# EVALUATION OF THE BENEFITS OF ADDING WASTE FIBERGLASS ROOFING SHINGLES TO HOT-MIX ASPHALT



Prepared with Cooperation with

**THE OHIO DEPARTMENT OF TRANSPORTATION**

and

**THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION**

**FINAL REPORT**

by

CTL Engineering, Inc.
2860 Fisher Road
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16. Abstract

The decreased availability of landfills, growing concern over waste disposal, and rising cost of asphalt cement, resulted in an increased interest in incorporating waste asphalt roofing shingles in the production of asphalt concrete mixes. This project addressed Hot-Mix, surface course asphalt concrete mixes produced with an addition of waste fiberglass asphalt roofing shingles that were obtained from the shingle manufacturing process. A total of twenty-six asphalt concrete mixes were studied. The variables included: aggregate type, shingle producers, level of shingle addition (0,5,10, and 15%), and type of shingle size reduction. Properties of the produced asphalt concrete mixes were evaluated based on the results of applicable tests that were performed.
It was concluded that the asphalt concrete mixes made with the addition of fiberglass waste roofing shingles that were evaluated in this research project showed superior performance to that of conventional asphalt mixes in terms of improved structural capacity, resilient characteristics, and resistance to moisture induced damage. The use of these shingle mixes would produce pavements having improved serviceability by virtue of reduced temperature susceptibility, improved resilient characteristics, and reduced rutting and deformation. This study, however, was limited in its scope and did not include mixture properties below 0°C (32°F) and aging properties of these mixtures.

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## DISCLAIMER

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# CHAPTER 1

# INTRODUCTION

## 1.1. OVERVIEW.

The concept of recycling waste roofing shingles by incorporating them in asphalt concrete paving mixes is receiving greater attention by the engineering community as it looks for ways to combine pavement economy and good performance with a reduction in the amount of waste materials being placed in landfills. Although the introduction of waste roofing shingles into an asphalt concrete mixture appears to be a sound approach, the following questions need to be addressed before a responsible decision about such addition can be made.

1. What are the effects of the addition of waste roofing shingles on the physical properties of an asphalt concrete mix?

2. What is the optimum level of shingle addition for a given application?

3. How well does asphalt cement from shingles blend with virgin asphalt cement in an asphalt concrete mix?

Since increased use of recycled materials is expected to be the trend over time, a better understanding of the potential impact of waste roofing shingles on the physical properties of asphalt concrete pavement mixes is needed.

## 1.2. OBJECTIVES.

The objectives of this research project were to:

1. Determine the sources and approximate quantities of waste asphalt roofing shingles that are available in Ohio.

2. Evaluate the technical validity for use of waste shingle materials, derived from the manufacturing process, in asphalt concrete paving mixes.

3. Based on the findings from objectives 1 and 2, establish testing criteria and recommend design and material use guidelines for these mixes.

## 1.3. SCOPE OF WORK.

This project addressed Hot-Mix, surface course asphalt concrete mixes produced with the addition of waste asphalt roofing shingles that were obtained as scrap material from the shingle manufacturing process. Only fiberglass roofing shingles were used during this study.

## 1.4. RESEARCH APPROACH.

To achieve the objectives of this study, a survey of the availability of waste asphalt roofing shingle (WARS) materials in Ohio was conducted. Samples of asphalt concrete produced with and without the addition of WARS were prepared and tested. A total of twenty-six asphalt concrete mixes having various combinations of aggregate type, WARS addition levels, WARS origin, and size reduction method were evaluated. Properties of the produced asphalt concrete mixes were evaluated based on the results of applicable laboratory tests that were performed.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. GENERAL INFORMATION.

Approximately 75 percent of the waste generated in the United States each year is buried in landfills. The number of operating landfills is shrinking, as there were 1,300 fewer operating landfills in 1993 than in 1991 [1].

Due to strict environmental standards and filling of disposal sites beyond capacity, more than 11,000 disposal sites (mainly landfills) have closed since 1980. The decrease in availability of landfills and increased generation of waste materials have resulted (in some states) in extraordinarily high disposal fees. It is believed that as landfills become scarce, the tipping fees will reach a point where it will no longer be economical to dump the waste in landfills. Presently, such a situation can be found in eastern states such as New Jersey, where tipping fees are as high as $100 per ton [2].

Approximately 11 million tons of roofing shingle waste is generated in the United States each year. Ten million tons represent waste from roof replacement jobs, while one million tons represent scrap material from the manufacturing process. Without recycling alternatives, this amounts to 22 million cubic yards of waste [3]. The idea of incorporating waste asphalt roofing shingles into the production of asphalt concrete mixes would appear to be very promising, since both materials consist of the same types of components.

## 2.2. ASPHALT ROOFING SHINGLE COMPONENTS.

The general composition of asphalt roofing shingles is shown in Table 2.1. [4].

Table 2.1. Asphalt roofing shingle composition, %.

| Component | Shingle Type | | |
|---|---|---|---|
| | Organic | Fiberglass | Old |
| Asphalt | 30 | 13 | 31 |
| Filler | 26 | 40 | 25 |
| Granules | 33 | 38 | 32 |
| Mat | - | 2 | - |
| Felt | 10 | - | 12 |
| Cut-out | 1 | 1 | - |

In the shingle structure, a mat or felt serves as a supporting membrane, while asphalt cement is used as a saturant and coating. Fillers and granules are used as additional coating materials.

An organic modified paper, known as "felt", has been used for years as the supporting membrane for asphalt roofing shingles. This felt is composed primarily of cellulose fibers derived from recycled waste paper or wood chips, and is thicker and more absorbent than conventional paper. At one time, cotton or wool fibers derived from rags were added to the traditional paper felt, but since 1942 this practice has been discontinued.

As an alternative to the organic paper felt, an inorganic fiberglass supporting membrane, known as a "mat", was introduced to the roofing industry in the late 1950's. By the late 1970's, improved technology had made the fiberglass mat competitive with the paper felt. The thickness and unit weight of a fiberglass mat is usually much less than that of a paper felt. According to the Residential Asphalt Roofing Manual [5], a fiberglass mat may be 0.030 inches thick versus 0.055 inches for a paper felt, and weigh 2 to 3 pounds per 100 square feet versus 12 pounds for a paper felt.

One of the functions that must be performed by the asphalt cement used in the production of organic (paper felt) roofing shingles is that of saturating the felt fibers and filling the voids between them. This requires the asphalt to be soft and flexible at the beginning of the production process so that it can completely saturate the felt material. The second function of the asphalt cement is to coat the saturated felt and serve as the medium for incorporation of mineral surfacing. Asphalt used for coating is mixed with fillers that consist of finely pulverized minerals. To protect the shingle from damaging ultraviolet rays from the sun, small granules made from crushed rock are adhered to the sufrace coat of asphalt on the side of the shingle that will be exposed to weathering conditions. To prevent shingles from sticking to each other during manufacturing, transportation, and storage, the back surfaces of the shingles are covered with finely crushed minerals.

The asphalt content of fiberglass asphalt shingles is lower than the asphalt content of organic felt asphalt shingles. This lower asphalt cement content is a result of the elimination of the mat saturation process for fiberglass shingles .

## 2.3. USE OF WASTE ROOFING SHINGLES IN HIGHWAY APPLICATIONS.

Organic and fiberglass roofing shingles are the two types that are currently produced in the United States and are available as scrap from manufacturing processes. A third type, called "old" shingles, produced 15 to 20 years ago, is now commonly available from roof replacement jobs.

According to available information, waste asphalt shingles, after proper preparation, have been used in the production of both cold and hot asphalt concrete mixes. Cold-mixes are used routinely by municipalities in the Eastern United States as material to patch potholes in ramps and bridges, maintain parking lots and driveways, fill utility cuts, and serve as a subbase material.

