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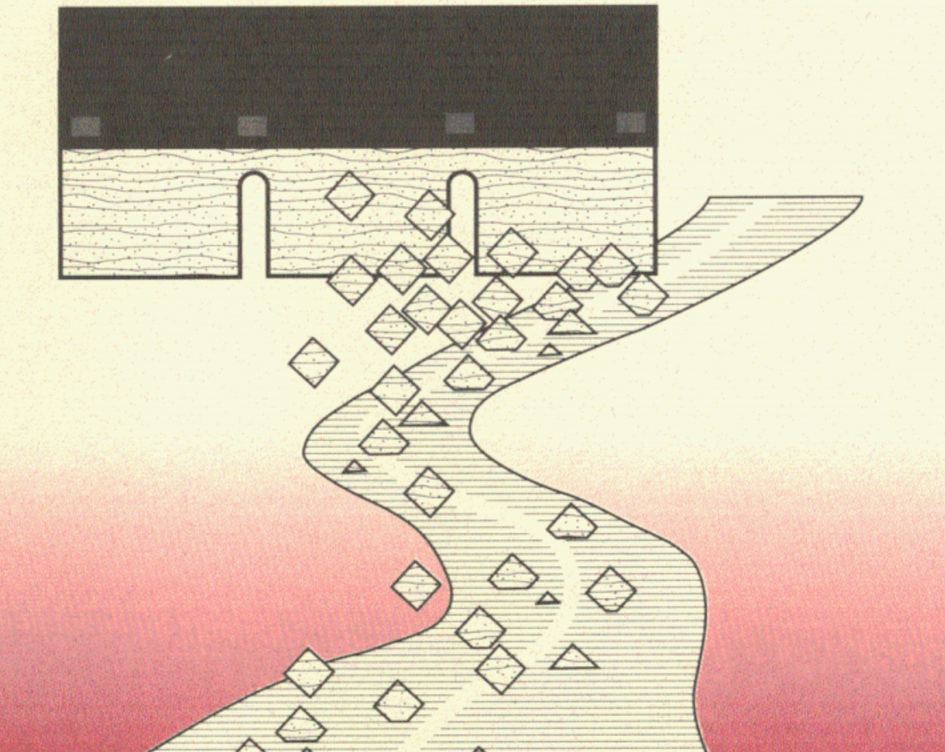
Influence of Roofing Shingles on Asphalt Concrete Mixture Properties



MINNESOTA DEPARTMENT OF TRANSPORTATION

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Influence of Roofing Shingles on Asphalt Concrete Mixture Properties

Final Report

June 1993

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16. Abstract (Limit: 200 words)

It is estimated that the production of new roofing shingles generates approximately 1,000,000 tons of waste annually in the U.S., and about 36,000 tons of this waste is in the Twin Cities Metro Area of Minnesota. With another 8.5 million tons of waste materials which are similar to those used in asphalt concrete, it seems viable that their use in hot-mix would be an attractive alternative to disposing of them in landfills. This report presents the results of an effort to evaluate the use of roofing waste generated by manufacturers and from reconstruction projects.

It was shown that up to 5%, by weight of mixture, manufacturing waste roofing shingles could be used in asphalt concrete with a minimum impact on the properties of the mixture. At a level of 7.5%, a noticeable softening of the mixture occurs, and this might be detrimental to pavement performance. The use of shingles from roof reconstruction projects resulted in the embrittlement of the mixture which may be undesirable for low temperature cracking of pavements. The manufactured shingle waste seems to work well in stone mastic asphalt mixtures.

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EXECUTIVE SUMMARY

Introduction

It is estimated that the production of new roofing shingles generates approximately 1,000,000 tons of waste annually in the United States, and about 36,000 tons of this waste is in the Twin Cities Metro Area of Minnesota. Another 8.5 million tons of waste material come from the rebuilding of shingle or hot-mop roofs each year on a national scale. Disposal of this waste material is usually accomplished by transporting and depositing it in landfills. If a suitable means of reusing these materials can be found, then their environmental liability could be significantly reduced.

Since asphalt roofing shingles are comprised of approximately 35 percent asphalt, 45 percent sand, and 20 percent mineral filler, an alternative to landfill deposition is to use the roofing waste in a related bituminous material. Such applications could include its use in granular base stabilization for layers underlying the pavement surface, patching materials for repairing potholes, or in hot mix asphalt concrete for use in base and surface layers [1,2]. In this study, the use of roofing wastes in a dense-graded and gap-graded mixtures were examined with respect to their effects on mixture behavior and properties.

Dense-graded asphalt mixtures are those most commonly used for paving. The term implies a relatively even distribution aggregate size throughout the mixture. On the other hand, a gap-graded mixture has fewer of the intermediate size aggregate particles, allowing for stone-to-stone contact to provide greater shear strength.

There are numerous potential benefits which could result from the use of waste shingle material in asphalt mixtures. Some of the these include:

1. A reduction in the cost of shingle waste disposal.
2. An environmental benefit resulting from the conservation of landfill space.
3. A reduced cost in the production of hot mix asphalt concrete resulting from reduction in the use of new materials.
4. An improved resistance to pavement cracking due to the reinforcement provided by fibers in the shingles.
5. An improved resistance to pavement rutting due to a combination of the fibers and harder asphalt used in the shingles.

Background

Researchers at the University of Nevada, Reno, investigated the economic and technical aspects of using waste roofing from reconstruction in hot-mix asphalt [2,3]. They concluded that the use of roofing waste tended to make the asphalt mixtures stiffer. This could be reasonably expected due to the harder asphalt and the reinforcing effect of the fibers contained in the shingles. They stated that up to 20 percent of mixture volume (10 to 12 percent by weight) could be accommodated without detrimental effects.

In a recent American Society for Testing and Materials paper, Kenneth Grzybowski of

PRI Asphalt Technologies, Inc., suggested using between five and 10 percent reroof shingles by mixture weight in gap-graded asphalt hot mix. He stated that reductions in new asphalt contents up to 50 percent were possible, while gaining improvements in resistance to permanent deformation.

While both of these studies focused on the use of construction roofing waste in dense- or gap-graded asphalt mixtures, the idea using manufacturing waste in these mixtures is a relatively new notion. In this report, the properties of mixtures containing both the manufacturing waste and the reroof waste were evaluated.

Roofing waste has been shown to increase the stiffness of asphalt concrete paving mixtures. In a cold climate such as Minnesota's, this could lead to problems with thermal cracking. Therefore, cold temperature properties were a main focus of experimental investigation in this project. Since increasing the amount of shingles in a mix tends to increase the stiffness, a study of the relationship between the amount of added shingles and stiffness parameters such as resilient modulus was another part of the test program.

Another mixture component that can affect the mix stiffness is the asphalt cement. If an asphalt is too soft, it can lead to a pavement that may rut at warm temperatures. For that reason this project investigated the effects of different asphalt cement grades on mix stiffness; two grades were tested.

The Nevada research cited earlier confirms that the source of the shingle material can strongly influence mixture properties. Although the material in that study was recycled reroof material, it is reasonable to expect variations between the two different types of manufactured scrap used in this study. The experimental design allowed for evaluation of the effects of three shingle sources, both on the mix design process and the fundamental mixture properties.

Stone mastic asphalt is a concept which has recently gained widespread publicity in the United States [4]. Originally developed in Germany in the 1960's as a means of combating studded tire wear, the idea was widely adopted in Europe for rut-resistant overlays [5]. The idea is to create stone-to-stone contact in the coarse aggregate, and bind it together using a mastic of a relatively hard asphalt cement, fine aggregate, and a polymer or fiber additive to prevent the asphalt from draining out of the mixture [6]. Since roofing shingles contain a stiff binder as well as fibers, it seemed that they could be used in place of the more expensive conventional additives.

Objective

The objective of this study was to evaluate the use of waste shingles from manufacturing and roof reconstruction projects in hot mix asphalt concrete mixtures. In dense-graded asphalt mixtures, it was hypothesized that the waste material might serve as an extender for the new asphalt in the mix as well as a fiber reinforcement. In the stone mastic asphalt (SMA), it could serve as the binder stiffener typically used to prevent the asphalt from draining out of these types of mixtures.

Scope

The treatment of the two types of mixtures can be viewed as two separate experiments, because of the considerations in formulating each of them. The dense-graded mixture evaluation included two grades of asphalt cement, one aggregate gradation, three levels of roofing shingle content, and two roofing waste types. In the SMA mixtures, one asphalt cement grade, one aggregate gradation, one level of shingle waste content, and three types of fiber additives (including two roofing waste types) were used. The control material for the SMA mixtures contained a commercial cellulose fiber. A sample of field mixed material was obtained from the Wright County Highway Department for comparison to the laboratory prepared mixtures.

Materials

The manufactured roofing waste was generated at the Certainteed Corporation's plant in Shakopee, Minnesota, and processed by Omann Brothers Construction Company in Rogers, Minnesota. Fiberglass and felt-backed shingles were separated for this study, although they are combined in the normal process. It is believed that this will have minimal impact on the actual use of the material since the fiberglass-backed shingles comprise only five percent of the normal production. When the waste shingles are received at Omann Brothers, they are processed through a hammermill to reduce them to a size of approximately 25 mm (1 inch), and then cooled with water to prevent them from agglomerating. At this point, the waste roofing material is stockpiled until it is used. The roofing material received for laboratory testing was noted to be extremely wet, and it had to be thoroughly dried before it was combined with the other materials in the mix. Potential problems may arise in the field if the moisture is not completely driven out of the material during hot mix production. Residual water from the shingles could cause inadequate compaction or stripping in mixtures with moisture sensitive aggregates.

Minnesota currently has no facilities for processing roofing waste from reconstruction projects. Processed reroof waste material was obtained from ReClaim, Inc., of Tampa Florida, and it is marketed under the tradename of ReACT's HMA. The material was fine and powdery in appearance, and, in contrast to the processed manufacturing waste, it was extremely dry.

Two grades of commonly used neat asphalt were used in making the mixtures. These were an 85/100 and a 120/150 penetration grade asphalt cements from Koch Refining in Inver Grove Heights, Minnesota. Only the 85/100 penetration asphalt was used in producing the SMA mixtures.

The aggregates differed between the dense-graded and SMA mixtures. The dense-graded mixtures were produced with a blend of crushed river gravel from Commercial Asphalt, Inc., Lakeland, Minnesota and a coarse granite from Meridian Aggregates in Granite Falls, Minnesota. The gradation of the dense mixtures followed the Minnesota Department of Transportation (Mn/DOT) specification for a type 2341 mixture. The SMA mixtures were made exclusively from the granite aggregate, and its gradation was that used by the German Federal Department of Transportation.

The paper fibers used in the control SMA mixture is marketed under the tradename Arbocel, and it is produced by J. Rettenmaier and Sohne of Germany.

Testing and Results

The testing program was designed to define the properties of the materials relevant to pavement performance. The roofing waste mixtures were tested along with control mixtures in order to ascertain their characteristics relative to each other.

The first part of the project was designing the dense-graded mixtures using the Marshall method. Examining the effects of the roofing shingles on the volumetric proportions and compaction behavior was the purpose of this exercise. It was found that increasing the content of roofing shingles reduced the mixtures' demand for new asphalt. This was true more so for the fiberglass and reroof mixtures than those containing felt-backed roofing shingles. The compactability of mixtures generally increased with roofing waste content. Thus, it can be concluded that the mixtures containing roofing waste were easier to compact than the conventional mixtures.

The elastic behavior or stiffness of the dense-graded mixtures at various temperatures was characterized using the resilient modulus test. The use of manufactured shingle waste resulted in a less temperature susceptible asphalt mixture. The reroof waste also reduced the mixture temperature susceptibility, but to a lesser degree. The mixture stiffnesses were adversely decreased when the shingle content exceeded five percent by weight of the aggregate. The roofing waste mixtures for the SMA experiment had similar stiffnesses to that found for the cellulose fiber control mixture.

Moisture sensitivity was evaluated using a modified Lottman conditioning procedure. The resilient modulus and tensile strength of the mixture is tested, then samples are subjected to partial saturation and frozen. After 24 hours, the samples are thawed and tested again for resilient modulus and tensile strength. The loss of tensile strength or modulus is taken as an indication of moisture induced damage. It was found that the use of manufactured shingle waste did not significantly change the moisture susceptibility of the mixtures, but that samples containing reroof material had increased susceptibility to moisture damage relative to the control mixture. The manufactured roofing waste seemed to actually improve the resistance to water damage in the SMA mixtures.

The resistance to cold temperature cracking was examined using an indirect tensile test performed at a slow rate of loading in order to simulate volumetric changes induced by daily temperature changes. The tensile strength and tensile strain at the peak stress were the parameters used in this evaluation. A material which has a greater ability to strain at low temperatures should be less likely to fracture due to thermal changes. Tensile strengths at low temperatures were shown to decrease with increasing roofing waste content. The strain at peak stress increased for the mixture containing felt-backed shingles with the harder asphalt cement. However, the mixtures made with the reroof material showed a decrease in strain capacity with increased shingle content, implying that this material will be more brittle at cold temperatures than the control mixture. For the SMA mixtures, the behavior of the roofing waste modified mixtures was about the same as that of the control mixture containing cellulose fibers.

The field mixture obtained from Wright County was subjected to the same sort of testing sequence as the laboratory mixtures. Results showed that it behaved similarly to the laboratory mixture containing five percent felt-backed shingle waste from the manufacturing process.

Recommendations

The following recommendations are made with regard to the use of roofing shingle waste in Minnesota asphalt mixtures:

1. The Minnesota Department of Transportation should produce a permissive specification which allows up to five percent manufactured roofing shingle waste to be used in hot mix asphalt base courses on high-volume roads and in all hot mix asphalt layers on low volume roads. The use of this waste material should be dictated by economics which will be influenced by the transportation and processing costs. Contractors might be encouraged to try the material if they are allowed a bid premium for using it.

2. There are currently no facilities which process reroof scrap material in Minnesota. An economic incentive, such as the availability of low interest loans, might be used to encourage the development of such facilities. Another alternative would be to wait until the cost of placing this material in a landfill becomes higher than the cost of processing and reusing it. If this material becomes available, a thorough evaluation of the material should be conducted to ascertain whether it is more suitable than the reroof material used in this study. Care would need to be taken to assess the potential for asbestos dust when dealing with reroof scrap material.

3. The performance of projects built with processed shingle waste should be monitored through the Minnesota Department of Transportation's pavement management system to see if they differ from conventional materials.

4. A field trial should be constructed in which manufactured shingle waste is used in a stone mastic asphalt mixture. The performance and cost of this material should be compared against more conventional approaches to SMA. Based upon the laboratory results from this study, the shingle waste SMA should have a performance comparable to the conventional SMA.

5. Improved means of processing shingle waste should be developed to reduce the amount of moisture in the material. It was not proven conclusively in this study that the moisture in the material is harmful to the final product. However, from the standpoints of hot-mix plant efficiency and the assurance of the final product quality, it would be best to attempt to reduce the amount of water present in the shingle waste.

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CHAPTER 1
INTRODUCTION

BACKGROUND

It is estimated that roofing shingle production generates approximately 432,000 tons of waste annually in the United States, and about 36,000 tons of this is in the Twin Cities Metro Area of Minnesota. Another 8.5 million tons of waste material come from the rebuilding of shingle or hot-mop roofs. Disposal of this waste material is usually accomplished by transporting and depositing it in landfills. If a suitable means of reusing these materials can be found, then their environmental liability could be significantly reduced.

Since asphalt roofing shingles are comprised of approximately 35 percent asphalt, 45 percent sand, and 20 percent mineral filler, an alternative to landfill deposition is to use the roofing waste in a related bituminous material. Such applications could include its use in granular base stabilization, patching materials, or in hot-mix asphalt concrete. In this report, the use of roofing wastes in dense-graded and gap-graded asphalt mixtures will be examined with respect to their effects on mixture behavior and properties.

OBJECTIVE

The objective of this study was to evaluate the use of roofing shingle waste from the manufacturing process and from re-roof construction in hot-mix asphalt concrete mixtures. In dense-graded mixtures, it was hypothesized that the waste material might serve as a binder extender as well as a fiber reinforcement. In the stone mastic asphalt (SMA), it could serve as the binder stiffener to prevent drain down by replacing the fibers or mineral fillers commonly used in these mixtures.

SCOPE

The treatment of dense-graded and SMA mixtures can viewed as two experiments, because of the different considerations in formulating each of them. The dense graded mixture evaluation included two grades of asphalt cement, one gradation, three levels of roofing shingle content (0, 5.0, and 7.5 percent by weight of aggregate), and three roofing waste types (fiberglass-backed, felt-backed, and re-roof). In the stone mastic asphalt mixtures, one asphalt cement grade, one aggregate gradation, one roofing shingle content, and three types of fiber additives were used. The control material for the SMA mixtures contained a commercial cellulose fiber.

CHAPTER 2
LITERATURE REVIEW

INTRODUCTION

An extensive literature search was conducted in preparation for the laboratory phase of this project. The purpose of this search was to identify any earlier published work that is relevant to this research. Materials characterization information about asphalt roofing products, reports of research work studying the use of roofing materials in asphalt pavements, and information on the emerging stone mastic technology has been obtained. This information forms a starting point for this research project.

ASPHALT ROOFING SHINGLES

A logical place to begin is with roofing shingles themselves. Their composition and properties are relevant to the performance of any asphalt mixture to which they might be added. Therefore, a thorough understanding of these aspects is essential.

There are specifications for roofing shingles set out in American Society for Testing and Materials (ASTM) Specifications D 225-86 [1] [Asphalt Shingles (Organic Felt) Surfaced with Mineral Granules] and D 3462-87 [2] [Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules]. While ASTM provides specifications for roofing shingles, the properties specified allow for a wide range of products. Individual manufacturers have their own, more detailed and largely proprietary specifications. A summary of the ASTM requirements is given in Table 1.

ASTM D 225 (organic-backed shingles) specifies that the felt is to be produced primarily from organic fibers; the felt in the organic shingles used in this study was made from virgin and recycled wood fibers. This is to be a single thickness of dry felt with a uniform and relatively smooth surface. It is first impregnated with a hot saturant asphalt, then coated on both sides with more asphalt, and finally surfaced with mineral granules. The saturant asphalt and the coating asphalt need not be identical; each has a different mechanical role within the shingle and therefore may be specified differently by the shingle manufacturer. For example, the coating asphalt's main purposes are water-proofing and the adhesion of the surface granules, while the saturant asphalt primarily is a treatment for the fiber backing. The specification allows for compounding the coating asphalt with a mineral stabilizer; in the case of the shingles in this study, this is powdered limestone. No restrictions are given as to the nature of the asphalt cements used.

Table 1. ASTM Specifications for Roofing Shingles.

Property	Organic Felt Shingles (ASTM D 225)	Glass Felt Shingles (ASTM D3462)
Asphalt penetration, 0.1mm	N/A	15 minimum
Asphalt Softening Point,°F	N/A	235 maximum 190 minimum
Minimum Average Mass per Unit Area, lb/100 ft^2	95.0	70.0
Minimum Mass per Unit Area of Mineral Matter passing No. 6 and retained on No. 70, lb/100 ft^2	18.5	25.0
Maximum Mass Percent of Mineral Matter passing No. 70 and retained on No. 200, based on total asphalt and mineral matter passing No. 70	70.0	70.0

ASTM D 3462 presents the specification for glass felt shingles. These shingles must be comprised of one or more thicknesses of glass felt, which is defined as a thin porous sheet predominantly comprised of glass fibers containing a substantially water-insoluble binding agent. If more than one layer is used, they must be stuck to each other with a continuous layer of asphaltic material. The felt is first impregnated with a saturant asphalt and then the single or laminated felt is coated on the outside with coating asphalt and granular material. This specification allows both the saturant and coating asphalts to be compounded with fibers as well as mineral stabilizer. The specification currently allows asbestos fibers; this may be a safety concern when working with reroof glass felt shingles. The glass felt shingles used in this study do not contain asbestos or any other fibers in the asphalt; they are stabilized with powdered limestone just like the organic shingles.

There are several differences between ASTM D 225 (Organic Felt) and ASTM D 3462 (Glass Felt), the most obvious being the different felt backing material. Another important difference is that fibrous asphalt stabilizers are permitted for glass felt shingles but not for organic-backed shingles. There are other differences. ASTM D 3462, for example, contains specifications for shingle performance (i.e., tear strength, wind resistance) that are absent in ASTM D 225. ASTM D 225, on the other hand, has greater detail in its specifications for masses and distributions of granular material. Of course, these specifications are intended to control the performance of shingles on roofs, not in pavements. Nonetheless, some of these specifications may be relevant to the performance of the shingle material as part of a paving mixture.

This study included an evaluation of both types of manufactured shingle scrap material, as well as reroof material. For the manufactured scrap materials (one organic-backed shingle and one glass fiber-backed), limited materials characterization information has been obtained from the manufacturer [3]; general statements about the composition of shingles can be made based on this and the literature [4]. The third source for shingle material, reroof, is a processed waste product derived from material that has been removed from existing roofs as part of repair or renovation projects. This material is not as well characterized as the manufactured scrap, as there are many additional material variables to be considered. Among these are the type of roofing construction (which can affect the composition of the roofing material), environmental exposure (which can age harden the asphalt in the roof), and the presence of contaminants such as roofing nails or other debris. A major portion of this study was the assessment of the properties of all three of these materials.

Table 2 lists the primary components of asphalt roofing shingles and approximate ranges. The exact composition of the shingle varies according to manufacturer, backing type (organic or glass felt), and the intended roofing application. They are generally added to the shingles in roughly equal proportions, with the exact amounts determined by the specific shingle product involved. Both types of asphalt are air-blown, a process used to increase the viscosity of asphalts for roofing applications, but which also decrease the temperature susceptibility of asphalt cements. Since the asphalt comprises a large portion of the shingle mass (see Table 2), it is likely that it will contribute significantly to the performance of asphalt paving mixtures modified with shingles.

Table 2. Components of Asphalt Shingles.

