it is noted that adequate resistance to moisture damage is a significant factor in the obtaining good performance from stabilized base course mixes, and that DOT s should consider any good test that they are comfortable with, to evaluate resistance of designed FDR mixes to moisture damage.

Three different tests for evaluation of moisture susceptibility of stabilized base course materials need to be discussed. The first procedure is based on the determination of retained tensile strength of mixes. Generally, the ratio of tensile strength of unconditioned and conditioned samples and/or the tensile strength of conditioned samples (conditioned through a series of specific number of freezing and thawing or wetting and drying cycles or simply by soaking for a specific period) is determined and checked against a minimum specified value. For example, the maximum soaked tensile strength is considered for the selection of optimum asphalt content for mixes reclaimed with foamed asphalt. Low conditioned strength is indicative of a mix with high moisture damage potential.

The second procedure, the Tube suction Test, (developed by the Texas Transportation Institute), which has been developed specifically for cement stabilized base course mixes, is based on the determination capillary rise of moisture within test samples. This test has been modified from the original test procedure, which was developed for evaluating granular materials (*23, 24*). The steps in this test consists of compacting a sample, conditioning the sample for simulating field conditions, placing the sample in de-ionized water, and monitoring the moisture condition at the surface with a dielectric probe. Excessive amount of free water within the sample is indicative of a mix with high potential of moisture damage in freeze-thaw environments. Appropriate relationships between significant loss in strength and measured dielectric constant have been developed and work is currently underway for development of a procedure for using both compression strength and Tube Suction test results for use in determination of optimum amounts of cementitious stabilizer (*23*).

The third procedure, a stripping test, which has been developed by IntroTek Inc., is based on simulating cycles of pore pressure and suction with the use of laboratory equipment. Basically, the test equipment consists of a system to use a supply of compressed air to load and apply vacuum to force air out and in (respectively) through a sample, which is keep in water maintained at a constant temperature. Repeated cycles of pore pressure and suction cause a stripping of asphalt binder from the mixes. Conditioned samples can be tested for strength, and appropriate decision regarding the suitability of a mix can be made. One additional feature of the equipment is its ability to detect stripped materials, by measuring the turbidity of the water through a sensor. Work is underway at Worcester Polytechnic Institute (WPI) for developing a procedure using this equipment for evaluation of moisture susceptibility of HMA and reclaimed mixes.

SECTION 21: CONCLUSIONS AND RECOMMENDATIONS

Based on the research conducted in this study, the following conclusions are obtained.

1. The Superpave gyratory compactor can be used successfully for compacting full depth reclamation mixes. Care should be taken to discard plus 37.5 mm material before compaction.
2. A dry density versus total fluid content criteria can be used to determine the optimum total fluid content. If an asphalt emulsion is used, then the total fluid consists of preexisting water in the material plus the emulsion.
3. In all the cases the in-place densities were closer to densities at 50 gyration. For all cases except cement, the in-place densities were 96-98 % of densities at 50 gyrations. The in-place density for the cement section was at 92 % of the density at 50 gyrations
4. Comparison of mix design results with samples compacted to 75 and 50 gyrations showed that the optimum total fluid contents obtained for samples compacted to 75 gyrations (7 % for water and 5-6.5% for emulsion) were not significantly different from the optimum total fluid contents obtained for samples compacted to 50 gyrations (7 % for water and 5-6.5% for emulsion).
5. Any one of the additives considered in this study improves resistance of FDR against moisture damage. Cement and emulsion plus lime mixes show very high resistance to moisture damage compared to the other mixes. However, on the basis of wet tensile strength, emulsion plus lime is better than any other additive considered in this study.
6. From consideration of strength gain during curing, 3 % emulsion plus 2 % lime seems to provide a much better mix compared to a mix with 3 % emulsion only.
7. Based on the resilient modulus values, the layer coefficients were determined to be as

follows:

Cement-5% - 0.28

Emulsion-3.4 % plus 2 % lime – 0.37

Emulsion-2.2% - 0.24

8. Comparison of improvement in structural number showed that Emulsion-3.4 % plus 2 % lime showed the highest increase, followed by cement, water and emulsion section.
9. A comparison of cost per mile per 1000 ESAL increase in life showed that recycling with emulsion (3.4 %) and lime (2 %) is the most cost effective option.
10. A visual evaluation of recycled sections after one year showed no significant distress in any section, except in the water section where a moderate amount of edge cracking was noted.

Based on the above conclusions the following recommendations are made regarding mix design and construction of Full Depth Reclamation (FDR).

1. Use of a slotted mold is recommended to allow squeezing out of water during compaction of full depth reclamation mixes.
2. Use of samples in sealed bags (CoreLok^{TM} method) is recommended for determination of bulk specific gravity in the laboratory.
3. Use density and resilient modulus versus total fluid content criteria for selecting optimum additive contents.
4. Use emulsion and lime, and cement in low percentage, for full depth reclamation of materials similar to the materials studied in this project.
5. FDR samples for mix design should be compacted to 50 gyrations during mix design, and

a minimum of 95 % of density of in-place loose mix samples, compacted to 50 gyration, be achieved in a control strip in the field. Compaction in actual project must achieve at least 98 percent of the control strip density. These compaction considerations are suggested on the basis of good experience with the use of similar specifications for Hot Mix Asphalt (HMA).

6. Increase in structural numbers for FDR layers should be considered for designing binder and surface layers.
7. Use a suitable test procedure, such as the soaked or conditioned strength or Tube suction test or stripping test, should be considered for evaluation of moisture susceptibility of designed mixes.

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