Presently, ReClaim, Inc. is one of the nation's leading companies that recycle discarded asphalt roofing shingles. The company offers two patented products: RePave™, which is a pothole patching material, and ReActs™, which is an additive for asphalt concrete mixes. RePave™ contains 20% dry roofing material, 77% stone, and

3% solvents [6].

According to the Department of Public Works for City of Bayonne, New Jersey, RePave™ offers a cost savings of up to 80 % over conventional pothole repair methods [2,7]. The New Jersey DOT tested RePave™ over a period of 18 months and found its performance to be satisfactory [2,8].

In the fall of 1990, the City of Chicago placed on the city streets about 15 tons of Asphalt Recovery Systems cold patch material that consisted primarily of waste roofing shingle. The experience of Cook County, Illinois, with this type of cold patching material was favorable and resulted in wide use of it on county roads [9]. Granulated or shredded reclaimed asphalt shingles were introduced as a 5 to 10% (by weight) additive into hot-mix asphalt concrete. In the past few years, several road and parking lot sections incorporating waste shingles have been constructed and their performance is being monitored on a continuing basis.

In Florida, a mix with 10% asphalt shingles was used at the Disney World parking lot near Orlando; thus far, the parking lot has exhibited excellent performance. In the same vicinity, an entrance drive to the parking lot of an asphalt plant was paved with a mix containing waste shingles and is reported to have performed much better than conventional asphalt mixes [4].

ReActs™ has been suggested as an additive to Hot-Mix Asphalt (HMA) at a level of up to 20% by weight. Its suggested benefits beside reduction of the virgin materials include increased stability and better performance; reduced fatigue cracking, rutting, shoving, and raveling; and longer life expectancy [10].

The gradation for ReActs™ is presented in Table 2.2.

Table 2.2. Typical gradation for ReActs™.

| Sieve No. | % Passing by Weight |
|---|---|
| 4 | 100 |
| 8 | 100 |
| 20 | 90 min. |
| 70 | 10 max. |
| 100 | 5 max. |

Preparation of reclaimed asphalt shingles that are to be recycled can be divided into two steps. The first step is necessary for roof tear-off materials, and consists of separation of the lumber and other heavier debris beforehand, and removal of nails and other foreign particles by passing the material through a system of magnets. The second step is common for waste material from all sources, and involves the process of granulating or shredding the shingles to a maximum size of 12.5 mm prior to incorporation in the HMA to ensure meltdown and uniform dispersion [3,11,12,13].

ReClaim uses a proprietary mechanical process to recycle roofing material into RePave™ and ReActs™ HMA. The company obtains its material from three sources:

residential roofing, commercial roofing, and plants that produce roofing scrap. In New Jersey, ReClaim has more than 1,400 roofers as clients and more than 100 haulers who bring their material to one of its facilities or 20 drop-off sites. Residents also may leave roofing material at the drop-off sites [2]. In New Jersey, about 600,000 tons of asphalt-based roofing material waste is generated annually, and about 60,000 tons are recycled annually by ReClaim. The New Jersey DOT conducted limited testing on ReActs™ which included extraction and Abson recovery testing and a preliminary mix design [8]. The mix had 10% ReActs™ and the optimum asphalt content was 6.5%, of which 3% was virgin asphalt (AC-20) and the remaining 3.5% was provided by the ReActs™ material. The test data obtained from the NJDOT experiments is presented in Tables 2.3, 2.4, and 2.5.

Table 2.3.ReActs™ gradation before and after extraction of asphalt.

| Sieve No. | % Passing by Weight | |
|---|---|---|
| | As Received | After Extraction |
| 4 | 100 | 100 |
| 8 | 99.7 | 100 |
| 30 | 50.3 | 58 |
| 50 | 20.4 | 37.6 |
| 100 | 6.3 | 26.8 |
| 200 | 2.9 | 19.1 |
| % Asphalt | ---- | 28.6 |

Table 2.4.Penetration, viscosity, and ductility of asphalt recovered from ReActs™.

| Property | 100% ReActs™ AC | 54% ReActs™ AC, 46% AC 20 |
|---|---|---|
| Pen. @ 77°F (0.1 mm) | 6 | 20 |
| Absolute Viscosity @ 140°F (poises) | ---- | 607,405 |
| Kinematic Viscosity @ 275°F (centistoke) | ---- | 4112 |
| Ductility @ 77°F (cm) | ---- | 4.75 |

Table 2.5. Marshall test data for mixes with 10% addition (by weight) of ReActs™.

| Marshall Test | Design |
|---|---|
| Stability, lbs. (N) | 5073 (22,565) |
| Flow, 0.01 in. (mm) | 13 (3.3) |
| Air Voids (%) | 4.4 |
| VMA (%) | 20.35 |
| VFA (%) | 78.4 |
| $G_{mm}$ | 2.630 |
| lbs./cft | 156.8 |

ReActs™ was used in the construction of a road section near Philadelphia, Pennsylvania [3]. Specification approval regarding ReActs™ is pending with the Pennsylvania, New Jersey, and New York Departments of Transportation.

Canada is the world's largest exporter of asphalt shingles, and IKO Industries Limited, a roofing shingle manufacturer, accounts for over 75% of Canadian roofing shingle export. The company has developed its own recycling program, in which shingle chips that are waste from the manufacturing process are sold to farmers to be used as road bedding material for driveways.

IKO Industries Limited also produces Granulated Bituminous Shingle Material (GBSM), which is used as additive to hot-mix asphalt concrete and has the following components:

30 - 35% asphalt

10 - 15% organic fiber

55 - 60% mineral matter composed mainly of traprock

The experience of IKO in replacing virgin material with GBSM has indicated a 20 to 30% reduction in the virgin asphalt requirement for a typical mix design having a total asphalt content of 5 to 6% [13].

Dhillon Burleigh and Associates (DBA) Engineering, Ltd. [14], designed several job mix formulas for asphalt concrete mixes containing GBSM from IKO, and recycled asphalt pavement (RAP) material. Two GBSM-modified mixes were developed to comply with the specification for conventional base and surface course mixes used by City of Brampton, Canada. These mixes were placed on Williams Parkway in Brampton in September of 1992. The experience gained during the production and placement of

GBSM mixes has been summarized by DBA Engineering Ltd. as follows.

1. The mixes met or exceeded the specifications for conventional mixes for heavy volume traffic conditions.
2. No equipment modifications were required at the asphalt plants; the GBSM was handled through conventional RAP conveyors.
3. The mix placement at the site was exactly the same as for conventional mixes and no problems were encountered.
4. The GBSM surface course yielded a smooth and tight surface texture.
5. Visual observation indicated uniform distribution of GBSM in the mix; no segregation of the GBSM was evident.
6. Satisfactory compaction was achieved in the field with conventional equipment at no additional effort.

The material proportions and Marshall test results for the mixes placed in the City of Brampton as reported by DBA Engineering Ltd., are presented in Tables 2.6 and 2.7 for the surface course, and 2.8 and 2.9 for the base course.

Table 2.6. Composition of surface course asphalt concrete mix made with GBSM/RAP addition.

| Material | Percentage of Total Mix | Percentage of Total Aggregate |
|---|---|---|
| HL3 Stone* | 42.5 | 44.9 |
| Sand | 34.1 | 36.1 |
| Limestone Screenings | 8.5 | 9 |
| GBSM/RAP (30/70) | 10.0 | 10.0 |
| New Asphalt Cement | 4.9 | - |

* Aggregate maximum size 16.0 mm, nominal size 9.5 mm.