Component	Approximate Amount, % by weight	Notes
Asphalt Cement	25-35	Generally of two types
Granular Material	60-70	See **Table 3**
Backing	5-15	Paper or glass felt

The asphalt cement in roofing shingles is a mixture of two different asphalts, saturant and coating. Both are considerably harder than asphalt cements typically used in paving applications, with penetration values at 77 °F ranging from approximately 20 dmm to about 70 dmm, as opposed to typical values of 50 dmm to 300 dmm for paving asphalts. Harder asphalts are used in the manufacturing of roofing materials to prevent the flow of the material during periods of high temperatures.

The largest component (by weight) of asphalt roofing shingles is the granular material. There are several different types of this in each shingle: ceramic granules, headlap granules, backsurfacer sand, and asphalt stabilizer [3]. The properties of each are summarized in Table 3. The most significant in terms of shingle performance are the ceramic-coated colored granules. These are small crushed rock particles coated with ceramic metal oxides. Another granular component is headlap granules. These are comprised essentially of coal slag ground to roughly the same size as the ceramic particles. They make up the largest single portion, by weight, of granular material within the shingle. Backsurfacer sand, the smallest granular contribution by weight, is a washed, natural sand added in small amounts to keep the shingles from sticking together while packaged. Finally, powdered limestone is added as an asphalt stabilizer. These components and amounts may vary from manufacturer to manufacturer and according to shingle type. Since shingles are manufactured to high quality standards, these granular materials are of high quality vis-a-vis aggregates typically found in paving mixtures.

Table 3. Granular Components of Shingles.

Component	Typical Quantity, percent by weight of shingle	Typical Size
Ceramic Granules	10-20 %	passing No. 12 retained No. 40
Headlap Granules	15-25 %	Same as above
Backsurfacer Sand	5-10 %	passing No. 40 retained No. 140
Stabilizer	15-30 %	90% passing No. 100 70% passing No. 200

As with any engineering material, characterization of the properties of roofing waste is essential to control, analyze and predict the performance of an asphalt pavement containing roofing material. Before beginning any construction with a shingle modified paving mixture, additional testing, such as extractions, sieve analyses, etc., should be done on the shingle material, if previous test results on the shingle materials are not available. Although fairly uniform when manufactured, the end product that becomes available for recycling may be quite unpredictable.

FIBER REINFORCEMENT OF ASPHALT CONCRETE

Fibrous backing material comprises a significant portion of the asphalt roofing shingle waste used in this study. Because of this, it is important to understand the effects of the addition of fibers to asphalt paving mixes. A major goal of this study was to assess the applicability of earlier work using fibers not contained in shingles to the present project.

Fibers are used as an anti-draindown additive in stone-mastic (SMA) [5] and porous [6,7] asphalt mixes in Europe. These fibers can be cellulose, synthetic (polyester or polypropylene), or natural mineral fibers such as asbestos. This use of fibers was the basis for the stone-mastic portion of this study.

Fibers have also been successfully used in more conventional mixes in the United States. The City of Columbus, Ohio reports success using fiber-reinforced asphalt mixes to resist shoving and rutting in traffic lanes used by buses [8]. An Indiana study showed that fiber-reinforced mixtures used in overlays retard the growth of reflective cracks and generally improve the maintainability of the overlaid sections [9]. Both of the above studies used polypropylene fibers. Research at Clemson University [10] concluded that reinforcement with polyester fibers leads to increased tensile strength and toughness of mixes as compared to control mixes unmodified with fibers. All of these studies suggest that significant benefits can be gained from the addition of fibers to asphalt paving mixes.

A Finnish study [11] compared various properties of several different types of fibers, including cellulose and glass fibers, as well as mineral and synthetic fibers. One important parameter studied was surface area, since this affects the ability of the fiber to absorb asphalt cement. The study found that cellulose fibers, being porous and having flat cross-sections, exhibit an extremely high specific surface area in contrast to glass and other fibers. A qualitative examination of binding effect showed that cellulose fibers had the greatest stabilizing effect on liquid asphalt cement, followed by fiberglass, polyester, and mineral fibers. This could influence the optimum asphalt contents of asphalt mixtures containing shingle waste incorporating cellulose and glass fibers.

The Finnish study also examined the mechanical properties of fiber-asphalt composites. Elongation tests showed that the strain capacity of the asphalt was increased with the addition of fibers. Additionally, the asphalts became much stiffer (i.e. exhibited significantly higher viscosities) following the addition of fibers. Finally, the softening point temperature of the mixes containing fibers was higher than that for the unmodified mixes, suggesting increased stability at high temperatures.

ROOFING WASTE IN ASPHALT PAVEMENTS

Limited previous research has explored various aspects of using roofing waste in asphalt mixtures. Also, there are several private firms currently marketing paving products containing recycled asphalt shingle material. These commercial ventures are not based on any extensive body of research, but rather practical experience in the field.

One such company, Asphalt Recovery Systems of Chicago, has developed two uses for recycled roofing shingles [12]. One application is as a gravel substitute on unsurfaced roads. The shingles are simply ground to a 1.5 inch and smaller fraction and placed on a stone base. The other use they have developed is as a cold patching material. Ground shingle material is mixed with aggregate and an emulsion to produce the patching mix. This venture is interesting not only for the paving applications, but also for the processing technology they have developed to handle incoming waste material, which in their case is almost entirely reroof material. First, the material is passed over a series of magnets to remove nails or other metal debris. Then it is agitated to shake off loose dirt and gravel, and passed into a shredder which chops the raw shingles into roughly 4-inch by 8-inch pieces. While passing along a conveyor belt after shredding, any additional foreign matter is removed manually. The remaining shingle material is then shredded again to the appropriate size. No data on the long-term performance of these products are yet available.

Another company using asphalt shingles in paving mixtures is ReClaim, Inc., of Tampa [4]. They market a product, "ReACTS-HMA", which is processed shingle waste material. It can be used in hot-mix applications, either as an aggregate substitute (as in this study) or a binder modifier. In the former case, they recommend adding an amount of shingle material equal to 5 to 20 percent of the total mix weight; when added to the binder, they suggest 25 to 40 percent by weight of binder. Detailed technical information about this product is available from the manufacturer, which conforms to the earlier characterization of shingle materials in Tables 2 and 3 of this report.

One of the earliest published works on shingles in asphalt concrete pavements was reported by the University of Nevada, Reno. Their work included both an economic analysis study and a program of laboratory research with reroof waste materials. Both reports are of interest in terms of this research project.

One aspect of the Nevada research was an economic study [13]. Costs of asphalt cement (based on crude oil prices), of shingle waste processing and disposal, and of aggregates were evaluated. While prices have changed since this study was conducted in 1986, its general conclusions should still be valid. The Nevada study concludes that shingle-modified asphalt paving mixtures can be achieved at lower cost than conventional HMA.

The laboratory portion of the Nevada research was reported by Paulsen et al., and covered the use of roofing wastes in asphalt concrete mixtures [14]. Table 4 summarizes the test variables used in that study. Table 5 and Table 6 present additional details of the reported results.

Table 4. Test Variables in Nevada Study.

Test Variable	Values/Types used in Study
Roofing Waste Source*	Nevada, New Jersey, Texas, Illinois, Georgia
Roofing Gradation	1/4" and 1" top size
Asphalt Cement Type**	AR4000, AC+Cyclogen L, AC+Cyclogen H
Asphalt Cement Amount	4%, 5%, 6% (AR4000) 3%, 4%, 5% (Cyclogen)
Quantity of Roofing	10%, 20%, 30% by volume of mix

* All roofing material in the Nevada study was reroof

** Cyclogen L and Cyclogen H are recycling agents intended to soften the asphalt cement contained in the roofing material

Once the study had begun, the researchers limited themselves to two of the roofing waste sources: Nevada and New Jersey. Overall, there were large differences in the behavior of mixtures made with material from these sources. The Nevada material resulted in stiffer (ie. higher resilient modulus, Marshall and Hveem stability) asphalt concrete mixes than the New

Jersey roofing waste. This illustrates the high variability of reroof material, and the importance of materials testing before any construction projects begin.

Table 5 shows an example of typical mix design results obtained in the Nevada study. Although these values are for one particular asphalt cement type and amount, and one particular shingle source, top size and amount, they appear to be fairly representative. It should be noted, however, that changes in any one of the parameters used to design the above mix (cf. Table 4) can significantly alter the measured results.

Table 5. Typical Mix Design Results of Nevada Study.*

Parameter (units)	Value
Unit Weight (pcf)	136.2
Resilient Modulus (ksi)	750.0
Indirect Tensile Strength (psi)	208
Marshall Stability (lbs)	1960
Marshall Flow (0.01 inch)	19
Air Voids (%)	1.0

* Values are for 5% AR4000, 20% 1/4" Nevada shingles
** The Nevada Marshall compactor has a stationary base

Table 6 contains general information about trends apparent in the Nevada study. In general, it appears that the use of roofing waste leads to a stiffer mix, as indicated by increases in resilient modulus and tensile strength. Also, an increase in asphalt content tends to decrease stiffness, as does the addition of the recycling agent. This study examined these trends, not only for reroof material (as was used in the Nevada study) but for manufactured shingle scrap as well.

Table 6. Trends Observed in Nevada Study.

	Increased roofing %	Larger roofing size	Increased % AC	Cyclogen modifier
Resilient Modulus @ 77°F	increase	decrease	decrease	decrease
Indirect Tensile Strength	increase	decrease	none	decrease
Marshall Stability	none	none	decrease	decrease
Temperature Susceptibility	tends to decrease	increase	none	decrease

Paulsen, et al. [14] reported several conclusions based on their research. The study determined that paving mixtures containing up to 20 percent shingle material can be achieved with acceptable laboratory properties. It also concluded that the properties of the asphalt cement in the roofing waste should be considered when selecting the asphalt cement for the mixture, and that the gradations of the aggregates and the shingle material affect the performance of the mix. All of these conclusions were considered in the experimental design for this project.

STONE MASTIC ASPHALTS (SMA)

In addition to conventional dense-graded asphalt paving mixtures, roofing shingle waste might also be potentially added to stone mastic asphalt mixes. Stone mastic, also called splittmastixasphalt, is a design concept which could utilize both the hard asphalt cements and fibrous material found in roofing waste. Before attempting to add shingles to SMA, however, it is important to thoroughly understand the SMA concept.

Stone mastic asphalt was developed in Germany in the 1960's as a surface course resistant to studded tire wear [5]. In 1984, it became standardized in the German Technical

Specifications [15]. Currently, it is in wide use across northern Europe as a rut-resistant overlay or surface course [5]. In this country, use of the technology has been limited, although several states are currently conducting research into the viability of SMA for domestic applications [16].

There are four main aspects to the SMA concept [15]. Firstly, high resistance to permanent deformation is achieved by a stone skeleton of high-quality coarse aggregate. Second, because the coarse aggregates used are also specified to be abrasion resistant, the resulting pavement has high wear resistance. The pavement achieves durability from its relatively high asphalt cement content. Finally, segregation and asphalt draindown are controlled with stabilizing additives such as fibers or polymers.

Stone mastic asphalt is an open graded or gap graded mixture [5]. It is essentially a skeleton of coarse aggregate particles held together by a "mastic" of asphalt cement, fine aggregate, and, usually, an asphalt modifier. This modifier can either be fibers (hence the connection with roofing shingle waste) or polymers. The resulting mix is somewhat higher in asphalt content and lower in air voids than conventional hot mix asphalt (HMA) mixes used in this country. Table 7 presents some typical aggregate gradations for SMA, along with one HMA gradation for comparison. The same information is presented graphically in Figure 1. The plot clearly shows the difference between SMA and HMA.

For the most part, SMA aggregates are held to a high standard of quality [15]. The coarse aggregate is typically 100 percent crushed stone, usually gabbro, granite or basalt. Softer rocks such as sandstone and limestone are not used because they lack the required abrasion resistance. Since the coarse aggregate is the primary load-bearing portion of the pavement structure, it is important for it to have high strength and durability to resist wear under traffic, as well as appropriate surface characteristics to ensure particle interlock. The fine aggregates, also, must be of high quality to ensure proper performance of the asphalt "mastic". German specifications require at least 50 percent of the sand to be manufactured or crushed, and oftentimes the sand will be washed. SMA mixes are sensitive to the amounts, gradation, and quality of aggregates is essential to ensure satisfactory performance.

Asphalt cement is another part of the SMA formula which differs from the conventional HMA used in this country. The most notable difference is that SMA mixes have relatively high asphalt cement contents, on the order of 6.5 to 8 percent by total mix weight, as compared to

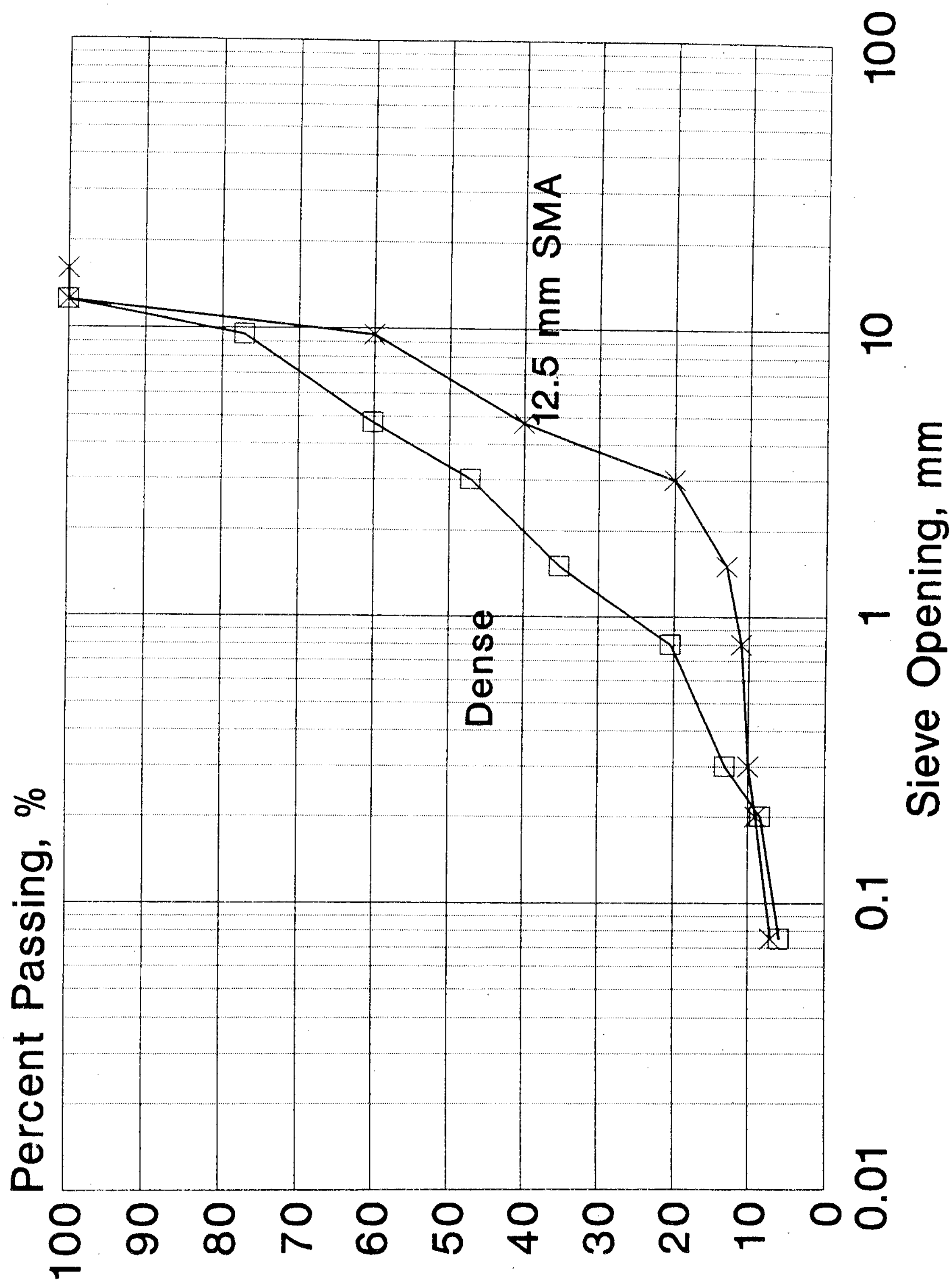

Figure 1. Aggregate Gradations

the 3 to 6 percent used in HMA. Additionally, the asphalt used is harder than typical American paving asphalts, with a penetration grade of 65 being usual for heavy traffic conditions. The high asphalt content is responsible for the flexibility and durability of the mix.

Table 7. Typical SMA Gradations. (after [5])

Sieve Size	% Passing		
	11mm SMA (Germany)	HABS 16 (Sweden)	Typical HMA (USA)
3/4 in.	100	100	100
5/8 in.	100	95-100	95-100
1/2 in.	88-100	30-60	90-100
3/8 in.	50-75	25-40	70-85
No. 4	30-50	20-30	44-74
No. 8	15-30	17-28	28-58
No. 16	12-25	15-25	20-50
No. 30	10-20	12-22	10-35
No. 50	10-15	10-20	5-21
No. 100	10-15	8-15	3-15
No. 200	8-13	7-12	2-10

SMA mix designs are based on an optimum air voids content of 2 or 3 percent, depending upon the location [5]. This compares to the 4 percent typically used for HMA using the Marshall mix design procedure. The low air void level also contributes to a highly durable pavement structure by limiting the opportunity for water and air to infiltrate the pavement structure.

In order to achieve such a high asphalt content without segregation or draindown, stabilizing additives are used. These can be synthetic or natural fibers (such as those found in asphalt roofing shingles) or polymer additives, or a combination of both [15]. Typical German practice is to use cellulose fibers exclusively, at a level of approximately 0.3 percent by weight of mix. A recent Belgian study [6] has confirmed the effectiveness of cellulose fibers in preventing asphalt draindown. Fibers have proven to be the most cost-effective modifier, not only because of their low cost but because of their relative ease of handling and mixing. They are added to the aggregates in the mixing plant just before the addition of the asphalt cement. A slight increase in mixing time is necessary to ensure adequate distribution of the fibers [15]. It is anticipated that the fibers found in asphalt shingle material will perform the same function when added to SMA mixes.

Research into SMA technology is currently taking place in North America. The state DOT's of Georgia, Missouri, Wisconsin, and Michigan have all placed test projects within the past two years [16,17]. These efforts combine European SMA technology with American construction practices, and the combination appears to be workable. No long term performance results are yet available from these projects, but they confirm the feasibility of constructing SMA pavements in this country.

Stone mastic asphalt is a premium product. It requires high quality materials and tight quality control through all phases of construction. Also, longer mixing times and higher mixing temperatures can add to the cost. SMA can cost anywhere from 15 to 30 percent more than conventional HMA pavements [16]. However, its better performance than HMA may make it more cost effective. Once placed, SMA is a highly durable, low-maintenance material. European SMA pavements typically last 20 to 25 percent longer than their HMA counterparts under similar climatic and traffic conditions [5]. This may justify the higher initial first cost.

CONCLUSION

The findings of this literature search are relevant to the experimental approach taken in the laboratory phase of this project. It is essential to understand the ramifications of earlier work as they apply to the present research.

Roofing waste has been shown to increase the stiffness of asphalt concrete paving mixtures. In a cold climate such as Minnesota's, this could lead to problems with thermal cracking. Therefore, cold temperature properties were a main focus of experimental investigation in this project. Since increasing the amount of shingles in a mix tends to increase the stiffness, a study of the relationship between amount of added shingles and stiffness parameters such as resilient modulus was another part of the test program.

Another mixture component that can affect mix stiffness is the asphalt cement. If an asphalt is too soft, it can lead to a pavement that may rut at warm temperatures. For that reason this project investigated the effects of different asphalt cement grades on mix stiffness. Two grades were tested.

The Nevada research cited earlier confirms that the source of the shingle material can strongly influence mixture properties. Although the material in that study was recycled reroof material, it is reasonable to expect variations between the two different types of manufactured scrap used in this study. The experimental design allowed for evaluation of the effects of three shingle sources, both on the mix design process and the fundamental mixture properties.

Because of the similarity of the fibrous material found in roofing waste to the fibers used in dense-graded and stone mastic asphalts, it is possible to achieve the same effect with roofing waste substituted for the fiber stabilizer. Since the literature indicated that harder asphalt cements are typically used in SMA designs, this experiment evaluated SMA mixes using a hard asphalt grade locally available, 85/100 pen. The use of only one asphalt cement in this part of the research allowed more detailed investigation of the influence of other variables.

CHAPTER 3
MATERIALS EVALUATION

LABORATORY-PREPARED MIXTURES

Materials

Asphalt

The neat asphalt cements added to the mixtures were 85/100 and 120/150 penetration grade [ASTM D 946] materials obtained from the Koch Refinery in Inver Grove Heights, Minnesota. Only the 85/100 penetration grade asphalt cement was used in the SMA mixtures, since the literature indicated the need for stiffer binders in these. Table 8 shows the viscosities of the materials at 60°C and 135°C, before and after aging in a rolling thin film oven. The 85/100 grade asphalt has a viscosity which is slightly lower than is required for an AC-20 grade [ASTM D 3381], and the 120/150 penetration grade could be classified as an AC-10 viscosity grade [ASTM D 3381].

Table 8. Neat Asphalt Cement Properties.

Penetration Grade	85/100	120/150
Viscosity, original		
60°C, P	1588	908
135°C, cSt	362	259
Viscosity, after RTFO		
60°C, P	5372	2804
135°C, cSt	275	449

Aggregates

The different gradations used for the dense-graded and SMA mixtures are shown in Figure 1 and Table 9. The dense gradation falls approximately in the middle of the specification band for a Minnesota Department of Transportation type 2341 mixture [18]. The SMA gradation is recommended by the German Federal Department of Transportation [15]. In both cases, the maximum aggregate size is 12.5 mm (1/2-in sieve).

Dense Gradations: The dense gradation is comprised of aggregates from two sources. The major portion (76 percent by weight) of the blend is a partially crushed river gravel from the Commercial Asphalt, Inc. pit located in Lakeland, Minnesota. The portion of the blend larger than 9.5 mm (3/8-in sieve) in size was a granite obtained from Meridian Aggregates in Granite Falls, Minnesota.

Table 9. Aggregate Properties.