Table 2.7. Properties of surface course asphalt concrete mix made with GBSM/RAP addition.

| Property | At Design AC | Requirements |
|---|---|---|
| Stability (N) @ 60°C | 10,650 | 8,900 minimum |
| Flow 0.25 mm (0.01 in.) | 9.2 | 8.0 min. |
| Percent Air Voids | 4.0 | 3.0 - 5.0 |
| VMA | 17.2 | 15.0 min. |
| $G_{mm}$ | 2.676 | - |

Table 2.8. Composition of base course asphalt concrete mix made with GBSM/RAP addition.

| Material | Percentage of Total Mix | Percentage of Total Aggregate |
|---|---|---|
| 19 mm Clear Stone | 27.1 | 28.5 |
| HL3 Stone | 19.0 | 20.0 |
| Sand | 25.3 | 26.5 |
| GBSM/RAP (12/88) | 25.0 | 25.0 |
| New Asphalt Cement | 3.6 | - |

Table 2.9. Properties of base course asphalt concrete mix made with GBSM/RAP addition.

| Property | At Design AC | Requirements |
|---|---|---|
| Stability (N) @ 60°C | 14,000 | 8,900 minimum |
| Flow 0.25 mm (0.01 in.) | 12.4 | 8.0 min. |
| Percent Air Voids | 4.0 | 3.0 - 5.0 |
| VMA | 15.3 | 13.5 min. |
| $G_{mm}$ | 2.667 | - |

The Minnesota Department of Transportation has experimented with the use of shingle scrap in HMA since 1990 [15,16]. The Willard Munger Recreational Trail, made with 9% shingle scrap (by weight of aggregate), was the first test section constructed in 1990 and is performing well at this writing. The cross-section of the pavement consists of 64 mm of HMA and a 100 mm of crushed concrete base. Subsequently, the University of Minnesota conducted a laboratory study to investigate the influence of roofing shingles on asphalt concrete mix properties. This study led to the construction of two more experimental paving projects in 1991.

The first project was located near the town of Mayer. The in-place bituminous roadway showing severe transverse cracks every 3 meters was overlaid with 38 mm leveling and 25 mm wearing courses. The paving project was divided into several test sections, which differed in the amount of added shingle scrap material. Both courses were made with 0, 5, or 7% shingle addition in different combinations. As of December of 1995 the pavement sections containing waste shingle material were performing at least as well as the control section. Transverse reflective cracking every 9 to 12 meters was the most visible type of distress.

The second project was located in Sibley County, Minnesota. This project was a complete reconstruction of two driving lines and two shoulders. The pavement cross-section consists of a 50 mm wearing course, a 50 mm binder course, a 100 mm base course, and a 280 mm aggregate base. A total of three different road sections were constructed using asphalt concretes having 5, 7, and 9% organic shingle scrap contents.

In November of 1995, the pavement was in excellent condition, with minimal transverse cracking every 87 meters and no cracking along the longitudinal centerline joint.

All of the described Minnesota projects were constructed exclusively with felt shingle scrap supplied by shingle producers. No major construction problems were reported in the paving of any of Minnesota's test sections. In the laboratory evaluation [15], a mix having a 9% waste asphalt shingle content demonstrated much higher Marshall stability then that of the conventional mix, as indicated in Table 2.10. The evaluation of core samples as presented in Table 2.11 indicated much lower tensile strengths and higher air voids for the shingle mix.

Table 2.10. Properties of control and mixes made with 9% asphalt roofing shingles [15].

| Mix Type | % Aggregate | % Shingle | % Asphalt | Stability, lbs. | %Air Void |
|---|---|---|---|---|---|
| Control | 100 | 0.0 | 5.0 | 1,560 | 4.2 |
| 9% Shingle | 91 | 9.0 | 3.0 | 2,464 | 3.3 |

Notes: % Aggregate + % Shingle = 100 % weight of dry mineral materials.
% Asphalt= % by weight of total mixture (asphalt cement and mineral materials).

Table 2.11. Test results for core samples [15].

| Mix Type | Density (Bulk) lbs/cu.ft | Indirect Tensile Strength (psi.) avg. / range | In-place Air Voids | %AC | AC Pen. |
|---|---|---|---|---|---|
| Control | 141.7 | 70 / 64-76 | 9.0 | 5.3 | 52 |
| 9% Shingle | 130.5 | 37 / 31-48 | 16.1 | 5.4 | 34 |

Notes: % AC - Percent of extracted asphalt cement by weight of mix.
AC Pen - Penetration of recovered asphalt cement at 77°C.

A laboratory study by Paulsen *et al.* considered two types of waste roofing shingles [17]. The results of the study indicated that acceptable asphalt concrete mixes can be prepared using waste roofing shingles; however, because roofing asphalt typically becomes highly weathered after years of exposure, asphalt concrete containing waste roofing shingles may experience durability problems. It was recommended that application of these mixes be limited to roads with light traffic, or to the lower layer of pavement sections.

Ohio has its own experience with asphalt mixtures containing waste asphalt roofing shingles. In October 1992, part of Galbraith Road in Reading City, Hamilton County, was resurfaced using ODOT Item 404 with 10% roofing shingles. Galbraith Road is heavily traveled with 25,000 vehicles a day including heavy truck traffic (according to private communication with the Hamilton County Engineer, JMA Consultants, and G.J. Thelen & Associates, Inc). The asphalt mix was prepared by the Valley Asphalt Plant located at Mosteller Road in Sharonville, and was composed of 46% sand, 39% No. 8 aggregate, 10% waste roofing shingles, and 5% asphalt cement. A total of about 660 tons of the ODOT Item 404 mixture was produced and placed. The required compaction of 93 to 97% of the maximum theoretical density was achieved with three passes of the breakdown roller, followed by three passes of the static roller. Samples were obtained and tested for a Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and Resistance to Plastic Flow. The test results are presented in Tables 2.12 and 2.13.

Table 2.12. Gradation and extraction test results for asphalt concrete used in Reading City, Ohio.

| Sieve Size | Percent Passing by Weight | |
|---|---|---|
| | Ohio Item 404 Specification | Sample from Actual Mix |
| 1/2 " | 100 | 100 |
| 3/8 " | 90 - 100 | 94.8 |
| No. 4 | 45 - 75 | 75.0 |
| No. 16 | 15 - 45 | 38.2 |
| No. 50 | 3 - 22 | 10.2 |
| No. 200 | 0 - 8.0 | 2.4 |
| Bitumen (% of total mix) | 4.5 - 12 | 6.7 |

Table 2.13. Properties of asphalt concrete mix used in Reading City, Ohio.

| Property | At Design AC | Requirements |
|---|---|---|
| Stability (lbs.) @ 140°F | 2,743 | 1,800 |
| Flow 0.25 mm (0.01 in.) | 10 | 8.0 min. |
| Percent Air Voids | 2.7 | 3.0 - 5.0 |
| VMA | 14.5 | 15.0 min. |
| Unit Weight (pcf) | 148.5 | |

As of three years after placement, the pavement was performing very well, according to officials from Reading City, Hamilton County, and JMA Consultants.

The Gerken Paving, Inc. and Gerken Materials, Inc. Companies of Napoleon, Ohio are currently introducing asphalt shingle scrap material from manufacturing process into hot asphalt mixes. In 1996, approximately 30,000 tons of hot asphalt concrete mixes that incorporated shingles were placed on roadways, parking lots, and residential driveways, according to Gerken officials. At this writing, these projects are being evaluated for their performance [18].

## 2.4. AVAILABILITY OF WASTE ROOFING SHINGLES IN OHIO.

Roofing shingle waste is generated either as a result of the manufacturing process or by removal of the existing material from roof-tops. The shingles removed from roofs end up in demolition landfills, whereas as waste from the manufacturing process is dumped in solid waste landfills. Neither demolition nor solid waste landfills are regulated in the State of Ohio; consequently no accurate statistics regarding waste roofing shingle availability can be obtained by way of a regulatory agency.

### 2.4.1. SCRAP FROM THE MANUFACTURING PROCESS.

Producers of fiberglass roofing shingles in Ohio were contacted and asked to estimate quantities of waste generated in the manufacturing process. The information obtained is presented in Table 2.14.

Table 2.14. Estimated quantities of fiberglass roofing shingle waste generated in manufacturing processes in Ohio.

| Manufacturer | Location | Estimated Waste Generated (tons/year) |
|---|---|---|
| The Celotex Corporation | Cincinnati, Ohio | 1,080 |
| CenterTeed Corporation | Milan, Ohio | 1,080 |
| Atlas Energy Products | Franklin, Ohio | 2,340 |
| Owen-Corning Fiberglass Corporation | Medina, Ohio | 2,140 |
| IKO Manufacturing, Inc. | Franklin, Ohio | 1,800 |
| Total | | 9,160 |

A total of 9,160 tons per year of manufactured waste was estimated on the basis of total production.

## 2.4.2. WASTE FROM ROOF REPLACEMENT ACTIVITIES.

A second source of waste roofing shingles is removal from existing residential rooftops. To estimate the quantities of waste shingle generated in this manner in Ohio, a telephone survey was conducted of roofing contractors listed in the Columbus telephone directory and the 1993 Ohio Roofing Contractors Association (ORCA) Membership Roster. A total of 29 contractors were contacted in February of 1996, of which 13 (45 %) performed tear-off of shingles from existing roofs; the remainder indicated that they were involved primarily in new or commercial construction, and were not involved in residential roof replacement. Table 2.15 summarizes the estimated shingle quantities generated by tear-off activities as reported by the contractors. The contractors generally reported the average number of "squares" of shingle removed per year, where a square indicates a 10 by 10 foot area of roof.

Based on the reported information as presented in Table 2.15, the total availability of waste shingle material from existing rooftops was estimated as follows.

- Approximate range of 39,000 to 49,000 squares reported by 13 contractors; average: 44,000 squares.

- Extrapolate to 45% (103) of all 230 ORCA members: 350,000 squares.

- Multiply by reduction factor of 0.75, since a disproportionate number of contractors from larger cities were surveyed: 260,000 squares.

- One square with a single layer of shingle weighs 0.12 tons.

- Total quantity assuming a single layer of shingle for each roof: 30,000 tons.

Since the contractors reported that many roofs have two or more shingle layers, the estimated quantity of waste shingle material generated in Ohio by removal from existing rooftops is 30,000 to 60,000 tons per year. The surveyed contractors reported that their disposal costs ranged from $ 5 to $ 30 per ton of shingle, depending on which landfill was used and the capacity of the disposal truck.

Table 2.15. Estimated quantities of waste shingle generated by tear-off from existing roofs, as reported by 13 Ohio roofing contractors.

| Roofing Contractor | Location | Estimated Quantity of Shingle from Tear-Off (squares / year) |
|---|---|---|
| Dick Baker Roofing, Inc. | Columbus | 5,200 |
| R. Bauer & Sons Roofing & Siding | Dayton | 850 - 1,000 |
| Branch Roofing, Inc. | Akron | 1,000 |
| C.A. Eckstein, Inc. | Cincinnati | 500 - 4,000 |
| Feazel Roofing | Columbus | 15,000 |
| Holt Roofing Co., Inc. | Toledo | 8,000 |
| Kecks Building Maintenance, Inc. | Columbus | 1,500 - 4,000 |
| Kelley Roofing & Repair, Inc. | Cincinnati | 2,000 |
| Roof Doctors, Inc. | Cincinnati | 500 - 1,000 |
| Roth Roofing & Remodeling | Cincinnati | 1,000 - 2,000 |
| Southwind Building & Roofing, Inc. | Columbus | 400 |
| Walter St. Clair Son | Cincinnati | 2,000 |
| Zero - Breese Company | Cincinnati | 1,500 - 3,000 |

# CHAPTER 3

# RESEARCH METHODS

## 3.1. EXPERIMENTAL DESIGN.

Test specimens for 26 asphalt concrete mixes that were examined during this research project were compacted by the Marshall method. One type of virgin asphalt (AC-20), two types of aggregate (gravel and limestone), and one type of asphalt roofing shingle (fiberglass) from two producers (Celotex Corporation - Cincinnati plant, and Owens-Corning Corporation - Medina plant) were used. To determine whether the method of shingle preparation has any influence on the final performance of the asphalt concrete, the shingles were reduced in size by two methods: granulation and shredding. Four levels of shingle addition, namely 0, 5, 10, and 15 % by weight, were investigated. Table 3.1 presents a matrix of the asphalt concrete mixes that were tested.

The optimum asphalt cement contents for mixes with 5, 10, and 15% shingle addition were established by use of a modified Marshall Mix Design Method, in which the tests for Marshall Stability and Flow were replaced by tests for Indirect Tensile Strength and Vertical Deformation, respectively. Five different asphalt cement contents were investigated for each of the twelve asphalt concrete test mixes having granulated shingles. The optimum asphalt cement contents determined for the granulated shingle mixes were then used in the preparation of the corresponding shredded shingle test mixes.

The optimum asphalt cement contents for test mixes having 0% shingle addition were provided by ODOT.

The physical properties of the mixes were evaluated by laboratory testing of standard specimens (100 mm diameter mold) prepared at the optimum asphalt cement contents. A minimum of three replicate specimens were tested for each experiment that was conducted.

Table 3.1. Matrix for 24 test mixes containing waste shingles.

| Level of Shingle Addition (%) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Limestone | | | | | | | Gravel | | | | | | |
| 0 | 5 | | 10 | | 15 | | 0 | 5 | | 10 | | 15 | |
| Type of Shingle Preparation: 1-Shredding; 2-Granulation | | | | | | | | | | | | | |
| | 1 | 2 | 1 | 2 | 1 | 2 | | 1 | 2 | 1 | 2 | 1 | 2 |
| Shingle Source: 1-Celotex; 2-Owens-Corning | | | | | | | | | | | | | |
| | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 |
| | 2 | 2 | 2 | 2 | 2 | 2 | | 2 | 2 | 2 | 2 | 2 | 2 |

## 3.2. PREPARATION OF ASPHALT ROOFING SHINGLES.

Waste material in the asphalt shingle manufacturing process is generated during the final stage of production, when shingle sheets are cut at the edges to obtain uniform widths. The generated pieces of shingle waste, known as end tabs, usually measure 7 to 10 cm long and 0.6 cm wide. To be used in asphalt concrete production, the "end tabs" must be further reduced in size. A Fritsch's P-10 laboratory shredder mill was employed to prepare the roofing shingle material that was used in this research project. Through a feed shaft, the pieces of shingle waste were placed into the working chamber of the shredder, where they were torn by the cutting crusher. The waste pieces remained in this chamber until they were reduced to a size that allowed particles to fall through a sieve mounted at the bottom of the chamber. The final reduced shingle size was predetermined by sieve selection.

To evaluate the effect of dispersion of roofing shingle material on asphalt concrete mix properties, two sieve sizes were chosen. Sieves with mesh openings of 4 and 12 mm were selected to obtain granulated and shredded roofing shingle particles, respectively. Shredded particles had dimensions up to 30 mm, and granulated particles had dimensions up to 4.75 mm.

## 3.3. PROGRAM OF TESTING.

Samples of asphalt roofing shingle, gravel and limestone aggregate, and compacted asphalt concrete were tested in this research project.

### 3.3.1. ASPHALT ROOFING SHINGLE.

Samples of asphalt roofing shingle were subjected to the following tests.

- ASTM D 2172, "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures".
- ASTM D 1856, "Recovery of Asphalt from Solution by Abson Method".
- ASTM D 2171, "Viscosity of Asphalts by Vacuum Capillary Viscometer".
- ASTM D 546, "Sieve Analysis of Mineral Filler for Road and Paving Materials".

### 3.3.2. AGGREGATE.

Samples of aggregate were subjected to the following tests.