Properties	Mn/DOT 2341 Specification	Laboratory Gradation[2]	SMA Gradation	Field Mix[1]
Bulk Specific Gravity	Not Applicable	2.630	2.510	Not Reported
Bulk Specific Gravity, SSD		2.670	2.550	
Apparent Specific Gravity		2.750	2.620	
Absorption Capacity, %		1.7	1.7	
Gradation (Percent Passing)				
19 mm (3/4-in)	100	100	100	100
16 mm (5/8-in)	95 - 100	100	100	97
12.5 mm (1/2-in)	---	100	100	89
9.5 mm (3/8-in)	75 - 95	77	60	84
4.75 mm (No. 4)	60 - 80	60	40	70
2.5 mm (No. 10)	50 - 65	45	18	55
1.0 mm (No. 20)	---	33	12	41
0.63 mm (No. 40)	15 - 30	15	11	24
0.25 mm (No. 80)	6 - 12	10	10	8
0.075mm (No. 200)	2 - 6	6	7	5

1: Values reported by Braun Engineering, June 5, 1992, for virgin aggregate source only
2: Original gradation - not adjusted for roofing shingle waste

In order to prevent aggregate gradation from becoming a covariable in the experiment, the dense-graded material's composition was adjusted for the mineral material content in the roofing shingles. The gradation of the mineral filler and ceramic coated aggregate was supplied by Certainteed Corporation in Shakopee, Minnesota and is shown in Table 10. The adjusted aggregate gradations are shown in Table 11.

SMA: The SMA gradation was exclusively granite. The finer portion (passing the 4.75 mm (No. 4) sieve) was obtained from Commercial Asphalt's St. Cloud, Minnesota pit. All material greater than 4.75 mm (No. 4 sieve) was comprised of the crushed granite from Granite Falls. The properties of the SMA aggregate are shown in Table 9.

Table 10. Composition of Manufacturing Roofing Waste (Supplied by Manufacturer)

Properties[1]	Felt	Fiberglass	Re-Roof	
Binder Content, %	approx. 28%	approx. 28%	30 -40%	
Binder Properties:				
Softening Point, °C (°F)	52-102 (125-215)	52-102 (125-215)	66 - 82 (150 - 180)	
Penetration, dmm (25°C)	23-70	23-70	20 minimum	
Ductility, cm (5cm/min, 25°C)	NA	NA	25 minimum	
Flash Point, °C (°F) COC	>260 (500)	>260 (500)	232 (450) minimum	
Moisture Content, %	NA	NA	5.0 maximum	
Gradation, Percent Passing[2]			Coarse	Fine
4.75 mm (No. 4)	100	100	95-100	100
2.36 mm (No. 8)	69	89	65-75	100
1.0 mm (No. 20)	45	65	15-35	100
0.3 mm (No. 50)	5	11	0-15	10 max
0.15 mm (No. 100)	0	1	0-10	5 max

NA: Not Available
1: Information provided by suppliers
2: Felt and Fiberglass gradations determined in U of M Lab

Roofing Waste

Three sources of roofing shingles were used; two sources were generated during the manufacturing of roofing shingles and one source was obtained from old materials removed from roofs during typical building repairs.

Manufacturing Waste: Both felt-backed and fiberglass roofing waste was generated by the Certainteed Corporation's Shakopee, Minnesota facility. Both types of waste were transported to Omann Brothers in Rogers, Minnesota for processing for use in asphalt concrete mixtures. The waste was ground by two hammermills in tandem, water cooled, and stockpiled. Water-cooling after grinding was considered necessary to prevent the material from agglomerating. It also created high moisture contents in the stockpile; 3.8 and 10.3 percent for fiberglass and felt, respectively, were typical. In the laboratory work, the material was dried under a fan at ambient temperature over a 12-hour period. However, potential compaction and moisture sensitivity problems in field mixtures could be created by this condition.

Table 11. Aggregate Gradations Adjusted for Roofing Waste

Sieve Size	Percent Passing			
	Control	2.5% Shingles	5% Shingles	7.5% Shingles
12.5 mm (1/2-in)	100	100	100	100
9.5 mm (3/8-in)	77	76	75	74
4.75 mm (No. 4)	60	60	57	56
3 mm (No. 8)	47	47	46	45
1.5 mm (No. 16)	34	34	33	33
0.8 mm (No. 30)	16	16	16	16
0.3 mm (No. 50)	9	9	9	10
0.2 mm (No. 100)	5	5	5	5
0.075 mm (No. 200)	3	3	3	3

The ground roofing waste (either type) had a size range of about 5 to 30 mm, although agglomeration of the particles (i.e., lumps typically 12 to 25 mm) made it impossible to perform a gradation analysis on the material. The specific gravity of the roofing waste material was determined using a modification to ASTM procedure C128. The specific gravities found using this method were approximately 1.29 for the felt-backed material, and 1.37 for the fiberglass shingles. Other physical properties, as provided by Certainteed, are shown in Table 10.

Re-Roof Waste: A supply of re-roof material commercially marketed under the trade name ReACTS-HMA, produced by Reclaim, Inc., Tampa Florida, was obtained from PRI Asphalt Technologies, Inc., also of Tampa, Florida. The properties of this material, as supplied by Reclaim, are shown in Table 10.

Cellulose Fiber

The cellulose fiber used in the SMA control mixture is marketed under the tradename Arbocel and is produced by J. Rettenmaier and Sohne of Germany. The material has a cellulose content of between 75 and 80 percent, and a bulk density of 25 to 30 g/l (1.87 pcf). The average fiber length is 1100 μm, and the average diameter is 45 μm [19].

Mixture Design

The optimum added asphalt content for all mixtures was determined using the Marshall method of mix design [ASTM D1559] as described below. For research purposes, optimum neat asphalt cement content was determined based on 4 percent air voids.

Aggregate Preparation

All aggregate stockpiles were oven dried and then sieved into individual fractions. Aggregates were recombined in three-sample batches (approx. 1,100 gram combined aggregate/sample) by combining specific quantities of each fraction to meet the requirements of each gradation.

Mixing

Mixing was accomplished according to ASTM D1559, except for the addition of the shingles and the inclusion of a cure time between mixing and compacting to more closely represent field storage conditions. All shingle materials were at ambient condition when they were added to the mixtures, and they were introduced during the mixing process after the aggregate had been initially coated. The roofing waste, while initially lumpy, showed no problems in readily dispersing into the mixtures; there were no noticeable pockets of roofing waste present in the final mixture. After mixing, the loose material was placed in a 135°C oven for three to four hours for short-term aging; this step was added per the recommendations of the Strategic Highway Research Program (SHRP). Compaction was achieved using a rotating-base, bevel-head Marshall hammer, applying 75-blows per side for dense-graded mixtures

The same procedure was used for both the dense and SMA gradations with the exception that the number of blows was reduced to 50 per side for the SMA to minimize crushing of the aggregate.

Mix Design Results-Dense Gradation

Initially, mix designs were prepared with none (i.e., control), 2.5, 5, and 7.5 percent shingles. The results from this preliminary work was used to select the two of the three percentages of roofing waste for further evaluation. The average results for the mix design parameters at the optimum neat asphalt cement content are shown in Table 12. Using either the fiberglass or the re-roof shingles resulted in a decrease in the optimum binder content; in general as the percentage of waste increases, the optimum binder decreases. There was generally no reduction in required neat asphalt cement content when either level of felt-backed shingles are added to the mixtures. The fiberglass shingles on the other hand resulted in a reduction from 12 (5 percent shingles) to 25 (7.5 percent shingles) percent of the control optimum asphalt cement content. Thus, less new asphalt would need to be purchased to produce a shingle modified mixture than a conventional mixture.

A review of data in Table 12 shows that there was little difference between the 2.5 and the 5 percent for either the felt-backed or fiberglass roofing waste mixes with the 120/150 pen asphalt cement. Since one of the goals of this research was to investigate the use of the maximum amount of waste materials, the 5 and 7.5 percent roofing waste levels were selected for the remainder of the research program.

Table 12. Summary of Marshall Mix Design Parameters for Dense Graded Mixtures.

AC Grade	Shingle Type	Shingle Percent	Marshall Mix Design[1] Test Results At Optimum Asphalt Cement Content					
			Opt. AC %TWM	Air Voids (%)	VMA (%)	Marshall Stability (lb.)	Marshall Flow (0.01-in)	Unit Wt. (pcf)
120/150	Control	0%	4.1	4.0	14.5	3115	10.0	150.2
	Felt	2.5%	4.2	4.0	15.1	3456	8.0	149.5
		5%	3.9	3.6	13.9	3407	9.0	148.1
		7.5%	3.9	3.9	15.0	2466	12.0	147.7
	Fiberglass	2.5%	4.2	4.0	13.5	3200	7.0	149.0
		5%	3.4	3.9	12.8	4264	9.0	149.3
		7.5%	2.9	4.3	12.2	4142	7.0	149.3
	Re-Roof	5%	3.6	3.7	13.1	4754	10.0	149.1
		7.5%	3.1	4.8	14.1	4461	13.0	146.6
85/100	Control	0%	4.3	4.9	14.2	2800	10.0	148.5
	Felt	5%	3.6	5.4	14.7	2697	13.0	146.3
		7.5%	3.6	4.8	15.1	3754	11.0	145.6
	Fiberglass	5%	3.4	3.8	12.7	3746	8.0	149.8
		7.5%	2.9	3.0	11.6	4119	10.0	150.6
	Re-Roof	5%	3.4	4.0	13.2	4567	12.0	148.6
		7.5%	2.9	3.5	13.3	5192	10.0	147.9

NA: Not Applicable
1: 75 Blow Marshall mix design

Mix Design Results-SMA

The waste shingle content used in the SMA mixtures was fixed at 10 percent by weight of the aggregate. The control material for this type of mixture contained cellulose fibers to stiffen the binder and prevent draindown. The fibers were added to the mix at a level of 0.3% fibers by weight of mix, per the manufacturer's recommendation.

Table 13 presents the average mix design parameters for the optimum neat binder content selected for each SMA mixture variable. It can be seen from this table that the stabilities of the SMA mixes are substantially lower and the flows higher than those for the conventional dense graded mixtures. This is most likely a function of the increased binder content, higher levels of roofing waste, and the reduced fines content (which can stiffen dense graded mixtures). Observations noted during laboratory testing indicated that while the stabilities were lower, the SMA mixtures sustained the maximum load for over 10 seconds (i.e., there was no characteristic drop-off of load that indicates maximum load). This was reflected in the higher flow values.

Influence of Roofing Waste on Total Binder Content

In order to understand the effect of the roofing waste on the total binder content, extractions were performed on selected dense-graded mixtures containing the felt material after mixing. Initially, extractions were attempted with a reflux extractor, however the clogging of filters with fine fibers from the roofing waste prohibited adequate filtration of the solvent. Selected dense graded samples were supplied to the MnDOT laboratory where centrifuge extractors were successfully used to determine the total binder content in the mixtures.

The results from the centrifuge extraction are shown in Table 14. At the 2.5 percent roofing waste level, the mixture gained about 1.5 percent total asphalt, and the gain was 2.7 percent when the roofing waste content was increased to 7.5 percent. The increase in asphalt contents for these mixtures is consistent with previously reported experience in fiber reinforced asphalt concrete mixtures [20]. Adding fibers to asphalt concrete increases the required amount of asphalt cement due to the increased surface area of particles in the mixture. The increased amount of binder may serve to aid the durability of the mixture. The loss of strength which may accompany the extra asphalt cement might be offset to a degree by the presence of the fibers.

Table 13. Summary of Marshall Mix Design Parameters for SMA.

Mixture	Shingle Type	Marshall Mix Design[1] Test Results At Optimum Asphalt Cement Content					
		Opt. AC %TWM	Air Voids (%)	VMA (%)	Marshall Stability (lb.)	Marshall Flow (0.01-in)	Unit Wt. (pcf)
85/100	Control (Cellulose)	6.0	2.8	11.9	1728	11	145.1
	Felt	3.5	2.8	17.9	1918	16	143.8
	Fiberglass	4.5	1.0	15.4	2600	17	148.7

NA: Not Applicable
1: 50 blow Marshall mix design

Table 14. Effect of Felt-Backed Roofing Waste on Binder Content for Dense-Graded Mixtures.

Optimum Added Asphalt Content, %	4.3	3.6	3.7
Roofing Waste Content, %	2.5	5.0	7.5
Total Binder Content, %	4.8	5.0	6.4

Determining Compactive Effort to Achieve 6 to 8 Percent Air Voids

Dense Graded Mixtures

In order to mimic field density of the dense-graded mixtures, it was necessary to define a compactive effort which would result in an air void content of between six and eight percent at the optimum asphalt content. The desired compactive effort was determined by developing a graphical relationship between samples compacted at various levels of blows (ie., 15, 30, 50, and 75 blows/side) and the resulting sample air voids for each set of mixture variables. All data are shown in Table 15.

Table 15. Influence of Compactive Effort and Air Voids for Dense Graded Mixtures.

AC Grade	Percent Shingles	Shingle Type	Percent Air Voids			
			Number of Blows per Side			
			15	30	50	75
85/100	0	--	9.4	7.5	5.9	4.0
	2.5%	Felt	8.1	5.2	3.4	4.0
		Fiberglass	7.3	4.5	3.9	4.0
		ReRoof	7.2	5.2	3.4	4.0
	5%	Felt	11.3	8.5	7.0	4.0
		Fiberglass	6.2	4.6	3.0	4.0
		ReRoof	7.8	5.1	3.4	4.0
	7.5%	Felt	8.9	7.1	5.0	4.0
		Fiberglass	7.0	4.7	2.6	4.0
		ReRoof	8.7	5.6	4.5	4.0
120/150	0	--	9.0	7.4	5.8	4.0
	2.5%	Felt	9.1	6.9	4.3	4.0
		Fiberglass	6.6	5.0	3.9	4.0
		ReRoof	7.7	5.7	3.7	4.0
	5%	Felt	9.2	6.8	5.2	4.0
		Fiberglass	7.9	5.7	3.8	4.0
		ReRoof	7.7	5.4	3.7	4.0
	7.5%	Felt	8.3	4.1	3.9	4.0
		Fiberglass	6.6	4.5	3.0	4.0
		ReRoof	7.2	5.6	3.9	4.0

Figures 2 and 3 show typical graphical relationships indicating how the air void contents varied with Marshall compaction for the dense-graded mixtures. It can be seen that for the felt-backed roofing shingles, the mixture with higher concentration of shingles tended to compact more readily (Figure 2). While there was little difference between the 5 and 7.5 percent fiberglass shingles in the reduction of air voids with increasing compactive effort, there is a substantial difference between either level of shingles and the control. This indicates that the fiberglass shingles tend to densify more readily.

Table 16 summarizes the numbers of blows needed to achieve sample air voids between 6 and 8 percent when samples were prepared at the optimum binder content. This information was used to prepare samples for all further testing sequences.

SMA Mixtures

Figure 4 shows the impact of increasing compactive effort on air voids. It can be seen from this figure that SMA's are relatively insensitive to compactive effort. Therefore, a decision was made to hold the compactive effort constant at 50 blows/side for all SMA mixtures.

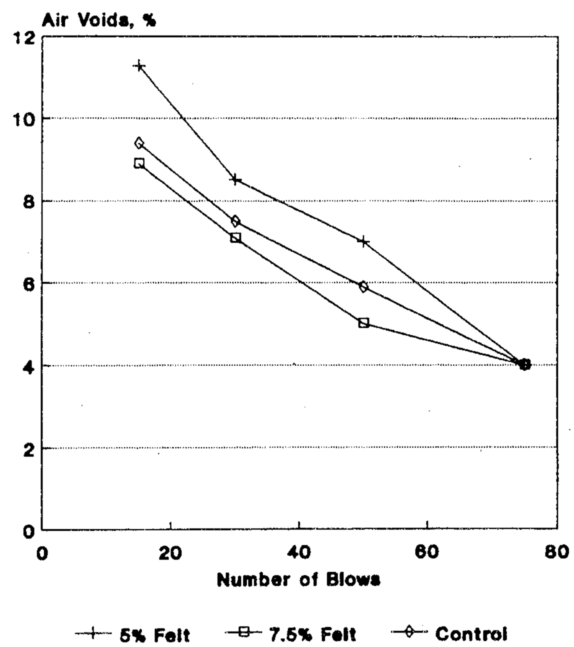

Figure 2. Influence of Compactive Effort on Air Voids for Mixtures Containing Felt Shingles and 85/100 AC.

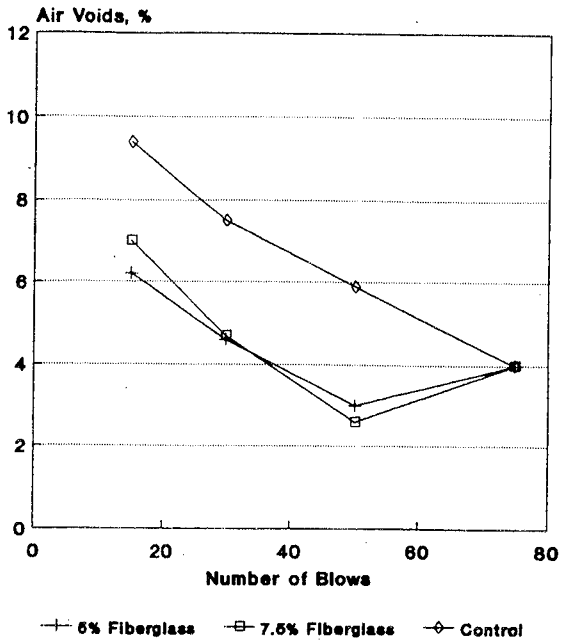

Figure 3. Influence of Compactive Effort on Air Voids for Mixtures Containing Fiberglass Shingles and 85/100 AC.

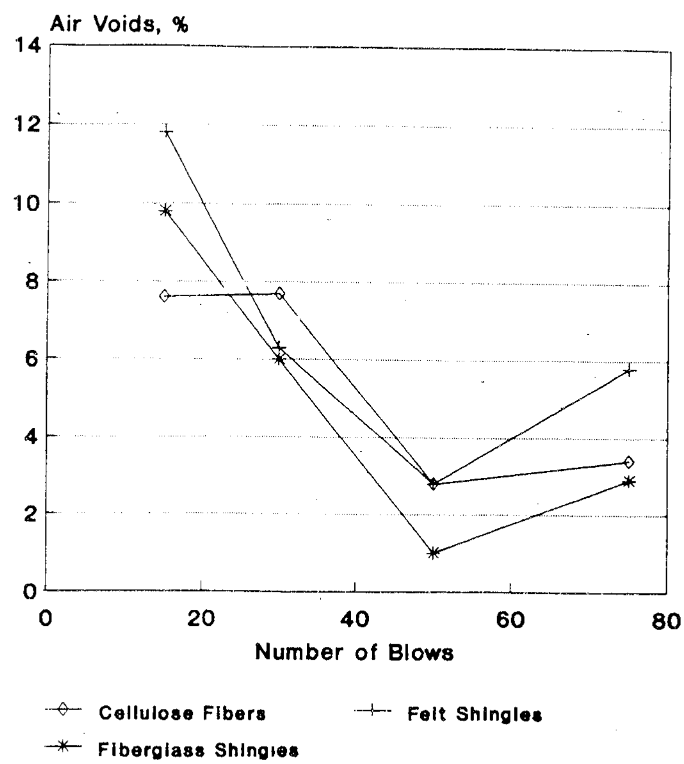

Figure 4. Influence of Compactive Effort on Air Voids for SMA Mixtures.

Table 16. Optimum Neat Asphalt Cement Content and Compactive Effort Used to Prepare Research Samples.

AC Grade	Percent Shingles	Shingle Type	Neat Asphalt Content, %[1]	No. Blows/side[2]
85/100	0	--	4.3	25
	2.5%	Felt	4.5	16
		Fiberglass	4.1	12
		ReRoof	4.2	12
	5%	Felt	3.9	28
		Fiberglass	3.9	15
		ReRoof	3.9	20
	7.5%	Felt	3.9	18
		Fiberglass	2.8	15
		ReRoof	2.8	20
120/150	0	--	4.3	25
	2.5%	Felt	4.5	20
		Fiberglass	4.1	10
		ReRoof	4.1	12
	5%	Felt	3.9	28
		Fiberglass	3.5	15
		ReRoof	3.8	20
	7.5%	Felt	3.8	18
		Fiberglass	3.1	15
		ReRoof	2.8	20

1: By Dry Weight of Aggregate
2: Based on target 6-8% air voids for testing samples

Mixture Evaluation

Testing Program

Figure 5 shows the flow chart for the testing sequence. The testing sequences were designed to address: 1) temperature susceptibility, 2) moisture sensitivity, 3) low temperature behavior, and 4) permanent deformation characteristics.

Temperature susceptibility of mixtures was evaluated by establishing the resilient modulus over a range of temperatures. Resilient modulus is determined from the repeated diametral loading of a conventional 10-cm (4-in). diameter sample while measuring the associated horizontal deformation; the detailed testing procedure is in ASTM D4123. An MTS closed-loop hydraulic test system with a 10-kN (2248 lb) capacity programmed for a 1-Hz frequency consisting of a 0.1-s load application followed by a 0.9-s rest period was used to apply the load. The resilient modulus was then calculated using the total recoverable horizontal strain, and Poisson's ratio of 0.2, 0.35, and 0.5 for temperatures of 1, 25, and 40°C, respectively. Values of Poisson's ratios were selected based upon the SHRP recommendations for testing Long-Term Pavement Performance materials.

Moisture sensitivity of mixtures was assessed by comparing the unconditioned resilient moduli and tensile strengths to values after the samples were moisture conditioned. This testing was completed in accordance with ASTM D4867; conventional 10-cm (4-in) diameter by approximately 6.4-cm (2.5-in) high samples were used. The resilient moduli values were determined as described above. The tensile strengths were determined for diametrally loaded samples at a constant rate of displacement of 50 mm/min (2 in/min). The moisture conditioning of the sample consisted of partially saturating (55-80 percent saturation), freezing, then thawing the samples in a 60°C (140°F) water bath. The samples were cooled to the 25°C (77°F) test temperature by storing in a 25°F (77°F) water bath for 2 to 3 hours. Results are expressed both as absolute values of unconditioned and conditioned values and the ratios (i.e., retained moduli and strengths) of conditioned to unconditioned.