- ASTM C 127, "Specific Gravity and Absorption of Coarse Aggregate".
- ASTM C 128, "Specific Gravity and Absorption of Fine Aggregate".
- ASTM C 136, "Sieve analysis of Fine and Coarse Aggregate".

### 3.3.3. ASPHALT CONCRETE.

#### 3.3.3.1. Mix Design Procedure.

Job Mix Formulas (JMFs) for two control asphalt concrete mixes (0% shingle addition) were supplied by the Ohio Department of Transportation. The JMFs for asphalt concrete mixes having 5, 10, and 15% shingle addition were determined in accordance with the following procedure.

Based on the established proportions of asphalt roofing shingle and new aggregate to be used in the mix, the ratio of the new aggregate to the aggregate in the shingles was calculated, and the combined aggregate gradation was calculated using gradations of the aggregate from the roofing shingles and the new aggregate. The amount of new aggregate (r), expressed as a percentage of total aggregate in the design mix, was calculated using the formula [19]:

$$r = \frac{P_{ns}}{P_{sm} - \frac{(P_{sm} \times P_{sb})}{100} + P_{ns}} \times 100$$

where

$r$ = new aggregate expressed as percentage of total aggregate.

$P_{ns}$ = new aggregate in the asphalt concrete mix.

$P_{sb}$ = asphalt content of the roofing shingles (percent by weight), as determined by extraction.

$P_{sm}$ = content of asphalt roofing shingle in the mix (percent by weight).

The requirement of new asphalt cement as a percentage of the total mix was calculated as:

$$P_{nb}=\frac{(100^2-P_{sb}r)\,Pb}{100\,(100-P_{sb})}-\frac{(100-r)\,P_{sb}}{100-P_{sb}}$$

where

$P_{nb}$ = new asphalt content (percent by weight of mix).

The percentage of shingle in the mix was calculated as:

$$P_{sm}=\frac{100\,(100-r)}{100-P_{sb}}-\frac{(100-r)\,P_b}{100-P_{sb}}$$

The percentage of new aggregate was calculated as:

$$P_{ns}=r-\frac{rP_b}{100}$$

Keeping the ratio of added asphalt roofing shingle to total aggregate constant, the required amount of virgin asphalt to be added to the mix was calculated. For each trial mix, asphalt cement contents at 0.5 percent increments of new asphalt cement were examined to establish the optimum asphalt cement content. Generally, the optimum asphalt cement content was calculated as an average of contents at which 4% air voids and maximum stability, and unit weight were achieved. In several instances, however, the unit weight factor had to be disregarded to secure a mix design that would result in an air void content close to 4%. Detailed information about the calculated weight of virgin asphalt cement and new aggregate (by sieve size) are presented in Appendix A.

#### 3.3.3.2. Specimen Preparation.

Normally, when virgin asphalt cement is the only binder used in the mixture the temperatures to which the asphalt must be heated to is based on an empirically established limits on kinematic viscosity for mixing and compaction temperatures. These limits are traditionally set as 170 ± 20 centistokes for mixing and 280 ± 20 centistokes for compaction. When modifiers, RAP, or roofing shingles are used with virgin asphalt, these viscosity ranges are not valid for the modified binder [20]. The viscosity - temperature relations are not linear on the log scale. In addition consideration must be given to the type of modified materials.

The Marshall method of compaction with 50 blows per face was used for specimen preparation. In this research study, considerations were given to both roofing shingles properties and laydown procedure. The upper limit on mixing as well as heating and introduction of the roofing shingles into the HMA was selected inorder not to accelerate aging of the mixtures with roofing shingles. The lower limit for compaction was set low enough to accomodate the higher rate of cooling that is associated with roofing shingle mixes. The roofing shingles were added directly to heated to 195°C aggregate and mixed well together. Virgin asphalt was heated to 149 ± 2°C and added to the aggregate-shingle mixture. All components were then mixed at 150 ± 5°C. The specimen compaction temperature was selected at 135 ± 2°C.

### 3.3.3.3. Test Procedures for Compacted Asphalt Concrete Specimens.

Compacted asphalt concrete specimens were subjected to the following tests.

- ASTM D 2041, "Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures".
- ASTM D 2726, "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens".
- ASTM D 4123, "Indirect Tension Test".

The effect of the considered variables on the performance of the mixes was evaluated by subjecting specimens produced at optimum asphalt cement contents to the following additional tests.

- ASTM D 1559, "Resistance to Plastic Flow of Bituminous Mixtures

Using Marshall Apparatus".

- ASTM D 4123, "Indirect Tension Test for Resilient Modulus of Bituminous Mixtures". Tests were conducted at three temperatures (0, 25, and 40°C), and one load frequency (1 Hz).
- Creep Modulus in Indirect Tensile Loading, in accordance with the Asphalt-Aggregate Mixture Analysis System (AAMAS) procedure published in National Cooperative Highway Research Program Report No. 338 (Indirect Tensile Creep loading at 25 ± 1°C).
- AASHTO T 283, "Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage".

CHAPTER 4

# TEST RESULTS AND ANALYSIS

The test data collected in this research project is summarized in Tables 4.1 through 4.22 and Figures 4.1 through 4.36. The data is presented in metric units.

## 4.1. LABORATORY TESTING OF AGGREGATE.

Aggregate from two sources was used in this study. Gravel aggregate was obtained from Lancaster Sand and Gravel, while limestone aggregate was obtained from Gerken Materials, Inc. Table 4.1 presents specific gravity and absorption data, and Table 4.2 presents gradation test results, for the aggregate as delivered.

Table 4.1. Specific gravity and absorption of aggregate as delivered.

| Property | Gravel | | Limestone | |
|---|---|---|---|---|
| | # 8 | Natural Sand | # 8 | Manufactured Sand |
| Sp.Gravity (Dry) | 2.504 | 2.522 | 2.543 | 2.675 |
| Sp.Gravity (SSD) | 2.572 | 2.585 | 2.613 | 2.728 |
| Sp.Gravity (Apparent) | 2.687 | 2.692 | 2.734 | 2.824 |
| % Absorption | 2.72 | 2.50 | 2.74 | 1.97 |

Table 4.2. Gradation of aggregate as delivered (percent passing by weight).

| Sieve Size (mm) | Gravel | | Limestone | |
|---|---|---|---|---|
| | #8 | Natural Sand | #8 | Manufactured Sand |
| 19.0 | 100 | 100 | 100 | 100 |
| 12.5 | 100 | 100 | 100 | 100 |
| 9.5 | 96.0 | 100 | 84.0 | 100 |
| 4.75 | 34.0 | 100 | 10.0 | 100 |
| 2.36 | 3.0 | 93.0 | 3.0 | 78.0 |
| 1.18 | 2.0 | 73.0 | 2.0 | 52.0 |
| 600 $\mu m$ | 2.0 | 41.0 | 2.0 | 33.0 |
| 300 $\mu m$ | 1.0 | 14.0 | 2.0 | 19.0 |
| 150 $\mu m$ | 1.0 | 4.0 | 1.0 | 10.0 |
| 75 $\mu m$ | 1.0 | 0.9 | 1.0 | 4.8 |

The delivered aggregates were sieved to individual sizes and later blended to meet the ODOT surface course specification.

## 4.2. LABORATORY TESTING OF ASPHALT ROOFING SHINGLES.

Fiberglass asphalt roofing shingles obtained from Owens-Corning Corporation (Medina plant) and Celotex Corporation (Cincinnati Plant) were tested for asphalt cement content and aggregate gradation, following size reduction by shredding or granulation. Tables 4.3 and 4.4 present the test results for roofing shingles produced by Owens-Corning and Celotex Corporation, respectively. Viscosity tests were planned but not completed successfully, because the asphalt cement recovered from the shingles was too viscous to be tested in accordance with the ASTM D 2171 procedure.

Table 4.3. Combined aggregate and fiberglass gradation of Owens-Corning shingle after size reduction (percent passing by weight).

| Sieve Size (mm) | Owens-Corning Shingle | |
|---|---|---|
| | Granulated | Shredded |
| 9.5 | 100.0 | 100 |
| 4.75 | 98.0 | 95.0 |
| 2.36 | 97.0 | 94.0 |
| 1.18 | 84.0 | 85.0 |
| 600 $\mu m$ | 59.0 | 69.0 |
| 300 $\mu m$ | 51.0 | 63.0 |
| 150 $\mu m$ | 46.0 | 56.0 |
| 75 $\mu m$ | 32.3 | 41.1 |
| AC Content | 20.8 | 25.9 |

Table 4.4. Combined aggregate and fiberglass gradation of Celotex shingle after size reduction (percent passing by weight).

| Sieve Size (mm) | Celotex Shingle | |
|---|---|---|
| | Granulated | Shredded |
| 9.5 | 100.0 | 100 |
| 4.75 | 98.0 | 98.0 |
| 2.36 | 98.0 | 98.0 |
| 1.18 | 85.0 | 85.0 |
| 600 $\mu$m | 65.0 | 64.0 |
| 300 $\mu$m | 58.0 | 58.0 |
| 150 $\mu$m | 54.0 | 53.0 |
| 75 $\mu$m | 42.4 | 36.7 |
| AC Content | 19.0 | 21.0 |

A comparison of the test results presented in Tables 4.3 and 4.4 indicates that the size reduction method affects not only the gradation but also the asphalt cement content of the produced material. This is due to the fact that during the size reduction process, part of the shingle material adheres to the inside shredder surfaces, particularly to the screen. The adhered shingle residue accumulates, finally plugging all screen openings, and has to be physically removed. The screen with small openings used to produce granulated shingle material accumulated much more asphalt cement, and had to be cleaned much more frequently, than the screen used to produce shredded shingle material. As a result, the granulated shingle material has a lower asphalt cement content than the shredded material.

## 4.3. LABORATORY TESTING OF CONTROL MIXES.

The control mixes were based on ODOT Item No. 448. The job mix formulas for both gravel and limestone aggregates were provided by ODOT.

Tables 4.5 and 4.6 present the aggregate gradations, asphalt cement content, and mix properties, respectively, for control mixes.

Table 4.5. Aggregate gradation and asphalt cement content for control mixes.

| Sieve Size (mm) | Aggregate Type | |
|---|---|---|
| | Limestone | Gravel |
| 12.5 | 100 | 100 |
| 9.5 | 93 | 97 |
| 4.75 | 58 | 60 |
| 2.36 | 43 | 42 |
| 1.18 | 29 | 31 |
| 600 $\mu$m | 19 | 21 |
| 300 $\mu$m | 12 | 8 |
| 150 $\mu$m | 7 | 4 |
| 75 $\mu$m | 3.6 | 3 |
| AC Content | 6.0 | 5.7 |

Table 4.6. Properties of control mixes.

| Property | Limestone Mix | Gravel Mix |
|---|---|---|
| Stability | 9,660 N | 6,710 N |
| Flow | 2.36 mm | 2.84 mm |
| Air Voids | 5.89% | 4.42% |
| VMA | 18.82% | 17.53% |
| Indirect Tensile Strength | 0.888 MPa | 0.621 MPa |
| Deformation | 1.6 mm | 2.0 mm |
| Resilient Modulus at 0°C | 10,150 MPa | 8,250 MPa |
| Resilient Modulus at 22°C | 3,010 MPa | 2,140 MPa |
| Resilient Modulus at 40°C | 730 MPa | 330 MPa |
| Unit Weight | 2,318 kg/m$^3$ | 2,252 kg/m$^3$ |
| Max. Theoretical. Sp. Gravity | 2.463 | 2.355 |

The test results presented in Table 4.6 are discussed together with the test results of mixes produced with roofing shingle addition in section 4.5 of this chapter.

## 4.4. DETERMINATION OF OPTIMUM ASPHALT CEMENT CONTENTS FOR ASPHALT CONCRETE MIXES WITH ROOFING SHINGLE ADDITION.

To reduce the number of specimens to be prepared for this phase of the project, the optimum asphalt cement content was determined for mixes with granulated roofing shingles only. The determined optimum AC contents were later applied to the shredded shingle mixes having the corresponding aggregate type and shingle content. This approach resulted in the preparation of a total of over 180 specimens for the twelve job mix formulas that were established.

The optimum asphalt cement content for each concrete mix with roofing shingle addition was determined as an average of the asphalt contents yielding 4 % air voids, maximum unit weight, and maximum indirect tensile strength. Several mixes reached a maximum unit weight at a very high asphalt cement content, and as a result the calculated optimum asphalt cement content did not satisfy the air voids requirement. In these instances, the optimum asphalt cement content was adjusted to assure a proper air void content. Tables 4.7 and 4.8 present the determined total optimum asphalt cement contents for mixes with limestone and gravel aggregate, respectively. It should be noted that in Table 4.7 the total asphalt cement content for Owens-Corning shingles using 10% addition was slightly higher than that using 15% addition. The difference was 0.05% which for all practical purposes is considered not significant and could be attributed to within the test variations. In general, the asphalt cement content increased as the level of addition increase. The results from the tests preformed for asphalt cement content determination are presented in Appendix A.

Table 4.7. Optimum asphalt cement contents for asphalt concrete mixes with limestone aggregate.

| Source of Shingles | Level of Addition, % | Total Optimum Asphalt Cement Content, % |
|---|---|---|
| Owens-Corning | 5 | 7.00 |
| | 10 | 7.25 |
| | 15 | 7.20 |
| Celotex | 5 | 7.00 |
| | 10 | 7.10 |
| | 15 | 7.20 |

Table 4.8. Optimum asphalt cement contents for asphalt concrete mixes with gravel aggregate.

| Source of Shingles | Level of Addition, % | Total Optimum Asphalt Cement Content, % |
|---|---|---|
| Owens-Corning | 5 | 6.40 |
| | 10 | 6.70 |
| | 15 | 6.70 |
| Celotex | 5 | 6.40 |
| | 10 | 6.70 |
| | 15 | 6.75 |

## 4.5. PERFORMANCE EVALUATION OF ASPHALT CONCRETE MIXES PRODUCED AT OPTIMUM ASPHALT CEMENT CONTENTS.

Nine standard cylindrical test specimens (100 mm diameter) were compacted for each of the examined asphalt concrete mixes, at the established optimum asphalt cement content. Weight and volumetric analysis were performed for all nine specimens. For strength testing, the specimens were sorted into subsets of three, according to air void content. Efforts were made to assure that the average air void contents for the three subsets were approximately equal.

The test data and figures in the following sections present average test values. Complete sets of test values are presented in Appendix C.

### 4.5.1. UNIT WEIGHT PARAMETERS.

Unit weight parameters determined for the asphalt concrete mixes at the optimum asphalt cement contents are presented in Tables 4.9 (limestone aggregate) and 4.10 (gravel aggregate).