Low temperature behavior was characterized for this research program as the indirect tensile strength, horizontal strain corresponding to maximum tensile strength, and strain energy at failure (i.e., area under the tensile strength vs. horizontal strain curve). The samples were

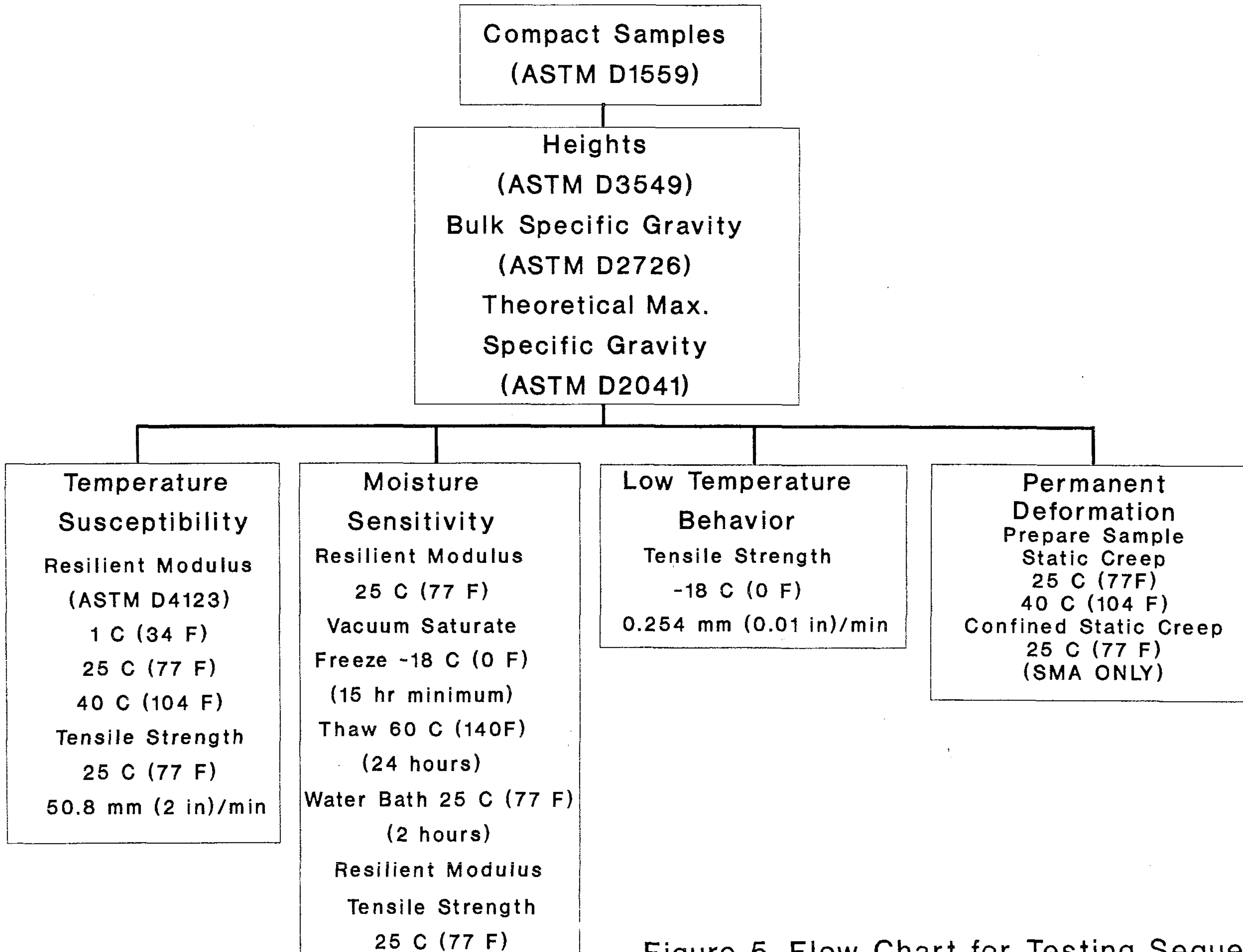

Figure 5. Flow Chart for Testing Sequence.

conventional 10-cm (4-in) diameter by approximately 6.4-cm (2.5-in) high samples. All testing was performed at -18°C (0°F) and a loading rate of 0.254 mm/min. (0.01 in/min).

Permanent deformation characteristics were determined using a static creep test and 10-cm (4-in) diameter by approximately 20-cm (8-in) high cylindrical specimens. Samples were prepared by compacting three conventional samples, extruding these samples one at a time into a tall mold, and applying a static load of approximately 13.4 kN (3000 lb) for 10 minutes. A tack coat was applied between each of the three samples to insure adequate adhesion between the samples. The testing sequence consisted of the application of a pre-conditioning load (100 kPa (14.5 psi)) for 5 minutes, followed by a brief recovery period of 2 minutes. At the end of this time, the 100 kPa (14.5 psi) was applied again for 1 hour and the axial deformation was measured across the center third of the sample in three locations around the circumference (1 sensor every 120°).

Data was reported as creep compliance (axial strain at 30 min./axial stress). It was originally intended to report these values at one hour, however a large portion of the samples failed by this time at the 40°C (104°F) temperature. Therefore the test time for the analysis was reduced so that all samples regardless of temperature could be compared.

Temperature Susceptibility

Dense Graded Mixtures: The results of the resilient modulus testing for all mixtures are listed in Table 17. The values shown are the average of three tests; the standard deviations shown are for the set of three samples. The coefficient of variation (i.e., the ratio of the standard deviation to the mean) within a set of three specimens was typically not more than eight percent for resilient modulus.

The resilient modulus versus temperature curves for dense-graded mixtures prepared with 120/150 penetration grade binder are shown in Figures 6 and 7. The most notable feature of these graphs is that the control mixture resilient modulus was consistently 1.5 to two times greater at 1°C than those containing the manufacturing roofing wastes; there was little difference for mixtures with the re-roof waste. At 25°C, the control mixture had a resilient modulus which was consistent with the 5 percent shingle modified mixtures, and at 40°C, it was slightly stiffer than all except the mixture containing 5 percent felt roofing waste. There was a significant

Table 17. Resilient Modulus Test Results for Dense Gradation Mixtures.

AC Grade	Shingle Type	Shingle Percent	Resilient Modulus, MPa (ksi)					
			1°C (34°F)		25°C (77°F)		40°C (104°F)	
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]	Std. Dev.
120/150	Control	0	5133 (745)	517 (75)	2376 (345)	310 (45)	1223 (177)	124 (18)
	Felt	5	2905 (421)	70 (10)	2260 (329)	164 (24)	1222 (177)	70 (10)
		7.5	2411 (349)	154 (22)	1226 (178)	70 (10)	591 (86)	105 (15)
	Fiberglass	5	4062 (589)	832 (120)	2028 (294)	64 (9)	849 (123)	95 (14)
		7.5	4070 (590)	516 (75)	1599 (232)	91 (13)	871 (126)	83 (12)
	Re-Roof	5	5024 (729)	439 (64)	2513 (365)	168 (24)	1390 (202)	146 (21)
		7.5	5349 (776)	150 (22)	2390 (347)	84 (12)	1119 (162)	87 (13)
85/100	Control	0	5420[2] (786)	117 (17)	2140[2] (301)	NA	1355 (197)	96 (14)
	Felt	5	3076[2] (446)	83 (12)	2584 (375)	7 (1)	1341 (194)	96 (14)
		7.5	2669 (387)	59 (9)	1930 (280)	575 (83)	968 (140)	46 (7)
	Fiberglass	5	2680 (389)	429 (62)	2429[2] (352)	180 (26)	1107 (160)	46 (7)
		7.5	3556 (516)	752 (109)	1630 (236)	88 (13)	744 (108)	38 (6)
	Re-Roof	5	4604 (668)	532 (77)	2507 (364)	177 (26)	1269[2] (184)	207 (30)
		7.5	4149 (602)	175 (25)	2075 (301)	213 (31)	1239 (180)	60 (9)

NA: Not Available
1: Mean is average of three samples
2: Fewer than three samples used to compute mean

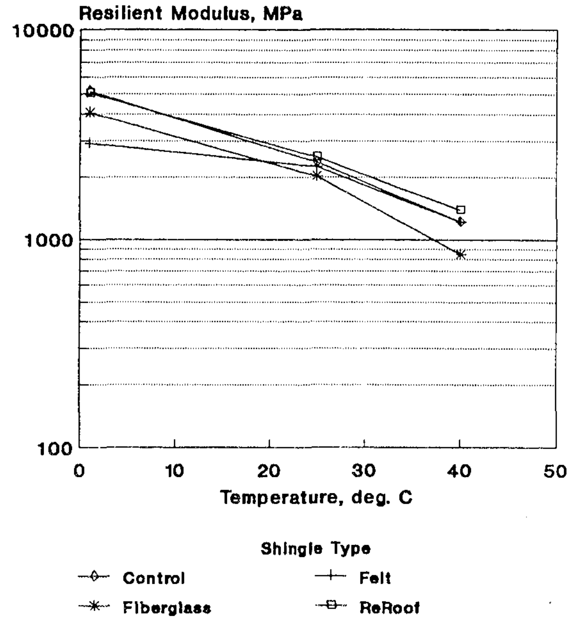

Figure 6. Temperature Susceptibility for Dense Graded Mixtures Containing 5% Shingles, 120/150 AC.

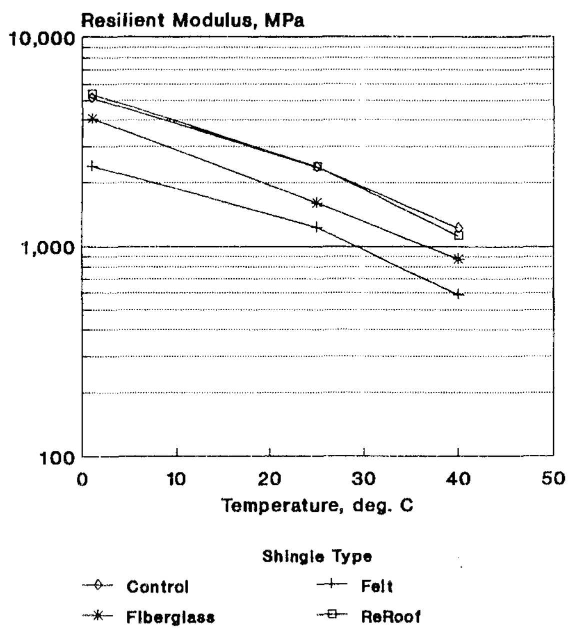

Figure 7. Temperature Susceptibility for Dense Graded Mixtures Containing 7.5% Shingles, 120/150 AC.

decrease in the mixture stiffness at all temperatures when the percent of any type of roofing shingle waste was increased from 5 to 7.5 percent.

The resilient modulus versus temperature curves for dense-graded mixtures prepared with 85/100 penetration grade binder are shown in Figures 8 and 9. Similar trends to those noted for the 120/150 pen asphalt cement can be seen for mixtures with the harder grade binder. The influence of increased manufacturing shingle waste from 5 to 7.5 percent is reduced when the stiffer binder was used.

In summary, the mixtures containing 5 percent shingles were stiffer than those containing 7.5 percent at 25 and 40°C. Fiberglass manufacturing shingle waste produced the softest mixtures at the 7.5 percent level, followed by the felt-backed shingles, with the stiffest mixtures being produced when the re-roof shingles were used. The softer behavior of the modified mixtures is most likely due to the increased binder content caused by the asphalt in the roofing waste, although it appears as though the temperature susceptibility is decreased by the inclusion of the waste material. Similar behavior at the 5 percent level of shingle waste was noted for mixtures containing either the 85/100 or 120/150 penetration grade asphalt cement. The reduction of overall mixture stiffness when the percentage of shingles was increased from 5 to 7.5 percent appear to be dependent upon the grade of neat binder; the softer the neat asphalt cement, the more reduction in mixture strength is noted.

SMA Mixtures: Table 18 and Figure 10 show the resilient modulus test results for the SMA mixtures. All of the mixtures behave consistently over the range of temperatures from 1 to 40°C. At 1°C, the SMA materials all have a resilient modulus of about 7,000 MPa, and at 25°C, the mean is approximately 2,500 MPa. The fiberglass-backed roofing SMA had a slightly stiffer behavior at 40°C than either the control or felt-backed shingle SMA.

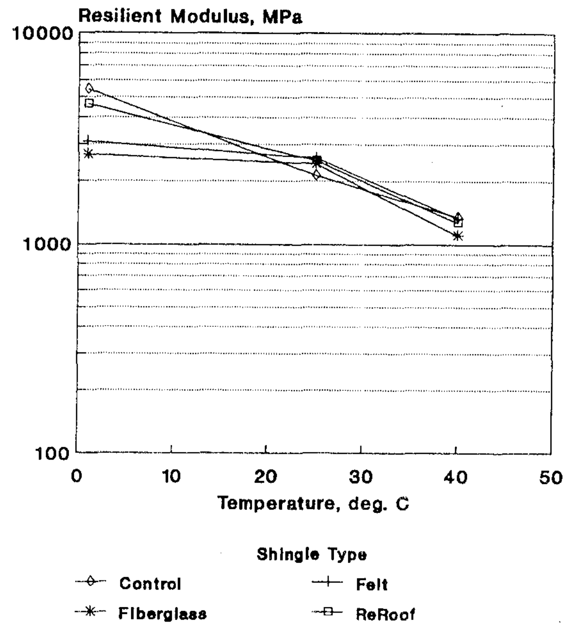

Figure 8. Temperature Susceptibility for Dense Graded Mixtures Containing 5% Shingles, 85/100 AC.

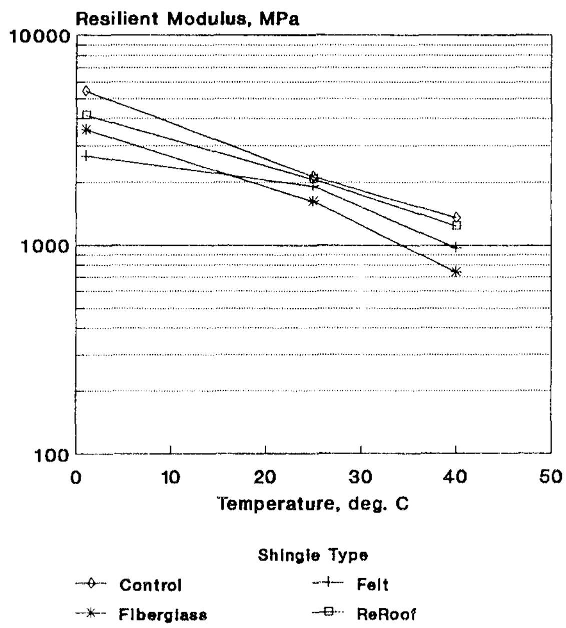

Figure 9. Temperature Susceptibility for Dense Graded Mixtures Containing 7.5% Shingles, 85/100 AC.

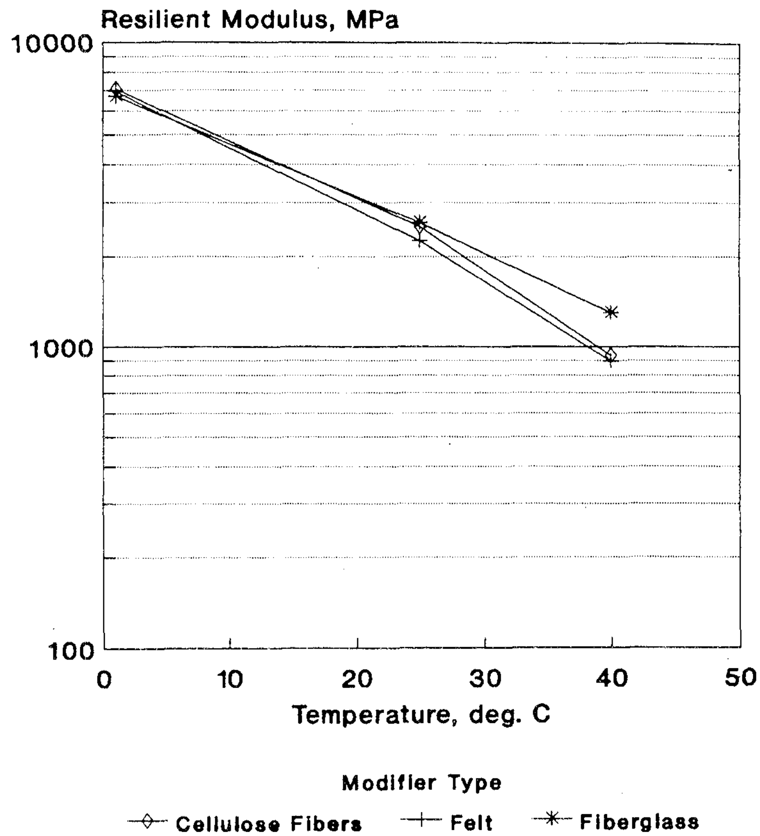

Figure 10. Temperature Susceptibility for SMA Mixtures.

Table 18. Resilient Modulus Test Results for SMA Mixtures.

AC Grade	Shingle Type	Shingle Percent	Resilient Modulus, ksi					
			1°C (34°F)		25°C (77°F)		40°C (104°F)	
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]	Std. Dev.
85/100	Control	0	7063 (1024)	591 (86)	2501 (363)	116 (17)	935 (136)	18 (3)
	Felt	10	6927 (1005)	288 (42)	2259 (328)	228 (33)	894 (130)	246 (36)
	Fiberglass	10	6681 (969)	573 (83)	2579 (374)	89 (13)	1300 (189)	147 (21)

NA: Not Available
1: Mean is average of three samples

Moisture Sensitivity

Dense Graded Mixtures: The resilient moduli data, both unconditioned and moisture conditioned are shown in Table 19.

The mixtures modified with the higher 7.5 percentage of felt-backed shingles showed a consistent 30 to 35 percent loss of moduli for both unconditioned and conditioned cases (Figure 11 and Figure 12). Since this loss of strength was consistent, there was no net change in the resilient modulus ratio (Figures 15 and 16). A similar uniform loss of strength is seen in the unconditioned and conditioned tensile strength data (Table 20, Figures 13 and 14). These results indicate that while the roofing shingles influenced the original strength, the inclusion of felt-backed shingles apparently had no effect on the moisture sensitivity of the mixture.

Table 19. Moisture Sensitivity of Dense Graded Mixtures (Resilient Modulus).

AC Grade	Shingle Type	Shingle Percent	Resilient Modulus, MPa (ksi)				
			Unconditioned 25°C (77°F)		Conditioned 25°C (77°F)		Ratio
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1] %
120/150	Control	0	2733 (396)	74 (11)	1540[2] (223)	1 (0)	56
	Felt	5	2863 (415)	37 (5)	1343 (195)	242 (36)	47
		7.5	1898[2] (275)	130 (19)	990[2] (143)	58 (8)	52
	Fiberglass	5	2541[2] (368)	97 (14)	1495 (217)	126 (18)	59
		7.5	2554 (370)	132 (19)	1497 (217)	59 (9)	59
	Re-Roof	5	3793 (550)	129 (19)	2128 (309)	125 (18)	56
		7.5	3768 (547)	238 (35)	1868 (271)	138 (20)	50
85/100	Control	0	3458 (502)	218 (32)	2782 (403)	102 (15)	81
	Felt	5	2835 (411)	175 (25)	1842 (267)	180 (26)	65
		7.5	2325 (337)	82 (12)	1502 (218)	127 (18)	65
	Fiberglass	5	2948 (428)	56 (8)	2445 (355)	103 (15)	83
		7.5	3124 (453)	131 (19)	1897[2] (275)	42 (6)	59
	Re-Roof	5	3325 (482)	189 (27)	1906 (276)	209 (30)	57
		7.5	3884 (563)	241 (35)	1993 (289)	96 (14)	51

NA: Not Available
1: Mean is average of three samples
2: Fewer than three samples used to compute mean

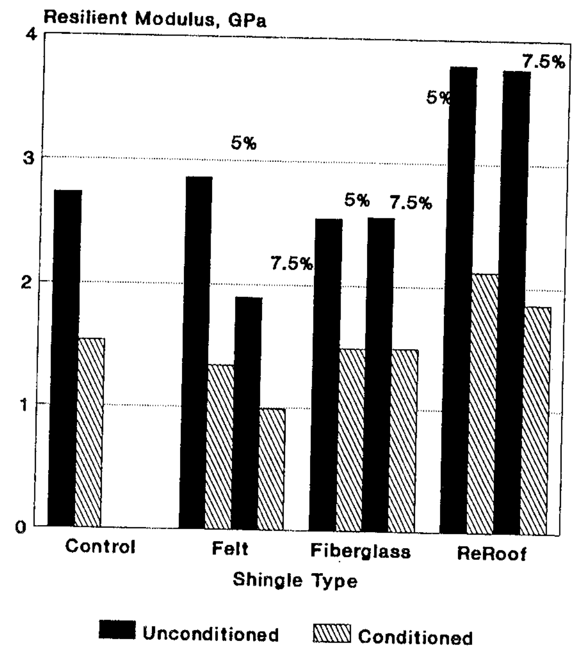

Figure 11. Moisture Sensitivity (Resilient Modulus) of Dense Graded Mixtures, 120/150 AC.

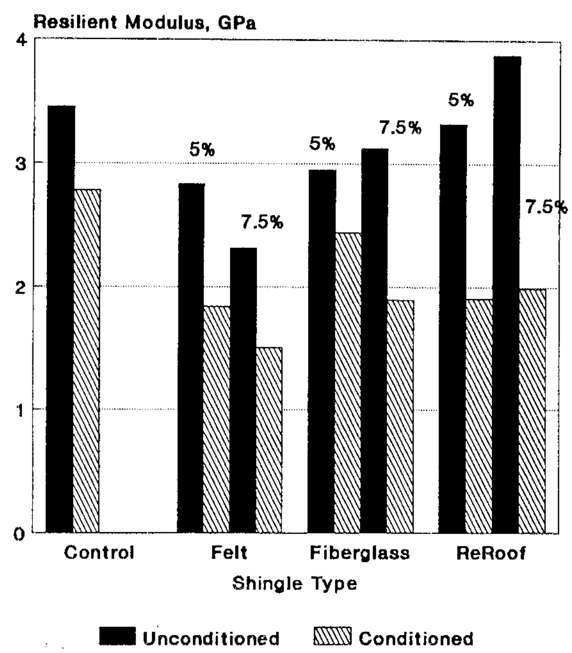

Figure 12. Moisture Sensitivity (Resilient Modulus) of Dense Graded Mixtures, 85/100 AC.