Table 4.9. Unit weight parameters for asphalt concrete mixes with limestone aggregate.

| Mix Type | Specific Gravity | | Unit Weight (kg/m$^3$) |
|---|---|---|---|
| | Saturated Surface Dry | Maximum Theoretical | |
| Control | 2.318 | 2.463 | 2,318 |
| 5% Celotex - G | 2.367 | 2.466 | 2,367 |
| 5% Celotex - S | 2.357 | 2.488 | 2,357 |
| 10% Celotex - G | 2.366 | 2.468 | 2,366 |
| 10% Celotex - S | 2.331 | 2.440 | 2,331 |
| 15% Celotex - G | 2.353 | 2.456 | 2,353 |
| 15% Celotex - S | 2.305 | 2.423 | 2,305 |
| 5% Owens-Corning - G | 2.371 | 2.484 | 2,371 |
| 5% Owens-Corning - S | 2.352 | 2.455 | 2,352 |
| 10% Owens-Corning - G | 2.374 | 2.466 | 2,374 |
| 10% Owens-Corning - S | 2.322 | 2.454 | 2,322 |
| 15% Owens-Corning - G | 2.356 | 2.457 | 2,356 |
| 15% Owens Corning - S | 2.291 | 2.447 | 2,291 |

Table 4.10. **Unit weight parameters for asphalt concrete mixes with gravel aggregate.**

| Mix Type | Specific Gravity | | Unit Weight ($kg/m^3$) |
|---|---|---|---|
| | Saturated Surface Dry | Maximum Theoretical | |
| Control | 2.252 | 2.355 | 2,252 |
| 5% Celotex - G | 2.286 | 2.353 | 2,286 |
| 5% Celotex - S | 2.273 | 2.334 | 2,273 |
| 10% Celotex - G | 2.296 | 2.384 | 2,296 |
| 10% Celotex - S | 2.260 | 2.332 | 2,260 |
| 15% Celotex - G | 2.300 | 2.391 | 2,300 |
| 15% Celotex - S | 2.242 | 2.339 | 2,242 |
| 5% Owens-Corning - G | 2.282 | 2.365 | 2,282 |
| 5% Owens-Corning - S | 2.270 | 2.370 | 2,270 |
| 10% Owens-Corning - G | 2.289 | 2.388 | 2,289 |
| 10% Owens-Corning - S | 2.249 | 2.356 | 2,249 |
| 15% Owens-Corning - G | 2.282 | 2.357 | 2,282 |
| 15% Owens Corning - S | 2.226 | 2.335 | 2,226 |

### 4.5.2. VOLUMETRIC ANALYSIS.

Volumetric analysis for asphalt concrete mixes at the optimum asphalt cement contents are presented in Tables 4.11 (limestone aggregate) and 4.12 (gravel aggregate).

Table 4.11. Volumetric analysis for asphalt concrete mixes with limestone aggregate.

| Mix Type | Air Voids (%) | Voids in Mineral Aggregate (%) | Voids Filled with Asphalt (%) |
|---|---|---|---|
| Control | 5.89 | 18.82 | 68.7 |
| 5% Celotex - G | 4.02 | 17.74 | 77.4 |
| 5% Celotex - S | 5.26 | 18.09 | 70.9 |
| 10% Celotex - G | 4.15 | 17.60 | 76.5 |
| 10% Celotex - S | 4.45 | 18.80 | 76.3 |
| 15% Celotex - G | 4.20 | 17.86 | 76.5 |
| 15% Celotex - S | 4.86 | 19.62 | 75.3 |
| 5% Owens-Corning - G | 4.53 | 17.45 | 74.1 |
| 5% Owens-Corning - S | 4.18 | 18.11 | 76.9 |
| 10% Owens-Corning - G | 3.73 | 17.20 | 78.3 |
| 10% Owens-Corning - S | 5.38 | 19.01 | 71.7 |
| 15% Owens-Corning - G | 4.11 | 17.38 | 76.4 |
| 15% Owens Corning - S | 6.38 | 19.68 | 67.6 |

Table 4.12. Volumetric analysis for asphalt concrete mixes with gravel aggregate.

| Mix Type | Air Voids (%) | Voids in Mineral Aggregate (%) | Voids Filled with Asphalt (%) |
|---|---|---|---|
| Control | 4.36 | 17.53 | 75.1 |
| 5% Celotex - G | 2.84 | 16.83 | 83.2 |
| 5% Celotex - S | 2.60 | 17.27 | 85.0 |
| 10% Celotex - G | 3.71 | 16.63 | 77.7 |
| 10% Celotex - S | 3.10 | 17.90 | 82.7 |
| 15% Celotex - G | 3.41 | 16.45 | 79.3 |
| 15% Celotex - S | 4.15 | 18.55 | 77.7 |
| 5% Owens-Corning - G | 3.49 | 16.80 | 79.2 |
| 5% Owens-Corning - S | 4.22 | 17.26 | 75.6 |
| 10% Owens-Corning - G | 4.15 | 16.64 | 75.1 |
| 10% Owens-Corning - S | 4.53 | 18.12 | 75.0 |
| 15% Owens-Corning - G | 3.18 | 16.66 | 81.0 |
| 15% Owens Corning - S | 4.69 | 18.76 | 75.1 |

In general, with the exception of the mix containing 10% granulated Owens-Corning asphalt shingle, asphalt concrete mixes with limestone aggregate had higher air void contents than mixes with gravel aggregate at the same level and type of shingle addition. All of the mixes with 5% shingle addition, and the majority of the mixes with 10 and 15% shingle addition, had lower air void contents than the control mixes for both types of aggregate.

The voids in mineral aggregate (VMA) is defined as the volume of intergranular void space between aggregate particles of a compacted paving mixture that includes air voids and the effective asphalt content, expressed as a percentage of the total volume of the sample. Asphalt concrete mixes with low VMA content could become very sensitive to the total fluids content. During placement and compaction these mixes tend to shove, and under traffic they tend to rut and bleed if the asphalt content is too high or ravel if the asphalt content is too low. In accordance with the Asphalt Institute Manual requirement, the desired VMA content for surface mixes designed for medium traffic is 16% [21]. The SHRP-A-408 manual sets a minimum 15% requirement for VMA content [22]. All of the asphalt concrete mixes in this project satisfied both VMA criteria.

The voids filled with asphalt (VFA) is the percentage of the intergranular voids between aggregate particles (VMA) that are filled with asphalt. Consideration of VFA helps prevent the design of mixes having marginally acceptable VMA. The main effect of the VFA criteria is to limit the maximum levels of VMA and asphalt cement content. VFA also restricts the allowable air void content for mixes that are near the minimum VMA criteria. The target range of VFA values for a medium traffic surface layer is 65% to 78% [22]. All but one of the examined asphalt concrete mixes with limestone aggregate, and seven of the thirteen mixes with gravel aggregate, met the VFA requirement. The limestone mix with 10% granulated Owens-Corning shingle exceeded the maximum allowable VFA value by 0.3%. Four of the six gravel mixes that exceeded the maximum allowable VFA value contained

Celotex shingles, while the remaining two contained Owens-Corning shingles. None of the examined mixes had a VFA value lower than the minimum requirement.

### 4.5.3. MARSHALL STABILITY AND FLOW.

Marshall stability and flow test results are presented in Table 4.13 and Figures 4.1 and 4.3 (limestone mixes), and Table 4.14 and Figures 4.2 and 4.4 (gravel mixes).

Table 4.13. Marshall stability and flow for asphalt concrete mixes with limestone aggregate.

| Mix Type | Marshall Stability (N) | Marshall Flow (mm) |
|---|---|---|
| Control | 9,660 | 2.36 |
| 5% Celotex - G | 11,270 | 3.52 |
| 5% Celotex - S | 10,890 | 4.83 |
| 10% Celotex - G | 11,510 | 3.81 |
| 10% Celotex - S | 10,100 | 3.68 |
| 15% Celotex - G | 11,760 | 4.40 |
| 15% Celotex - S | 10,610 | 3.89 |
| 5% Owens-Corning - G | 12,230 | 4.15 |
| 5% Owens-Corning - S | 11,430 | 3.98 |
| 10% Owens-Corning - G | 11,430 | 3.81 |
| 10% Owens-Corning - S | 9,970 | 4.15 |
| 15% Owens-Corning - G | 12,470 | 4.40 |
| 15% Owens-Corning - S | 10,550 | 4.41 |

Table 4.14. Marshall stability and flow for asphalt concrete mixes with gravel aggregate.