Table 20. Moisture Sensitivity of Dense Graded Mixtures (Tensile Strength).

AC Grade	Shingle Type	Shingle Percent	Tensile Strength, kPa (psi)				
			Unconditioned 25°C (77°F)		Conditioned 25°C (77°F)		Ratio %
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]
120/150	Control	0	643[2] (93)	NA	542[2] (79)	152 (22)	84
	Felt	5	787 (114)	61 (9)	511 (74)	86 (12)	65
		7.5	486 (71)	25 (4)	405 (59)	26 (4)	83
	Fiberglass	5	432 (63)	118 (17)	529 (77)	55 (8)	123
		7.5	430 (62)	80 (12)	566 (82)	34 (5)	132
	Re-Roof	5	778 (113)	85 (12)	667 (97)	160 (23)	72
		7.5	894 (130)	76 (11)	74 (11)	14 (2)	8
85/100	Control	0	908[2] (132)	19 (3)	747 (108)	223 (32)	82
	Felt	5	890 (129)	67 (10)	562 (82)	41 (6)	63
		7.5	587 (85)	32 (5)	467 (68)	29 (4)	79
	Fiberglass	5	465 (68)	93 (13)	732 (106)	14 (2)	157
		7.5	387 (56)	78 (11)	441[2] (64)	37 (5)	114
	Re-Roof	5	709 (103)	276 (40)	667 (97)	60 (9)	94
		7.5	620 (90)	40 (6)	442 (64)	70 (10)	71

NA: Not Available
1: Mean is average of three samples
2: Fewer than three samples used to compute mean

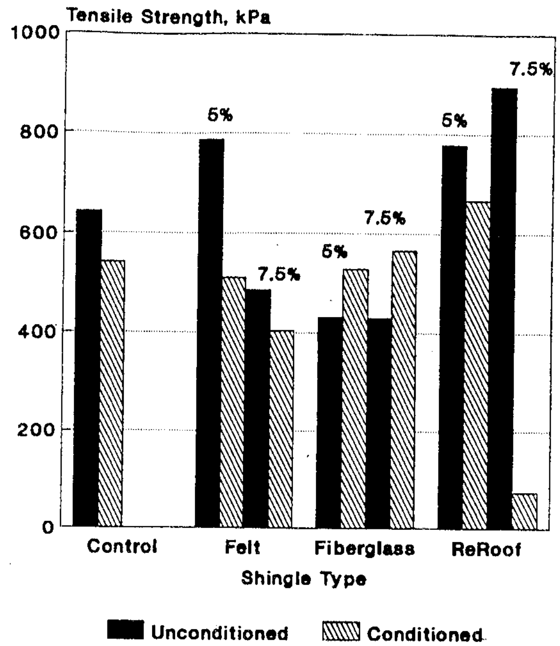

Figure 13. Moisture Sensitivity (Indirect Tensile Strength) of Dense Graded Mixtures, 120/150 AC.

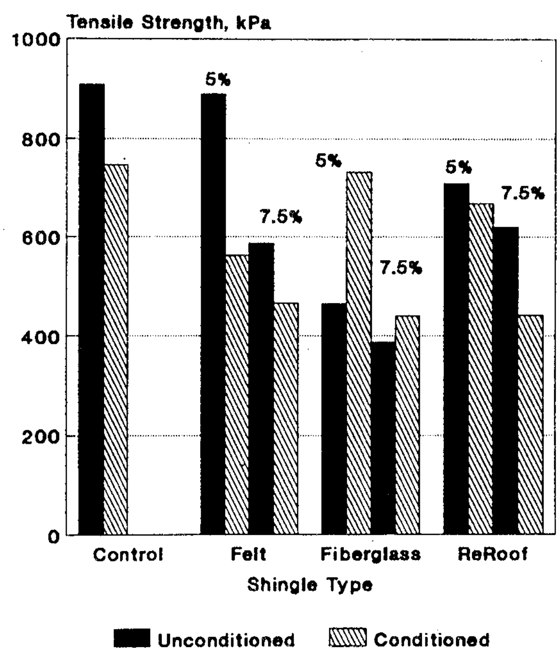

Figure 14. Moisture Sensitivity (Indirect Tensile Strength) of Dense Graded Mixtures, 85/100 AC.

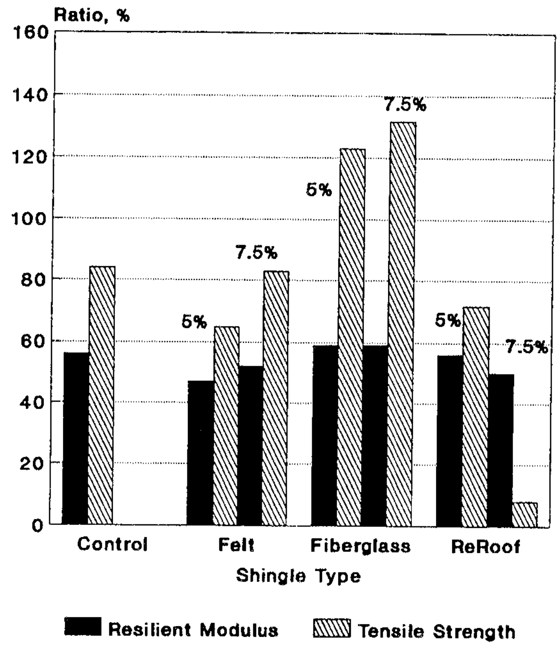

Figure 15. Moisture Sensitivity (Retained Parameter Ratios) for Dense Graded Mixtures, 120/150 AC.

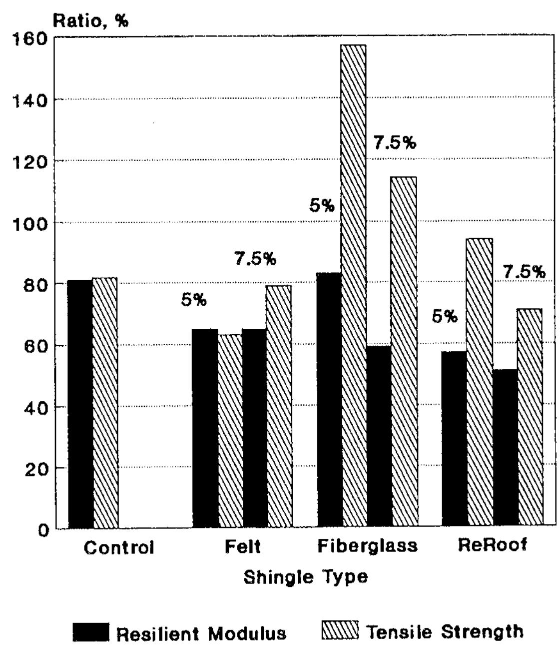

Figure 16. Moisture Sensitivity (Retained Parameter Ratios) for Dense Graded Mixtures, 85/100 AC.

Mixtures modified with the fiberglass shingles show mixed results, depending upon the grade of asphalt cement used and whether the resilient moduli or tensile strengths were being evaluated. With the softer 120/150 pen asphalt cement, there was no statistical difference in moduli values between the control and mixtures with either level of fiberglass shingles (Figure 11). When the harder 85/100 pen asphalt cement was used, there was a reduction in moduli, both unconditioned and conditioned, of approximately 10 and 30 percent for the 5 and 7.5 percent levels of fiberglass shingles, respectively (Figure 12). When the tensile strengths were evaluated, there was about a 10 percent loss in unconditioned tensile strength with the softer asphalt cement (Figure 13). This loss in unconditioned tensile strength increased to about 30 percent with the harder asphalt (Figure 14). Since the loss of strength was uniform, there was again no net change in the resilient modulus ratios (Figures 15 and 16).

However, when the conditioned tensile strengths were examined, a substantial increase in strength after conditioning was seen for both grades of binder. There was a uniform increase of tensile strength of over 20 percent for mixtures with the softer binder (Figure 15); this produced modified mixtures with conditioned tensile strengths similar to the control. There was a varied increase in conditioned strength for mixtures with the harder asphalt cement. The 5 percent of fiberglass shingles resulted in an increase of conditioned strength of about 50 percent while an increase of only 10 percent was seen for the 7.5 percent level. This consistent increase in conditioned tensile strength was seen as ratios of over 100 percent (Figure 15 and 16). Since this phenomena of consistently increasing strength is unusual, it would be difficult to conclude that fiberglass shingles decrease moisture sensitivity without further testing and field evaluations.

Use of re-roof shingles produced mixtures with approximately 40 percent higher unconditioned moduli when the softer 120/150 pen asphalt was used; there is little difference with the stiffer 85/100 pen asphalt. The reduction in mixture strength after conditioning was similar to that for the felt-backed shingles. The result was no net change in the resilient modulus ratio. The unconditioned tensile strengths appeared to be dependent both upon the percentage of re-roof shingles added and the grade of binder used. At the 5 percent shingle level, there was little difference between the control mixtures (either asphalt cement grade) and the modified mixtures. However, at the 7.5 percent level there was a 30 percent reduction in tensile strengths with the 85/100 pen asphalt cement. These differences were enhanced after conditioning. Samples essentially failed after conditioning when the 120/150 pen asphalt cement mixtures were modified with 7.5 percent re-roof. From this information, it would appear that the higher levels of the re-roof material could be detrimental to the mixture moisture sensitivity.

SMA Mixtures: The data for both unconditioned and conditioned resilient moduli are shown in Table 21. The use of either the felt-backed or fiberglass shingles in the SMA mixtures increased the unconditioned resilient modulus approximately 10 to 15 percent (Figure 17). The conditioned moduli for the control and mixtures with felt-backed shingles were similar; the fiberglass mixtures had conditioned moduli about 25 percent greater than either of the other mixtures. This can be seen in the increase in the resilient modulus ratio (Figure 19).

Table 21. Moisture Sensitivity of SMA Mixtures (Resilient Modulus).

AC Grade	Shingle Type	Shingle Percent	Resilient Modulus, MPa (ksi)				
			Unconditioned 25°C (77°F)		Conditioned 25°C (77°F)		Ratio %
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]
85/100	Control	0	2823 (409)	186 (27)	2268 (329)	262 (38)	80
	Felt	10	3275 (475)	179 (26)	2518 (365)	154 (22)	77
	Fiberglass	10	3124 (453)	103 (15)	2913 (433)	82 (12)	96

NA: Not Available
1: Mean is average of three samples

The unconditioned tensile strengths (Table 22) of the felt-backed and fiberglass modified mixtures were 25 and 10 percent lower than the cellulose control (Figure 18). However, the conditioned tensile strengths increased 15 to 20 percent over the conditioned values for the felt-backed and fiberglass mixtures, respectively. The cellulose control mixture showed a decrease in conditioned tensile strength of 25 percent. These changes can be seen in the tensile strength ratios (Figure 19).

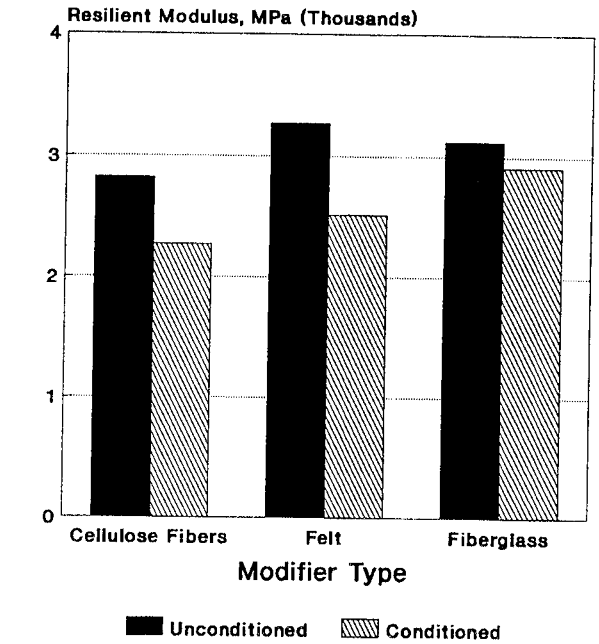

Figure 17. Moisture Sensitivity (Resilient Modulus) for SMA Mixtures.

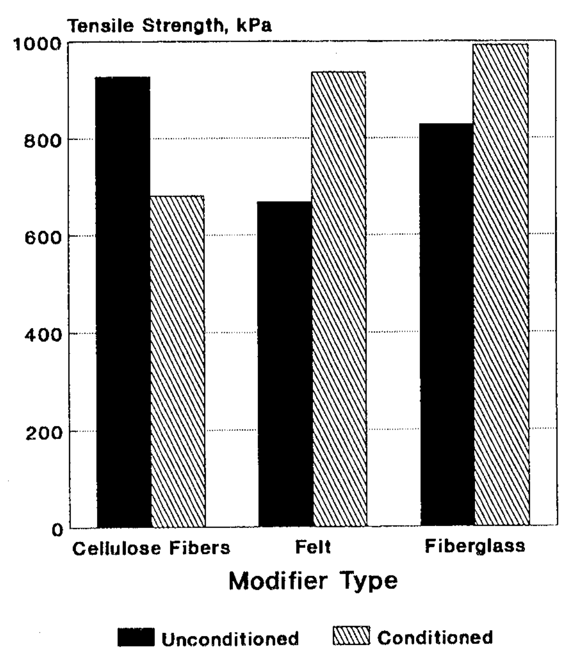

Figure 18. Moisture Sensitivity (Indirect Tensile Strength) for SMA Mixtures.

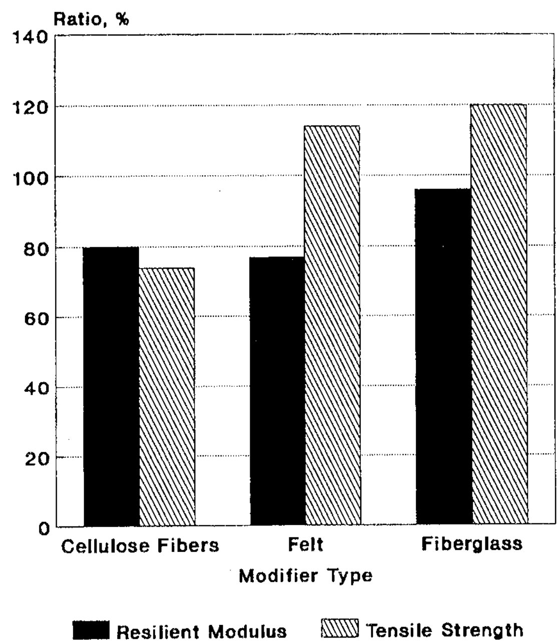

Figure 19. Moisture Sensitivity (Retained Parameter Ratios) for SMA Mixtures.

Table 22. Moisture Sensitivity of SMA Mixtures (Tensile Strength).

AC Grade	Shingle Type	Shingle Percent	Tensile Strength, kPa (psi)				
			Unconditioned 25°C (77°F)		Conditioned 25°C (77°F)		Ratio %
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]
85/100	Control	0	927 (134)	87 (13)	682 (99)	107 (16)	74
	Felt	10	669 (97)	161 (23)	936 (136)	35 (5)	114
	Fiberglass	10	827 (120)	73 (11)	993 (144)	51 (7)	120

NA: Not Available
1: Mean is average of three samples

These results indicate that at the 10 percent shingle level in the SMA gradation, the inclusion of roofing waste significantly decreases mixture moisture sensitivity. This can be seen in increases in both the absolute values and retained strengths. The implication would be that SMA mixtures prepared with the roofing waste material would be less susceptible to moisture damage.

Low Temperature Behavior

The general hypothesis for this evaluation is that higher strains at peak stress at cold temperatures could indicate a greater ability for the mixture to deform prior to thermal cracking. This hypothesis, although not confirmed with relationships between field and laboratory testing, was used to evaluate the influence of roofing waste on low temperature behavior.

Dense Graded Mixtures: The data from the low temperature (-18°C), slow rate of deformation (0.254 mm/min) indirect tensile test are shown in Table 23 and Figures 20 through 23.

For either grade of asphalt cement, adding roofing shingles to the mixtures resulted in a lower cold temperature tensile strength (Figures 20 and 21). When the felt-backed shingles were used, the tensile strength decreased about 10 percent at the 5 percent shingle level to around 55 percent at the 7.5 percent shingle level for the softer 120/150 pen asphalt mixtures. This loss in strength was accompanied by little change in strain at failure (Figure 22). While there was a significantly larger decrease (45 percent) at the 5 percent shingle level for mixtures with the harder 85/100 pen asphalt cement, the 7.5 percent level still showed a similar 55 percent loss. This decrease in tensile strength was accompanied by an increase in the corresponding strain at failure by about 25 percent for the 5 percent shingle level to over 40 percent for the 7.5 percent shingle level (Figure 23). The ability of the 85/100 pen mixtures with felt-backed shingles to strain at cold temperatures was at least equal to the unmodified 120/150 pen mixtures. This would indicate that a substantial improvement in low temperature behavior was gained with the inclusion of felt-backed shingles.

Similar trends in the decreasing of the tensile strengths were seen with the fiberglass shingles. However, these mixtures generally show a decrease in the corresponding strain as well; the decrease does not appear to be dependent upon the percentage of the shingles added. There is generally a 35 percent reduction in strain with the 120/150 pen asphalt; little change was noted with the 85/100 mixtures. This indicates that the use of fiberglass shingles would not offer an advantage in low temperature behavior.

Use of the re-roof material resulted in both a decrease in tensile strength and the corresponding strain. The decrease in strain appears to be related to the percentage of shingles added. For mixtures with the 120/150 pen asphalt cement, there was a 30 and 50 percent reduction in strain for the 5 and 7.5 percent level of re-roof shingles, respectively. A 15 and 45 percent reduction is strain is seen for the 5 and 7.5 percent level in mixtures with the 85/100 pen asphalt cement.

In summary, it appears that the use of the felt-backed roofing waste, when used with the harder binder, could improve low temperature behavior when compared to other types of shingles. However, it is possible that this is a function of the differences in neat binder contents between the mixtures; there is a difference of about 0.75 percent neat asphalt between the felt-backed and fiberglass mixtures. Without confirmation of these results with field experience, it is difficult to draw specific conclusions from this limited information.

Table 23. Low Temperature Behavior for Dense Graded Mixtures.

AC Grade	Shingle Type	Shingle Percent	-18°C (0°F) Properties, 0.25 mm/min (0.01-in/min)					
			Max. Tensile Strength kPa (psi)		Strain at Max. Strength (in/in)		Horizontal Strain Energy kPa-mm/mm (psi-in/in)	
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]	Std. Dev.
120/150	Control	0	2653 (385)	77 (11)	0.001727	0.000421	3.128 (0.454)	0.602 (0.087)
	Felt	5	2308 (335)	254 (37)	0.001571	0.000282	1.981 (0.287)	0.141 (0.020)
		7.5	1523 (222)	102 (15)	0.001685	0.000132	1.611 (0.234)	0.207 (0.030)
	Fiberglass	5	1971 (286)	113 (16)	0.001090	0.000212	1.254 (0.182)	0.187 (0.027)
		7.5[2]	1826 (265)	20 (3)	0.001156	0.000190	1.189 (0.172)	0.084 (0.012)
	Re-Roof	5	2415 (350)	166 (24)	0.001219	0.000225	1.664 (0.241)	0.183 (0.026)
		7.5[2]	1537 (223)	195 (28)	0.000852	0.000276	0.978 (0.142)	0.059 (0.009)
85/100	Control	0	3234 (468)	187 (27)	0.001326	0.000733	3.843 (0.557)	0.149 (0.022)
	Felt	5[2]	1868 (271)	NA	0.001678	NA	1.911 (0.277)	NA
		7.5	1413 (205)	251 (36)	0.001876	0.000536	1.465 (0.212)	0.196 (.0028)
	Fiberglass	5	2470 (358)	132 (19)	0.001309	0.000116	1.305 (0.189)	0.292 (0.042)
		7.5	1857 (269)	69 (10)	0.001525	0.000055	0.974 (0.141)	0.200 (0.029)
	Re-Roof	5	2429 (352)	273 (40)	0.001129	0.000100	1.491 (0.216)	0.231 (0.034)
		7.5[2]	1465 (213)	161 (23)	0.000730	0.000062	0.695 (0.101)	0.128 (0.018)

NA: Not Available   1: Mean is average of three samples   2: Fewer than three samples used to compute mean

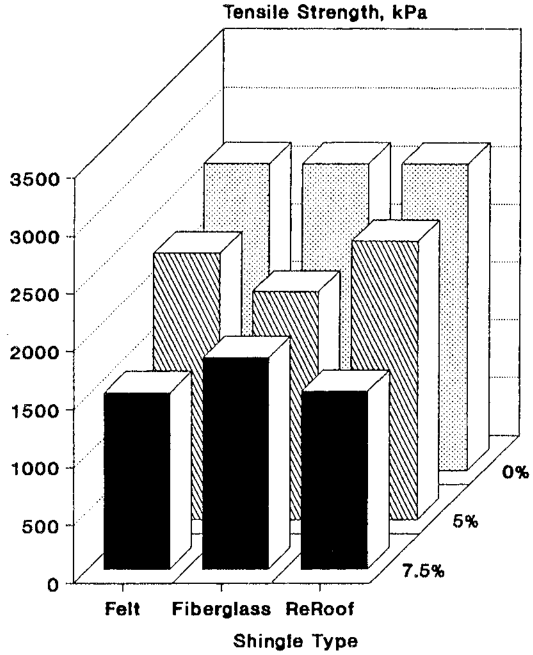

Figure 20. Low Temperature Properties (Peak Tensile Strength) for Dense Graded Mixtures, 120/150 AC.

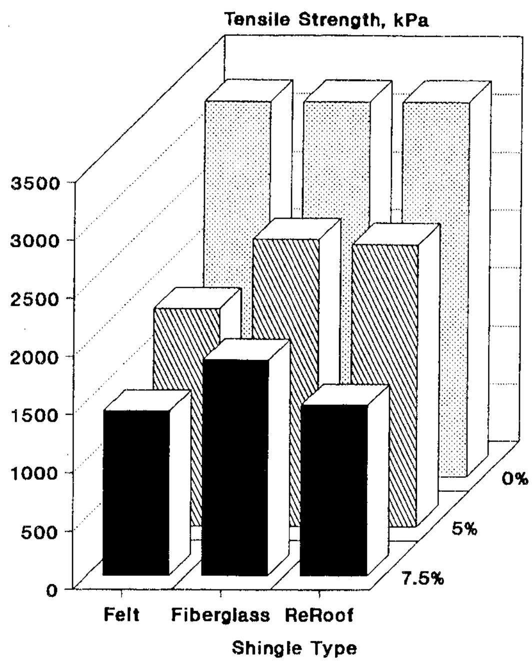

Figure 21. Low Temperature Properties (Peak Tensile Strength) for Dense Graded Mixtures, 85/100 AC.

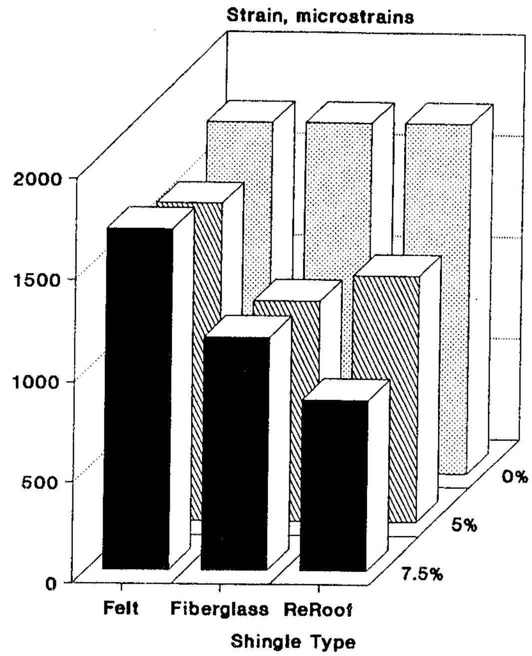

Figure 22. Low Temperature Properties (Strain at Peak Stress) for Dense Graded Mixtures, 120/150 AC.

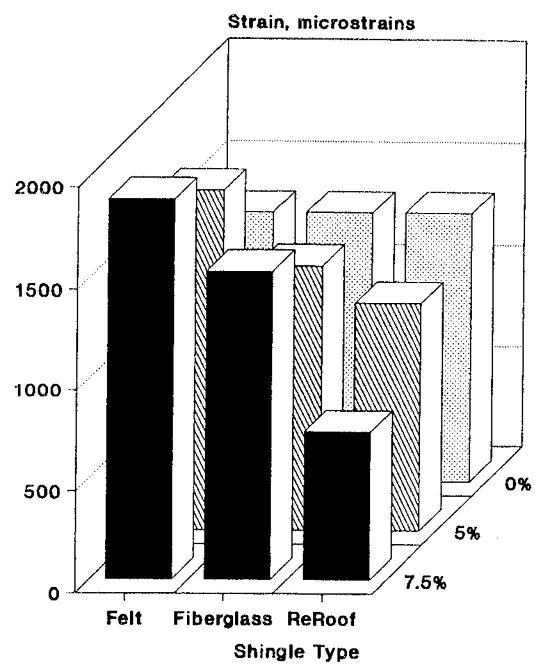

Figure 23. Low Temperature Properties (Strain at Peak Stress) for Dense Graded Mixtures, 85/100 AC.

SMA Mixtures: The data for these mixtures are presented in Table 24. The cold tensile strengths indicate that the felt-backed shingles were lower by about 20 percent for the felt-backed, and higher by about 20 percent for the fiberglass shingles as compared to the cellulose control (Figure 24). The corresponding strains (Figure 25) for the roofing waste modified mixtures were both lower by about 10 percent for the felt-backed and 35 percent for the fiberglass. These results would again indicate that the felt-backed shingle modified mixtures could perform better than fiberglass modified mixtures at cold temperatures.

Table 24. Low Temperature Behavior for SMA Mixtures.

AC Grade	Shingle Type	Shingle Percent	-18°C (0°F) Properties, 0.025 mm/min (0.01-in/min)					
			Max. Tensile Strength kPa (psi)		Strain at Max. Strength mm/mm (in/in)		Horizontal Strain Energy kPa-mm/mm (psi-in/in)	
			Mean[1]	Std. Dev.	Mean[1]	Std. Dev.	Mean[1]	Std. Dev.
85/100	Control	0	2755 (400)	33 (5)	0.001749	0.000222	2.889 (0.419)	0.401 (0.058)
	Felt	10[2]	2206 (320)	253 (37)	0.001605	0.000004	2.030 (0.294)	0.421 (0.061)
	Fiberglass	10[2]	3268 (474)	166 (24)	0.001145	0.000512	2.714 (0.394)	1.040 (0.151)

1: Mean is average of three samples
2: Fewer than three samples used to compute mean

While the reduction in the ability of the roofing waste modified mixtures to strain at cold temperatures appears to be a function of the type of roofing waste, it is also most likely a function of the reduced neat binder added to the mixture. The cellulose control mix was prepared with 6.0 percent neat binder while the felt-backed and fiberglass SMA's were prepared with 3.5 and 4.5 percent, respectively.

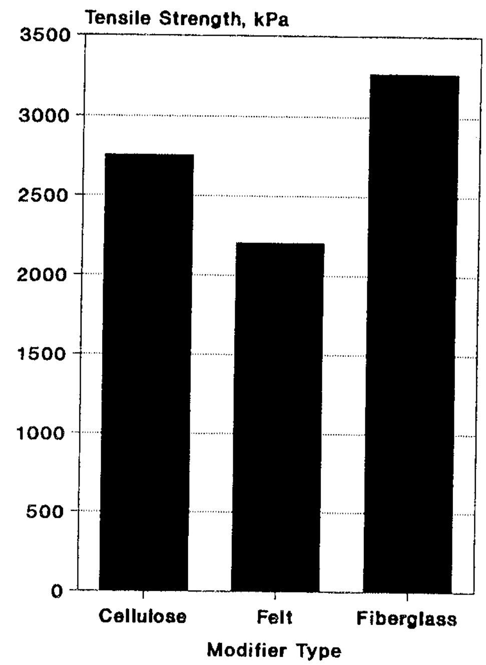

Figure 24. Low Temperature Properties (Peak Tensile Strength) for SMA Mixtures

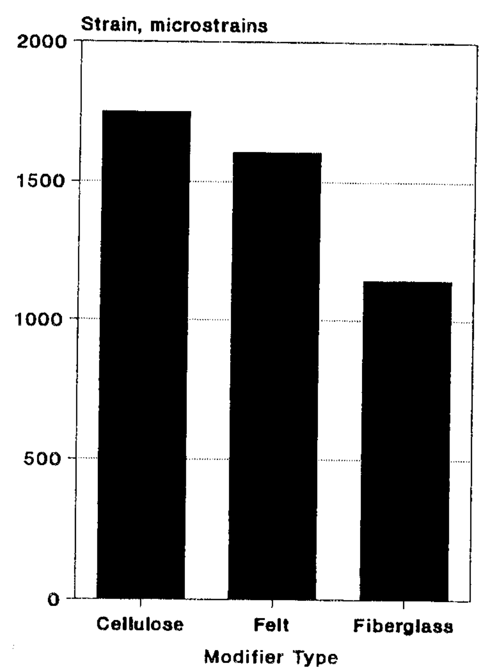

Figure 25. Low Temperature Properties (Strain at Peak Stress) for SMA Mixtures.

Permanent Deformation Characteristics

Dense Graded Mixtures: The data for these samples are shown in Table 25, and illustrated in Figures 26 through 28. Creep compliance is defined as the axial strain at some point in time over the center third of the sample divided by the applied stress. Therefore, a higher creep compliance indicates a greater tendency for deformation. Compliances were calculated at a time of 30 minutes past the beginning of the one hour creep phase of the test. Note that the values appearing in Table 25 were obtained by averaging the creep compliance values of two samples.

One trend readily apparent from the data is that, with one exception (felt shingles with 120/150 pen asphalt), the 30 minute creep compliance at the 7.5% shingle level was higher (indicating greater strain) than at the 5% level for the 25° C samples. This trend is reversed for the 40° C samples; the 7.5% shingle modified specimens exhibited lower creep compliances at 30 minutes. Also note that while the 85/100 unmodified samples had a lower creep compliance than all the shingle modified samples using 85/100 asphalt cement, samples prepared with 120/150 asphalt cement tend to display the opposite behavior (i.e. the creep compliance of the modified mixtures is generally lower than the control mixture). This suggests that the addition of shingles to mixes with the softer 120/150 pen asphalt improved the resistance to permanent deformation, while adding shingles to the harder 85/100 pen asphalt samples had the opposite effect.

Figure 28 shows a typical plot of creep compliance versus time in which many of these trends can be observed. The graph shows the creep compliance curves for mixes using 120/150 pen asphalt cement and fiberglass shingles. Note the instability in the 40° C control mixture; this type of behavior was observed in several of the specimens and indicates the onset of failure of the sample.

In general, samples tested at 40° C exhibited higher creep compliances than those tested at 25° C, for the same asphalt grade and shingle modification (Figures 26 and 27), as expected. However, there were a few exceptions to this, notably with the addition of 7.5% re-roof shingles. Further investigation is required to ascertain the cause of this anomaly.

Table 25. Creep Compliance for Dense Graded Mixtures

AC Grade	Shingle Type	Shingle Percent	Creep Compliance, Pa^{-1}, 30 min	
			25°C (77°F)	40°C (104°F)
120/150	Control	0	0.016050	0.043644
	Felt	5	0.025427	0.023714
		7.5	0.011957	0.020828
	Fiberglass	5	0.009080	0.019853
		7.5	0.010581	0.014377
	Re-Roof	5	0.010591	0.013850
		7.5	0.021956	0.009965
85/100	Control	0	0.008697	0.013569
	Felt	5	0.010513	0.039824
		7.5	0.014858	0.030800
	Fiberglass	5	0.009647	0.020432
		7.5	0.014958	0.014389
	Re-Roof	5	0.009897	0.014700
		7.5	0.020751	0.010901

To summarize, the following conclusions about permanent deformation behavior of dense graded mixtures are made:

1. The addition of shingles to dense graded mixtures tended to increase the 30 minute creep compliance for samples prepared with 85/100 asphalt cement, while the reverse tended to be true, with some exceptions, for mixtures prepared with 120/150 asphalt cement. Thus, it appears that improvements to permanent deformation resistance are dependent upon the properties of the neat asphalt added to the mixture.

2. At 25° C, an increase in the percentage of shingles in the mixture from 5 to 7.5 percent tended to lead to an increase in creep compliance (i.e. a "softer" sample). This was particularly true in the case of samples mixed with 85/100 pen asphalt cement.

3. At 40° C, an increase in the percentage of shingles led to a decrease in creep compliance (i.e., a "stiffer" mix).

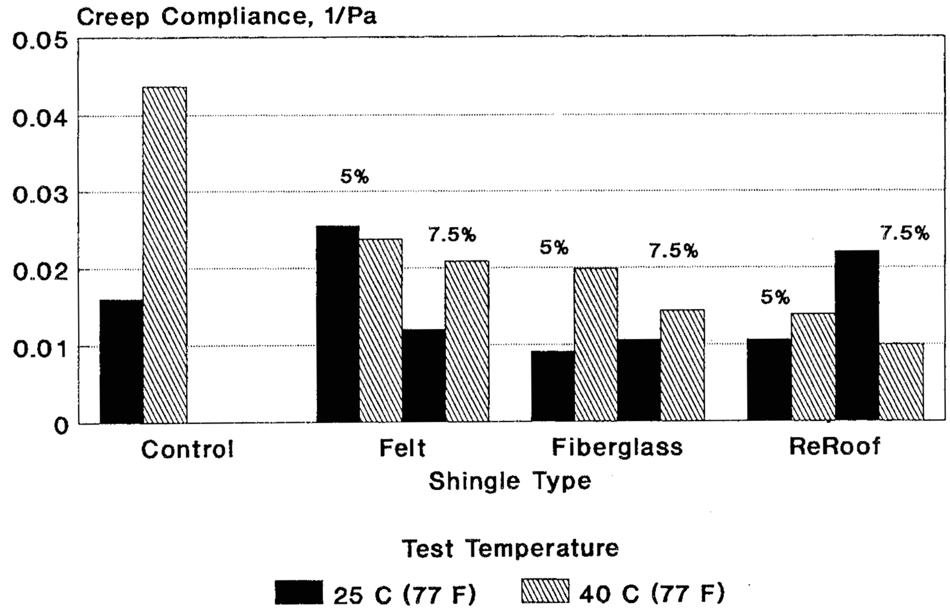

Figure 26. Creep Compliance for Dense Graded Mixtures, 120/150 AC.

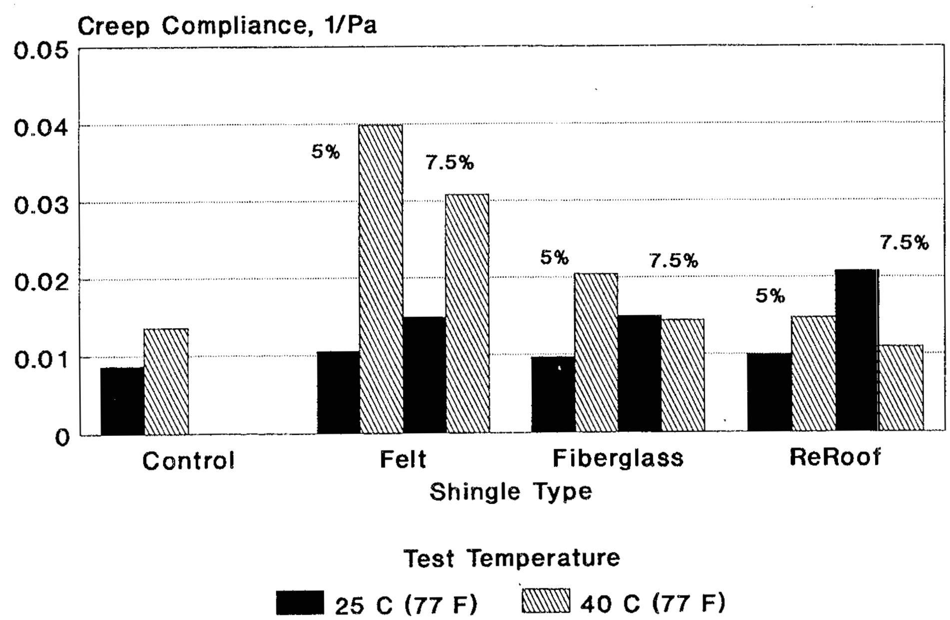

Figure 27. Creep Compliance for Dense Graded Mixtures, 85/100 AC.

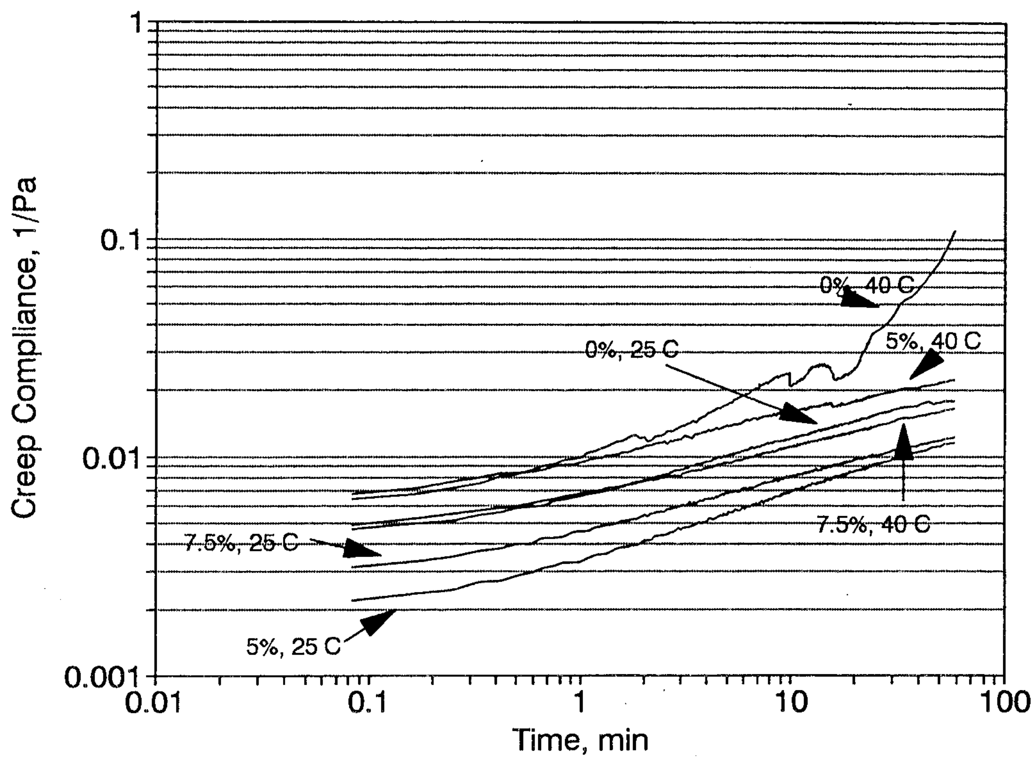

Figure 28. Creep Compliance Curves for Dense Graded Mixtures, Fiberglass Shingles, 120/150 AC.

4. Creep compliance at 40° C was generally higher than at 25° C. There were a few exceptions to this, however, especially in mixtures prepared with 7.5% re-roof waste.

SMA Mixtures: The testing program for the SMA mixes was the same as for the dense graded samples, except that only 85/100 pen grade asphalt cement was used. Also, a set of samples was tested under confining pressure. These samples were tested at 25° C in a triaxial chamber under 100 kPa (14.5 psi) confining pressure. The data from these tests are presented in Table 26, and Figures 29 and 30.

Table 26. Creep Compliance for SMA Mixtures

Modifier Type	Modifier Percent	Creep Compliance, Pa^{-1}, 30 min		
		Unconfined, 25°C (77°F)	Confined, 25°C (77°F)	Unconfined, 40°C (104°F)
Cellulose Fibers	0.3	0.024233	NA	0.063659
Felt Shingles	10	0.039427	0.031755	0.065395
Fiberglass Shingles	10	0.018369	0.015170	0.061288

Samples mixed with felt shingles exhibited a higher 30 minute unconfined creep compliance at 25° C than did samples mixed with either fiberglass shingles or cellulose fibers. This agreed with trends observed in the dense grades samples.

No data were available for the confined creep tests on the cellulose fiber modified samples proved. However, it can be seen that again, the felt shingle mixes had a higher creep compliance than did the fiberglass mixtures at 25° C.

At 40°C, all three mixture types exhibited similar deformation. The 30 minute creep compliance was higher than the 25° C compliance results. It was qualitatively observed during the testing that these samples tended to deform at approximately the same rate throughout the one-hour test period, as compared to the other specimens (both dense graded and SMA), which tended to "level off" somewhat after an initial period of high deformation rates. This behavior can be observed in Figure 29, which is a plot of creep compliance versus time for SMA mixtures modified with fiberglass shingles.

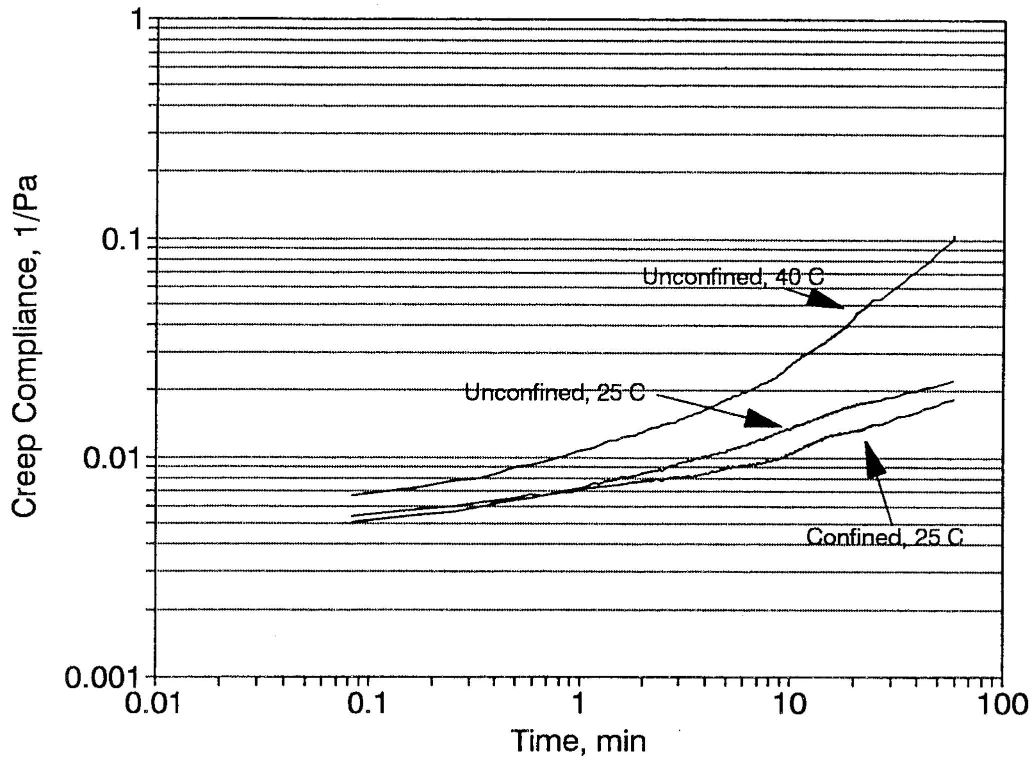

Figure 29. Creep Compliance Curves for SMA Mixtures, Fiberglass Shingles.

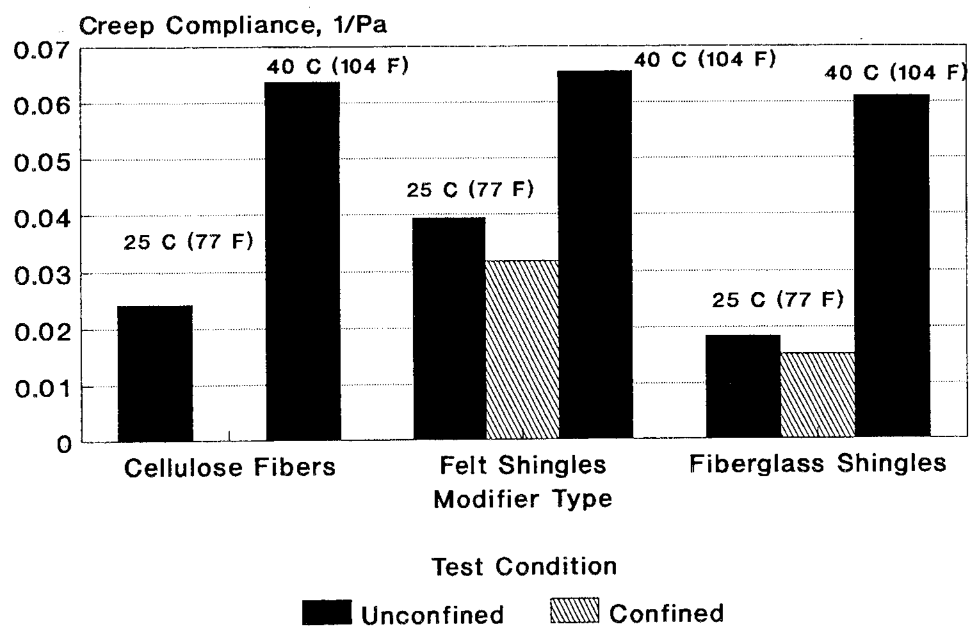

Figure 30. Creep Compliance for SMA Mixtures

In summary, the following conclusions about the permanent deformation characteristics of SMA mixtures are made:

1. At 25° C, the felt shingle modified mixes exhibited a significantly higher creep compliance than either the fiberglass shingle or cellulose fiber modified mixes. This was observed for both the confined and unconfined static creep tests, although no data were available for the cellulose modified mixtures in the confined test.

2. The creep compliance at 40°C was roughly the same for all three SMA mixtures. It might be expected that the shingle modified SMA's would behave similar to the conventional SMA mixture in the field.

3. The creep compliance at 40°C was significantly higher than the compliance at 25°C for all three SMA mixtures.

FIELD MIXTURES

Roofing waste modified asphalt concrete mixtures are currently used in Wright County, Minnesota as patching materials. A sample of these materials was obtained through the Wright County Engineering Department. This section will present a brief comparison between mixture properties for laboratory-prepared and commercially available roofing waste modified asphalt concrete mixtures.

Materials

Information as to the material composition of this sample was obtained from the original mix design data prepared by Braun for Omann Brothers Construction, November 19, 1990.

Asphalt

The neat asphalt cement added to the mixture was a 120/150 penetration grade material. Neither the binder properties nor source of the binder were noted in the mix design report.

Aggregate

Three stockpiles were used: 10 percent coarse aggregate, 17 percent intermediate aggregate, and 67 percent fine aggregate. The aggregate sources were not noted. Aggregate testing was limited to gradation only. Table 9 shows the combined aggregate gradation. Figure 31 shows a comparison between the gradations of laboratory-prepared and field mixtures. While there were some differences between the gradations, there is generally a good agreement between the two gradations.

Roofing Waste

The roofing waste used to prepare mixtures for Wright County is a mixture of both the felt and fiberglass manufacturing waste shingles generated by Certainteed Corporation's Shakopee, Minnesota facility. Based upon the predominance of the felt shingles being manufactured by Certainteed at this plant, it is estimated that the stockpile of shingles used was also predominately felt shingles.

Field mixtures used 6 percent mixed shingles by weight of aggregate. The extracted bitumen content of the shingles was 20.10 percent by weight of shingles.

Mixture Design

The mixture design reported by Braun Intertec is shown in Table 27 as well as a summary of the laboratory mix designs from the previous section. There are several differences evident between the field and laboratory mix designs. First, the field mixtures were prepared with a 50 blow mix design while the laboratory-prepared samples used a 75 blow design. Also, the optimum asphalt contents were significantly lower for the laboratory-prepared samples, ranging from 2.9 to 3.9 percent neat asphalt, as compared to the field mixture (5.2 percent). The stabilities for the field mixture (4.1 kN (930 lb)) were substantially lower than for any of the laboratory-prepared samples which range from 11.0 kN to 19.0 kN (2466 to 4264 lb). The unit weight of the field mix was also substantially lower (2207 kg/m^3 (138 pcf)) as compared to the laboratory-prepared samples (2363 to 2389 kg/m^3 (147.7 to 149.3 pcf)). The VMA was substantially higher for the field mixtures (18.1 percent) compared to the laboratory-prepared mixtures (ranging form 12.2 to 15.0 percent). A portion of these differences can be attributed to the difference in the compactive effort used to prepare the mix design samples. However, most of these differences are more likely attributable to differences in aggregate source than design method.

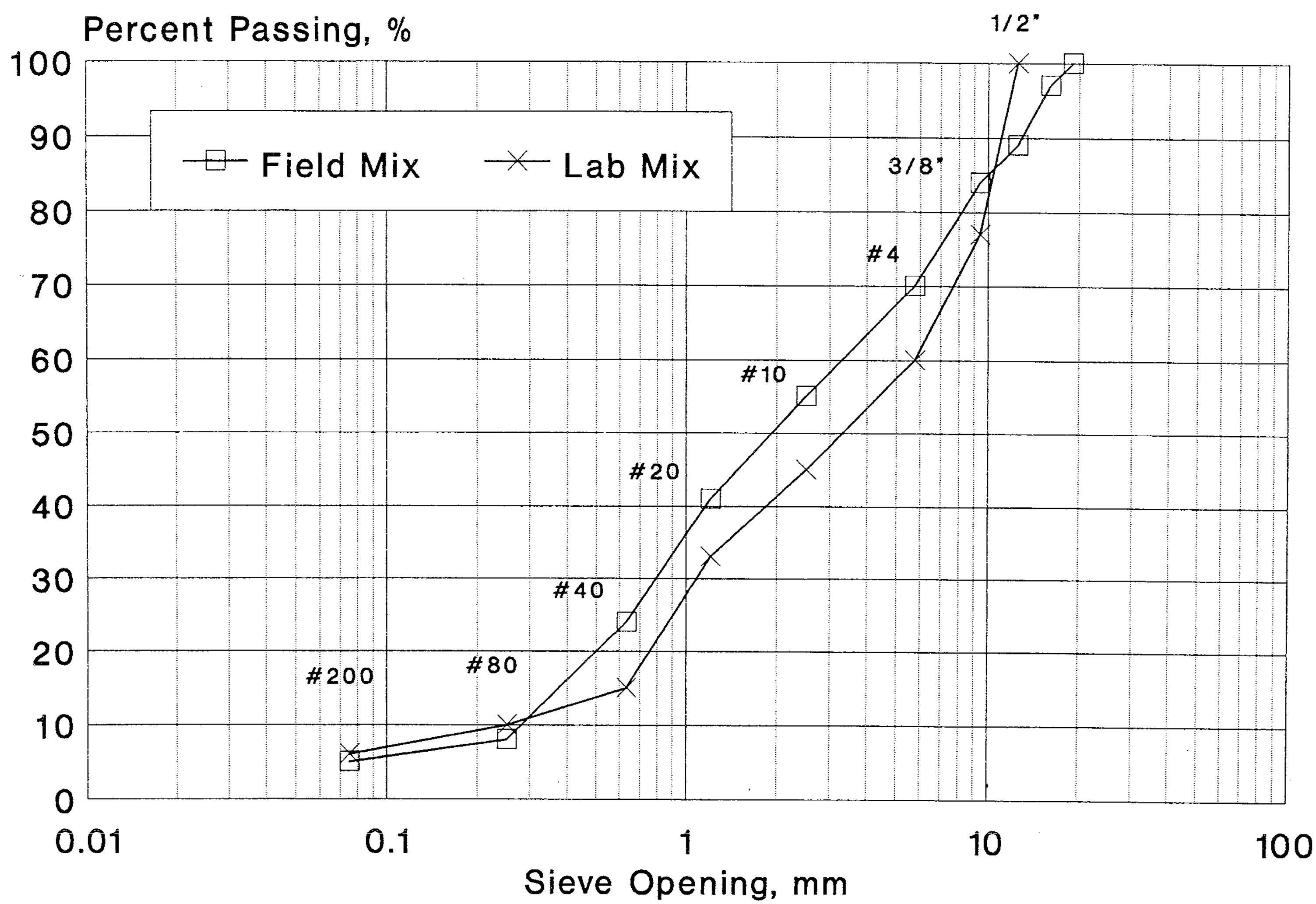

Figure 31. Gradation Bands for Field and Lab Mixes.

Table 27. Mix Design Test Results.

Mixture	Shingle Type	Percent	Marshall Mix Design Test Results At Optimum Asphalt Cement Content					
			Opt. AC %TWM	Air Voids (%)	VMA (%)	Marshall Stability (lb.)	Marshall Flow (0.01-in)	Unit Wt. (pcf)
Field[1]	Mixed	6%	5.2	6.0	18.1	930	9.7	138.0
Lab[2]	Control	0%	4.1	4.0	14.5	3115	10.0	150.2
	Felt	5%	3.9	3.6	13.9	3407	9.0	148.1
		7.5%	3.9	3.9	15.0	2466	12.0	147.7
	Fiberglass	5%	3.4	3.9	12.8	4264	9.0	149.3
		7.5%	2.9	4.3	12.2	4142	7.0	149.3
Mn/DOT[1]	NA	NA	NA	3 - 7	NA	500 - 3000	NA	NA

NA: Not Applicable
1: 50 Blow Marshall mix design
2: 75 Blow Marshall mix design

Mixture Analysis

The same testing sequence was followed for evaluating temperature susceptibility, moisture sensitivity, and low temperature behavior. Permanent deformation was not evaluated as there was insufficient material for preparing the large samples needed for this testing.

Temperature Susceptibility

The data are shown in Table 28 and Figures 32 and 33. It can be seen that the field mix resilient modulus versus temperature relationship most closely followed that for the 5 percent felt-backed shingle laboratory-prepared samples. This agrees with the premise that the majority of the shingles in the mixed roofing stockpiles used for the field mixtures are primarily felt-backed shingles.

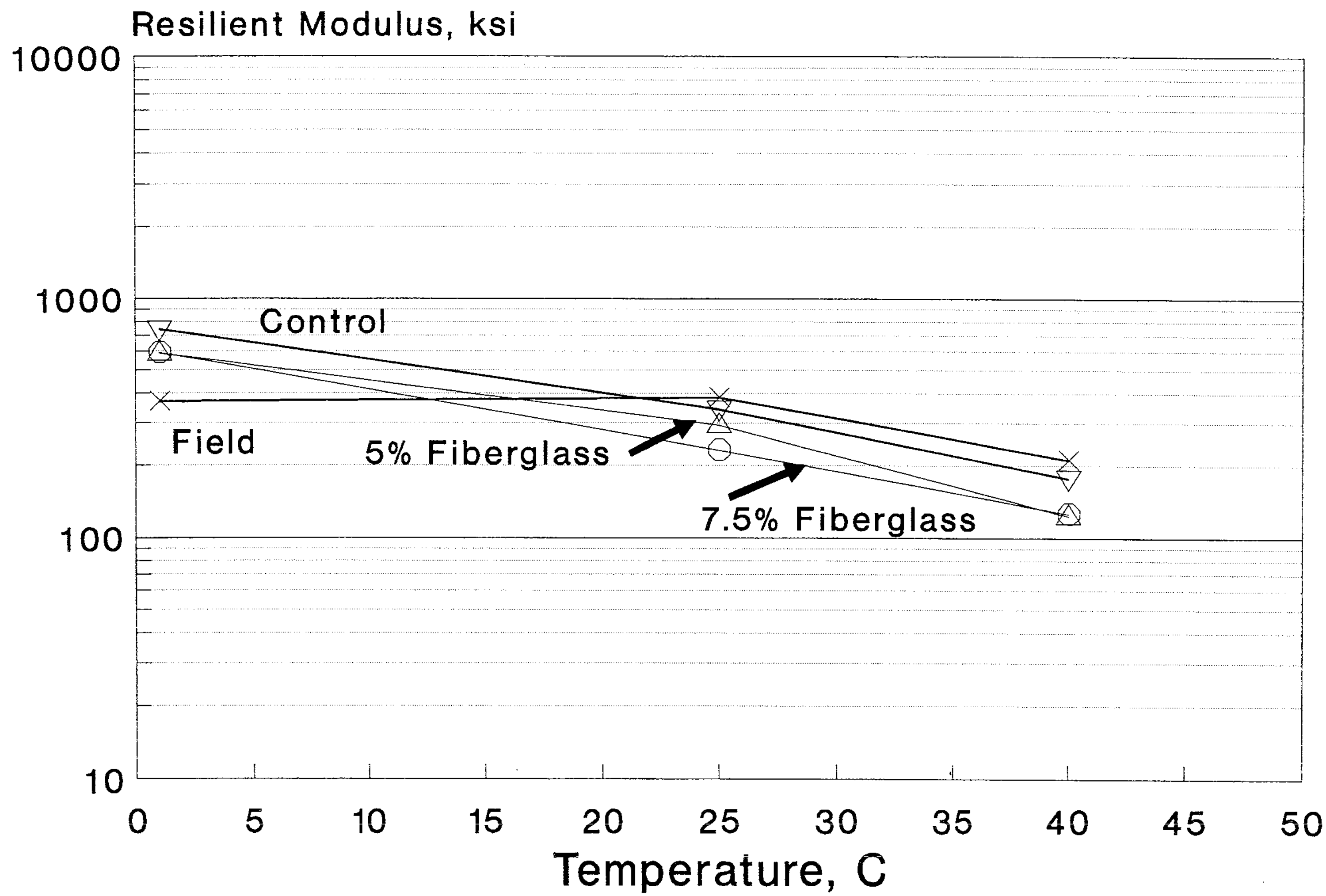

Figure 32. Temperature Susceptibility.

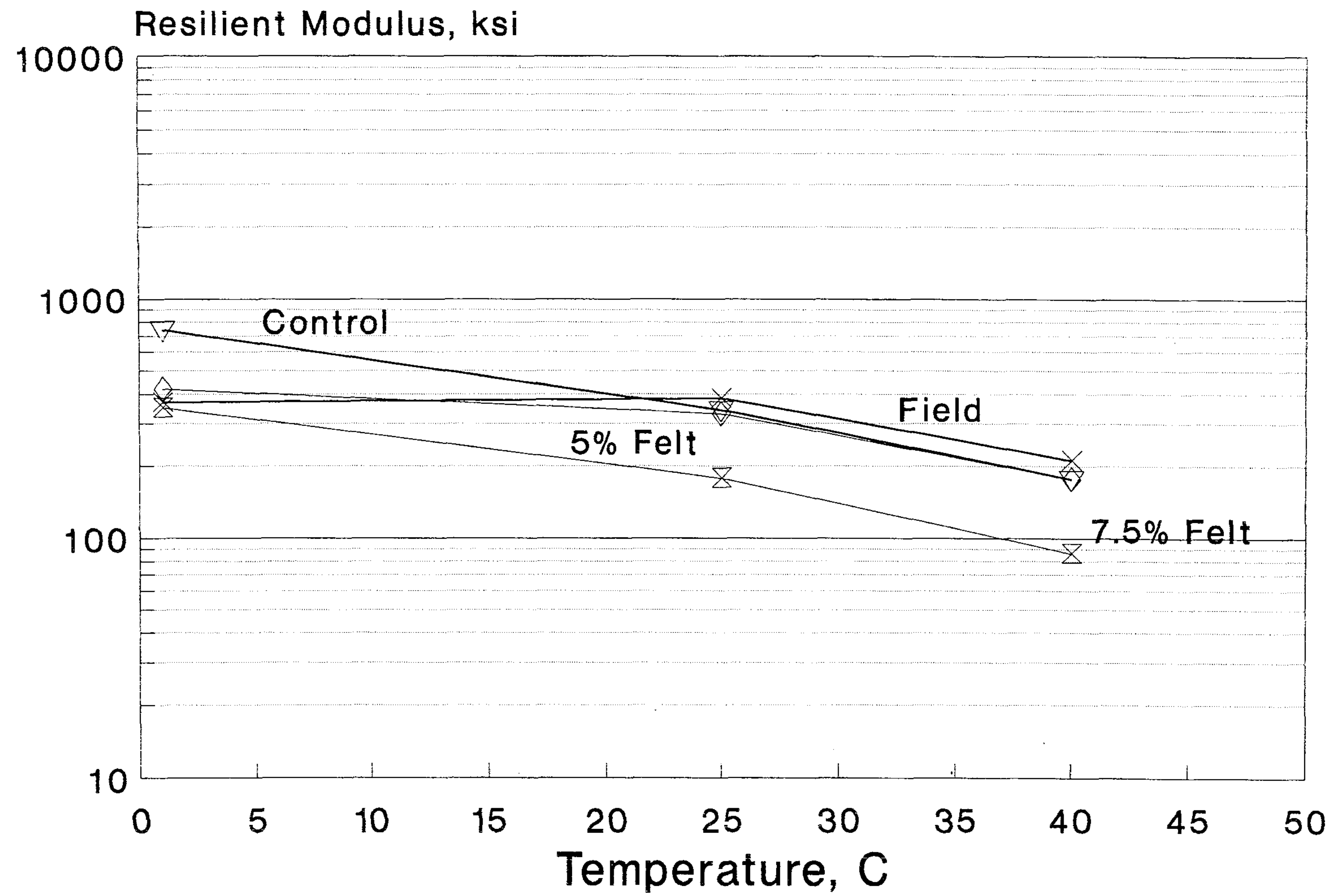

Figure 33. Temperature Susceptibility.

Table 28. Resilient Modulus Test Results.

Mixture	Sample No.		Resilient Modulus, ksi 1°C	25°C	40°C
Field 6% Mixed Shingles 120/150 Pen	1		359	364	201
	2		386	NA	228
	3		365	401	207
	Average		370	383	212
Laboratory 120/150 Pen Koch Refinery	0% (Average)	None (Control)	741	343	177
	5% Shingles (Average)	Felt	421	329	177
		Fiberglass	589	294	123
	7.5% Shingles (Average)	Felt	350	178	86
		Fiberglass	590	232	126

Note: All mixtures used the same grade of binder (i.e., 120/150) but the source for the field mix is not known. Also, while the gradations are similar, the aggregate sources are different between the field and laboratory mixtures.

Moisture Sensitivity

Table 29 and Figures 34 through 36 present the results of the unconditioned and conditioned resilient moduli, tensile strengths, and corresponding ratios, respectively. The field mixture had an unconditioned 1758 MPa (255 ksi) and conditioned moduli 848 MPa (123 ksi) between the values for laboratory-prepared samples containing felt-backed shingles and the 5 percent level of fiberglass.

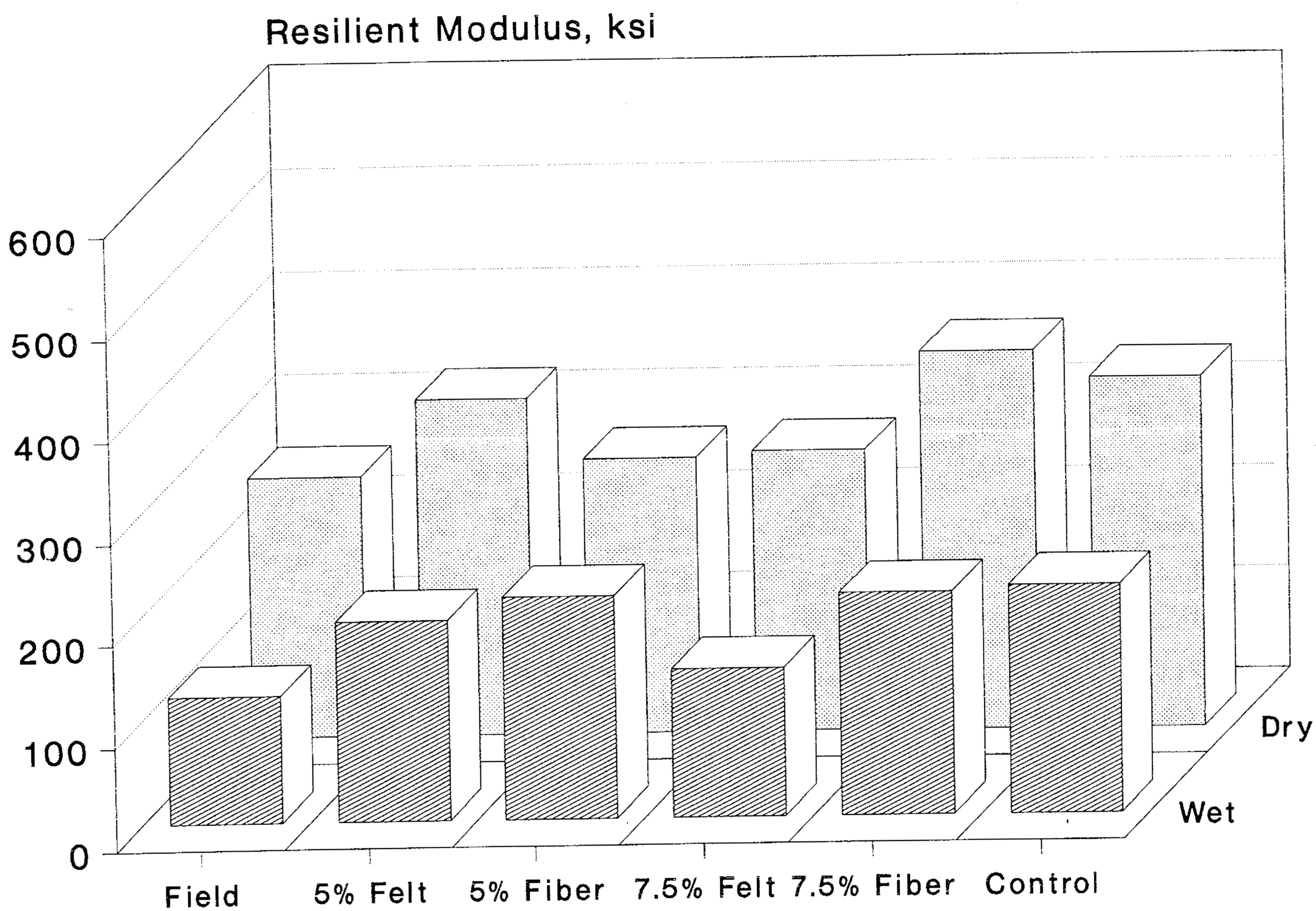

Figure 34. Moisture Sensitivity (Resilient Moduli Values).

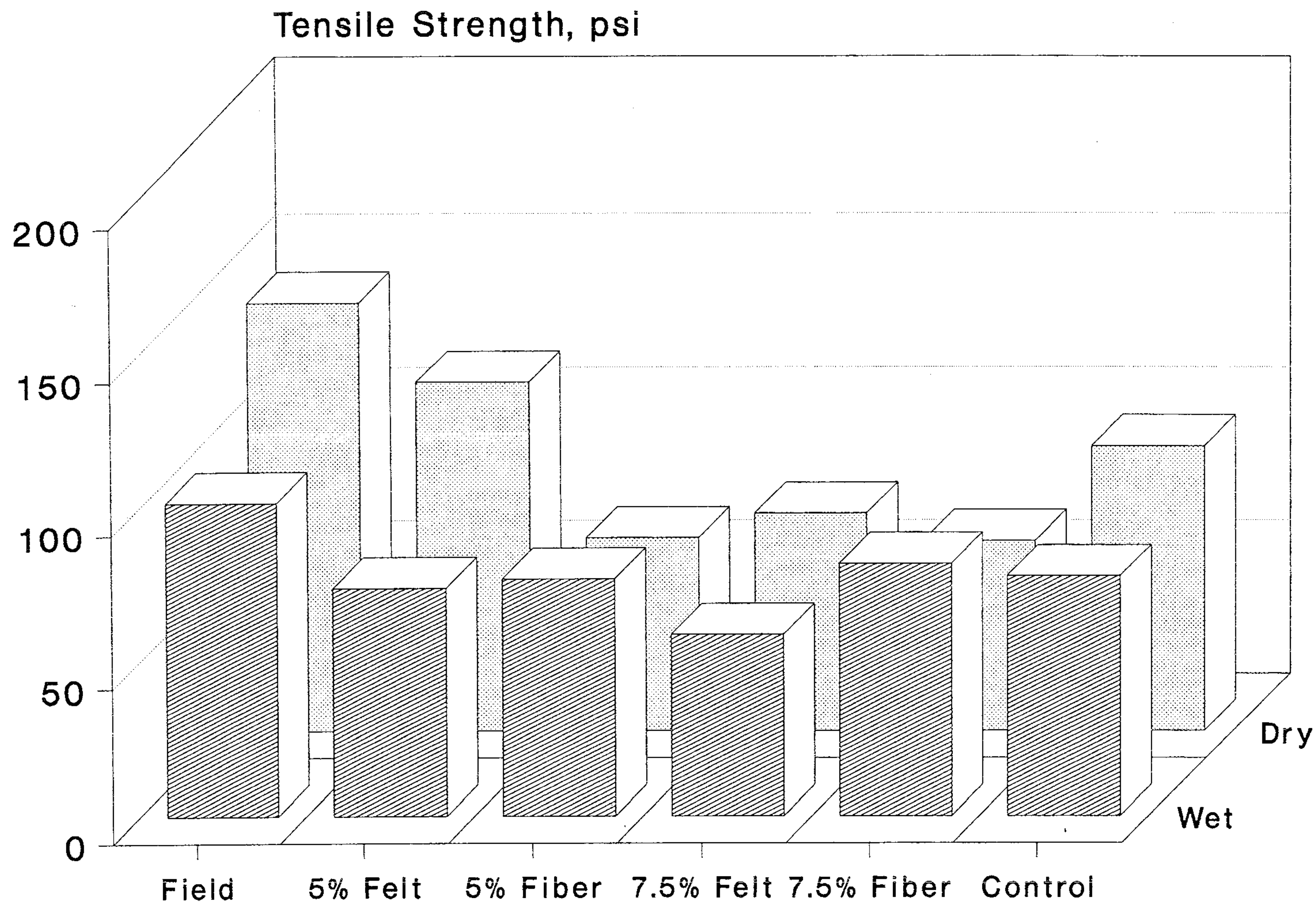

Figure 35. Moisture Sensitivity (Tensile Strength Values).

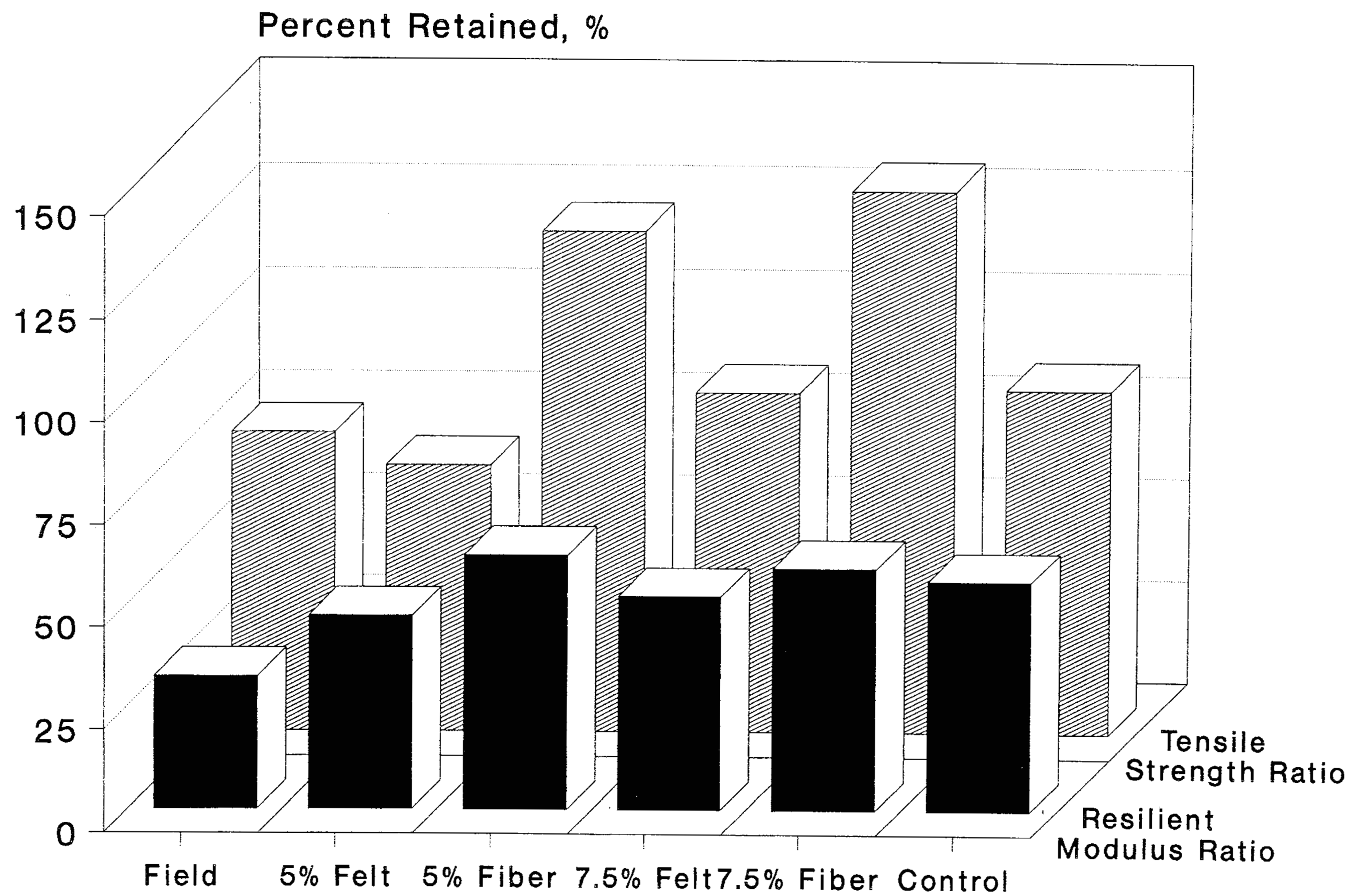

Figure 36. Moisture Sensitivity (Ratios).

Table 29. Moisture Sensitivity Test Results.

Mixture	Sample No.		Air Voids (%)	Resilient Modulus, ksi			Tensile Strength, psi		
				77°F Dry	77°F Wet	Ratio	77°F Dry	77°F Wet	Ratio
Field 6% Shingles 120/150 Pen	1		6.7	364	117	32	NA	104	74
	2		7.4	NA	NA	NA	140	NA	NA
	3		6.9	401	127	32	NA	99	71
	Average		7.0	255	123	32	140	0	73
Laboratory 120/150 Pen Koch Refinery	0% (Average)	None (Control)	9.3	396	223	56	NA	79	NA
	5% Shingles (Average)	Felt	8.2	329	195	47	114	74	65
		Fiberglass	9.7	369	217	62	63	77	122
	7.5% Shingles (Average)	Felt	11.3	275	144	52	71	59	83
		Fiberglass	11.1	370	217	59	62	82	132

NA: Data not available

Both the unconditioned and conditioned tensile strength values were substantially greater than any seen for the laboratory-prepared mixtures. This could be a function of such factors as increased neat binder content, differences in field (i.e., plant) and laboratory mixing processes, and aggregate source. While the absolute tensile strength values for the field mixture was greater, the conditioned tensile strength was less than the unconditioned strength. Again, this would indicate that the roofing waste product in the field mix was exhibiting similar trends as properties of the felt-backed laboratory-prepared samples. If the fiberglass shingles were dominate, an increase in the conditioned tensile strength would be expected. This is supported by a comparison of the ratios shown in Figure 36.

Low Temperature Behavior

The data are shown in Table 30 and Figure 37. The cold tensile strength of the field mixture is greater (397 psi) than any of the laboratory-prepared mixtures. The corresponding strain is roughly 50 to 75 percent lower than for the laboratory specimens.

Table 30. Low Temperature Behavior.

Mixture	Shingle Type	Percent Shingles	-18°C Properties, 0.01-in/min			1°C, 0.01-in/min		
			Max. Tensile Strength (psi)	Strain at Max. Strength (in/in)	Horizontal Strain Energy (psi-in/in)	Max. Tensile Strength (psi)	Strain at Max. Strength (in/in)	Horizontal Strain Energy (psi-in/in)
Field	Mixed	6%	422	0.000324	0.0923	171	0.000863	0.3695
			404	0.000238	0.0604	160	0.000918	0.4904
			365	0.001130	0.3982	147	0.000981	0.4183
		Average	397	0.000564	0.1836	159	0.000921	0.4261
Lab	Control	0%	385	0.001727	0.454	No Data Available		
	Felt	5%	335	0.001571	0.2873			
		7.5%	222	0.001685	0.2337			
	Fiberglass	5%	286	0.001090	0.1819			
		7.5%	265	0.001156	0.1725			

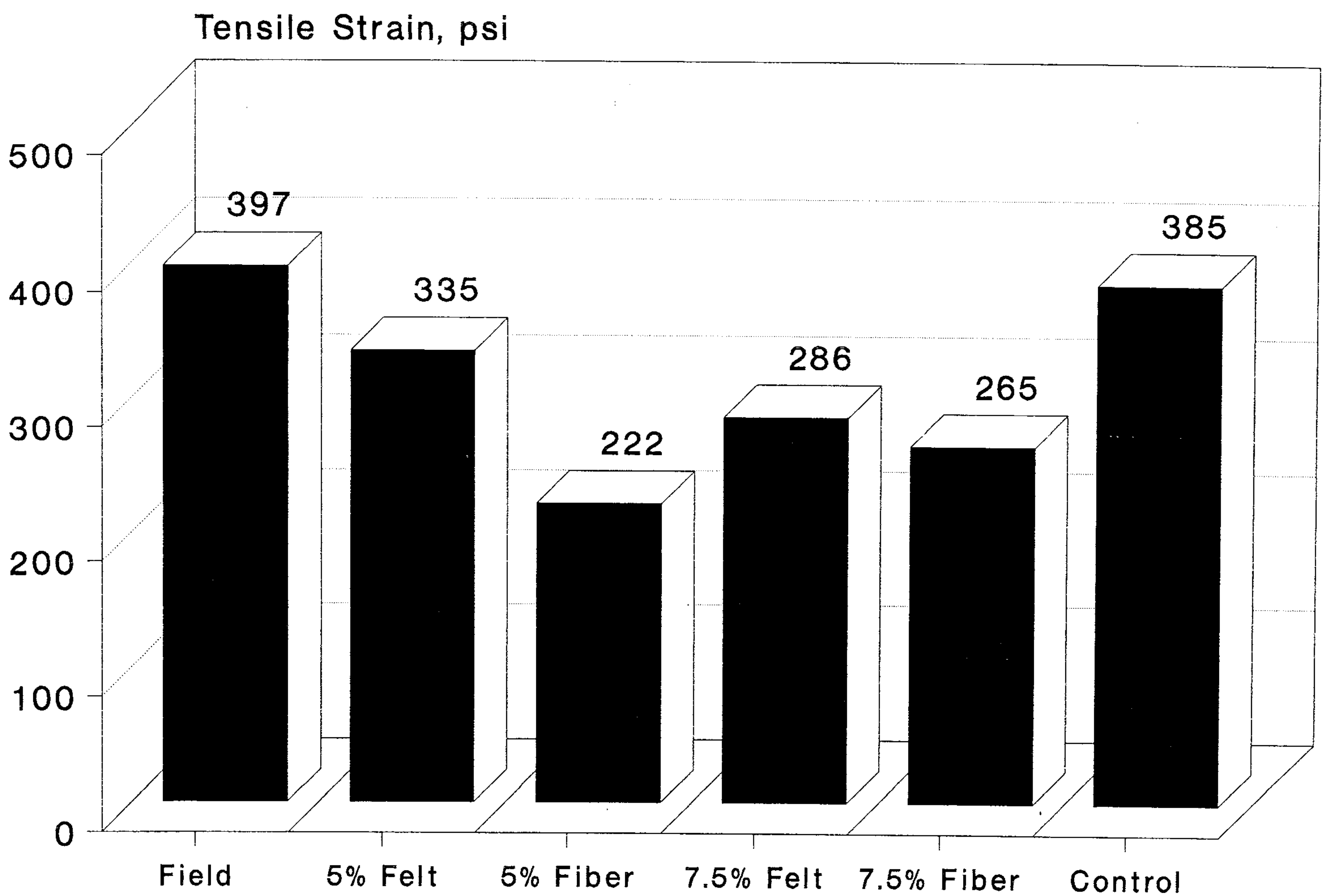

Figure 37. Low Temperature Tensile Strength.
(-18C, 0.01-in/min)

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

There are numerous potential benefits which could result from the use of waste shingle material in asphalt mixtures. Some of the these include:

1. A reduction in the cost of shingle waste disposal.
2. An environmental benefit resulting from the conservation of landfill space.
3. A reduced cost in the production of hot mix asphalt concrete resulting from reduction in the use of new materials.
4. An improved resistance to pavement cracking due to the reinforcement provided by fibers in the shingles.
5. An improved resistance to pavement rutting due to a combination of the fibers and harder asphalt used in the shingles.

The testing program presented herein was designed to define the properties of the materials relevant to pavement performance. The roofing waste mixtures were tested along with control mixtures in order to ascertain their characteristics relative to each other. The first part of the project was designing the dense-graded mixtures using the Marshall method. Examining the effects of the roofing shingles on the volumetric proportions and compaction behavior was the purpose of this exercise. The elastic behavior or stiffness of the mixtures at various temperatures was characterized using the resilient modulus test. Moisture sensitivity was evaluated using a modified Lottman conditioning procedure. The resistance to cold temperature cracking was examined using an indirect tensile test performed at a slow rate of loading in order to simulate volumetric changes induced by daily temperature changes. The tensile strength and tensile strain at the peak stress were the parameters used in this evaluation. The susceptibility of the materials to permanent deformation (rutting) was evaluated by creep testing; uniaxial for the dense-graded mixtures and uniaxial with confining pressure for the SMA mixtures. A field mixture obtained from Wright County was subjected to the same sort of testing sequence as the laboratory mixtures.

Based upon the results presented in this report, the following conclusions are made:

Laboratory-Prepared Samples

1. The use of roofing shingles can result in a reduction in optimum binder content. However, this appears to be dependent upon the source of the shingles: little reduction was achieved with the felt-backed shingles while a reduction of 10 to 25 percent of the unmodified optimum binder content was obtained with 5 and 7.5 percent, respectively of either the fiberglass or re-roof shingles.
2. The use of roofing shingles enhances the ability of the mixtures to densify under compactive effort.
3. The use of 5 percent of either the felt-backed or fiberglass shingles appears to result in a substantial decrease in temperature susceptibility at cold temperatures. This is true to a lesser extent when the re-roof shingles are used.
4. Percentages of shingles higher that 5 percent results in an overall decrease in mixture stiffness over a wide range of temperatures, while having little influence on the temperature susceptibility (i.e., slope of the log resilient modulus versus temperature relationship). This may be undesirable in some applications were the material is subject to high stresses at high temperatures such as the surface course on a high volume pavement.
5. The moisture sensitivity of the mixtures does not appear to be influenced by the use of felt-backed shingles. The use of fiberglass shingles consistently increases the after conditioned tensile strengths while having little impact on the conditioned resilient modulus. There is a significant increase in moisture sensitivity when the higher level (7.5 percent) of re-roof shingles were used.
6. The cold tensile strengths are reduced when shingles are added to the mixtures. The impact on the corresponding strains appear to be dependent upon the type of shingle used to modify the mixture. However, due to the differences in the optimum binder content between the types of shingles, it is possible that these

differences are a combined function of neat asphalt cement content and shingle type.

7. The permanent deformation characteristics are affected by the addition of shingles. The effect depends on the grade of asphalt cement used, and the type and amount of shingles added. When added to a mixture with a softer grade of asphalt, and improvement was noted. The opposite was noted when the 85/100 asphalt was used.

SMA Mixtures

1. Up to 10 percent manufactured roofing waste can be used in a stone-mastic application. The use of roofing waste can result in a reduction of the required neat binder content of the mixture from 25 to 40 percent of the unmodified optimum binder content.
2. SMA mixtures are less sensitive to compactive effort than conventional dense graded mixtures.
3. The resilient modulus of the three SMA mixtures did not vary significantly at 1 or 25°C. However, the fiberglass shingle material had a greater resilient modulus at 40°C.
4. The use of roofing waste in SMA appears to improve the moisture sensitivity of the mixtures.
5. The use of roofing waste lowers the cold tensile strengths of the mixtures. The corresponding strains are similar for mixtures with the felt-backed shingles and about 20 percent lower for mixtures with the fiberglass shingles. As with the dense graded mixtures, this is most likely a combined function of both the shingle type and the differences in the neat binder content.
6. The permanent deformation characteristics of SMA mixtures are greatly influenced by temperature. The effect of confining pressure on creep test results is small. Felt shingles tend to lead to greater creep deformations as compared to fiberglass shingles or cellulose fibers. This may indicate a greater potential for

permanent deformation problems in mixtures prepared with felt shingles, although the magnitude of these problems cannot be assessed without further pavement performance data.

Field Mixtures

1. The field mixture exhibited similar properties to laboratory-prepared samples, in particular mixtures with 5 and 7.5 percent of the felt-backed shingles. This agrees with the information on the type of shingle waste that was predominate in the shingle stockpile.
2. The inclusion of roofing waste reduced the mixture's stiffness at cold temperatures while producing similar stiffnesses at warmer temperatures; this indicates a decrease in temperature susceptibility. This conclusion agrees with the laboratory portion of the study.
3. Moisture sensitivity appears to be similar to laboratory-prepared samples. There is insufficient information on the sensitivity of non-roofing waste modified mixtures with the aggregate source used to prepare the field mix to draw a conclusion.
4. The low temperature behavior of the field mixture indicates that they exhibit a higher tensile strength and lower strain at maximum tensile stress than any of the laboratory prepared samples. The more brittle behavior of the field mix cannot be explained without knowing the source of the neat asphalt used in this mixture.

RECOMMENDATIONS

The following recommendations are made with regard to the use of roofing shingle waste in Minnesota asphalt mixtures:

1. The Minnesota Department of Transportation should produce a permissive specification which allows up to five percent manufactured roofing shingle waste

to be used in hot mix asphalt base courses on high-volume roads and in all hot mix asphalt layers on low volume roads. The use of this waste material should be dictated by economics which will be influenced by the transportation and processing costs. Contractors might be encouraged to try the material if they are allowed a bid premium for using it.

2. There are currently no facilities which process reroof scrap material in Minnesota. An economic incentive, such as the availability of low interest loans, might be used to encourage the development of such facilities. Another alternative would be to wait until the cost of placing this material in a landfill becomes higher than the cost of processing and reusing it. If this material becomes available, a thorough evaluation of the material should be conducted to ascertain whether it is more suitable than the reroof material used in this study. Care would need to be taken to assess the potential for asbestos dust when dealing with reroof scrap material.

3. The performance of projects built with processed shingle waste should be monitored through the Minnesota Department of Transportation's pavement management system to see if they differ from conventional materials.

4. A field trial should be constructed in which manufactured shingle waste is used in a stone mastic asphalt mixture. The performance and cost of this material should be compared against more conventional approaches to SMA. Based upon the laboratory results from this study, the shingle waste SMA should have a performance comparable to the conventional SMA.

5. Improved means of processing shingle waste should be developed to reduce the amount of moisture in the material. It was not proven conclusively in this study that the moisture in the material is harmful to the final product. However, from the standpoints of hot-mix plant efficiency and the assurance of the final product quality, it would be best to attempt to reduce the amount of water present in the shingle waste.

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