| Mix Type | Marshall Stability (N) | Marshall Flow (mm) |
|---|---|---|
| Control | 6,710 | 2.84 |
| 5% Celotex - G | 7,140 | 4.02 |
| 5% Celotex - S | 6,770 | 4.40 |
| 10% Celotex - G | 6,810 | 4.02 |
| 10% Celotex - S | 6,780 | 3.47 |
| 15% Celotex - G | 9,260 | 4.15 |
| 15% Celotex - S | 7,000 | 4.32 |
| 5% Owens-Corning - G | 7,420 | 3.52 |
| 5% Owens-Corning - S | 7,460 | 4.02 |
| 10% Owens-Corning - G | 7,370 | 3.60 |
| 10% Owens-Corning - S | 6,930 | 3.39 |
| 15% Owens-Corning - G | 10,250 | 3.43 |
| 15% Owens-Corning - S | 8,620 | 4.32 |

ODOT Specification Item No. 441.02 for asphalt concrete surface course mix with medium traffic requires a minimum Marshall stability of 5,338 Newtons, and flow in the range of 2 to 4 mm. All of the mixes in this project exceeded the minimum Marshall stability requirement. The addition of roofing shingles, regardless of type and size reduction method, resulted in an increase in Marshall stability. The mixes with 15% addition of granulated Owens-Corning shingle had the greatest Marshall stability for both limestone and gravel aggregate (12,470 and 10,250 Newtons, respectively). The gravel mix with 15% addition of Owens-Corning shingle

Figure 4.1. Effect of level of shingle addition on Marshall stability of asphalt concrete mixes with limestone aggregate.

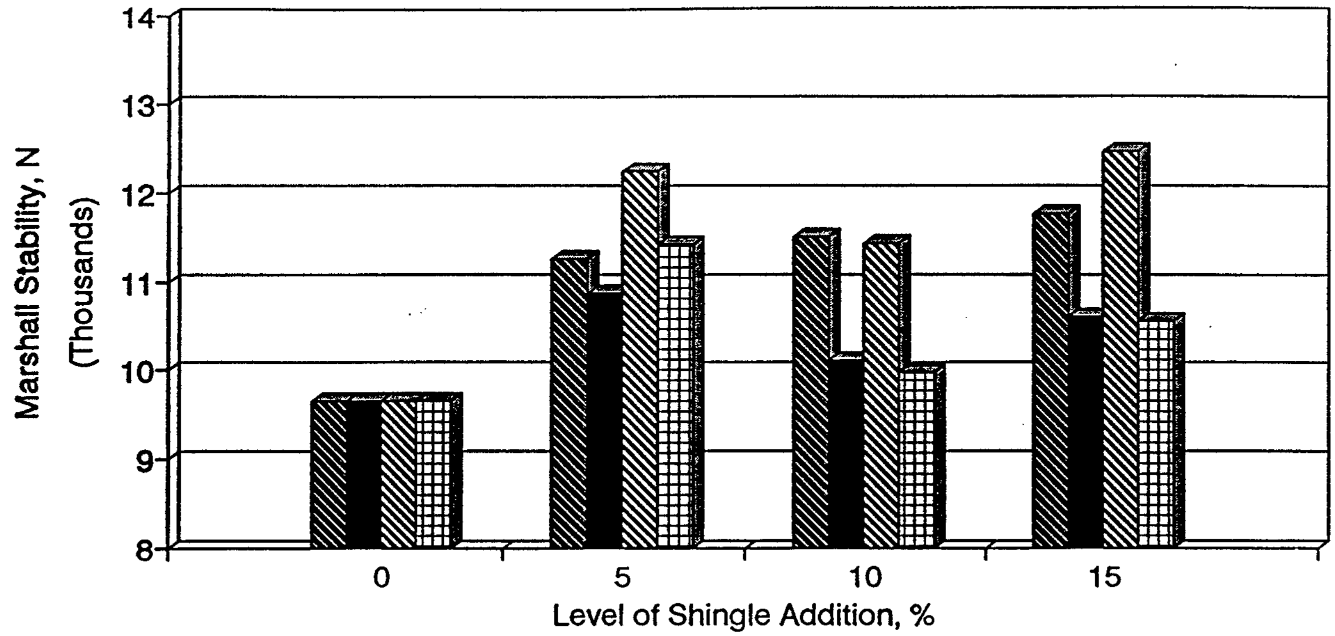



Figure 4.2. Effect of level of shingle addition on Marshall stability of asphalt concrete mixes with gravel aggregate.

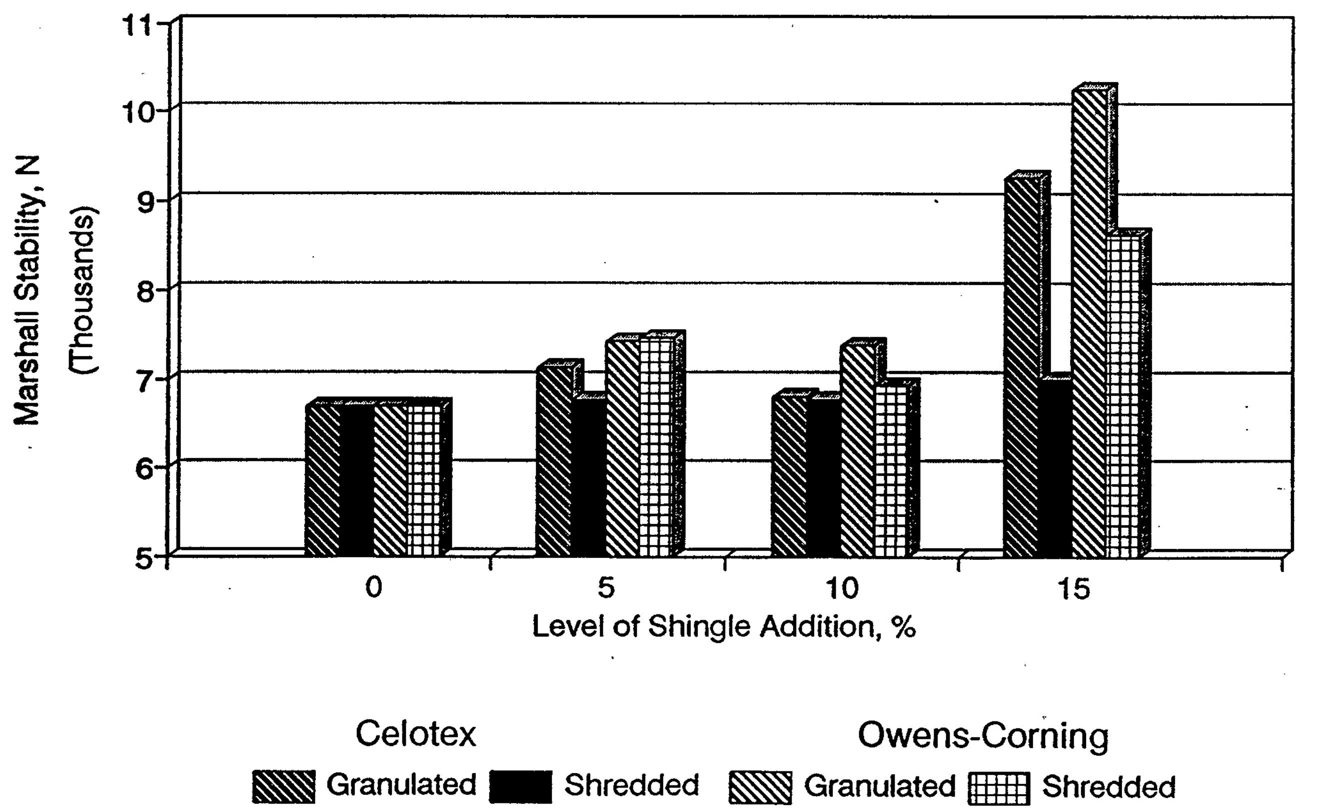


Figure 4.3. Effect of level of shingle addition on Marshall flow of asphalt concrete mixes with limestone aggregate.

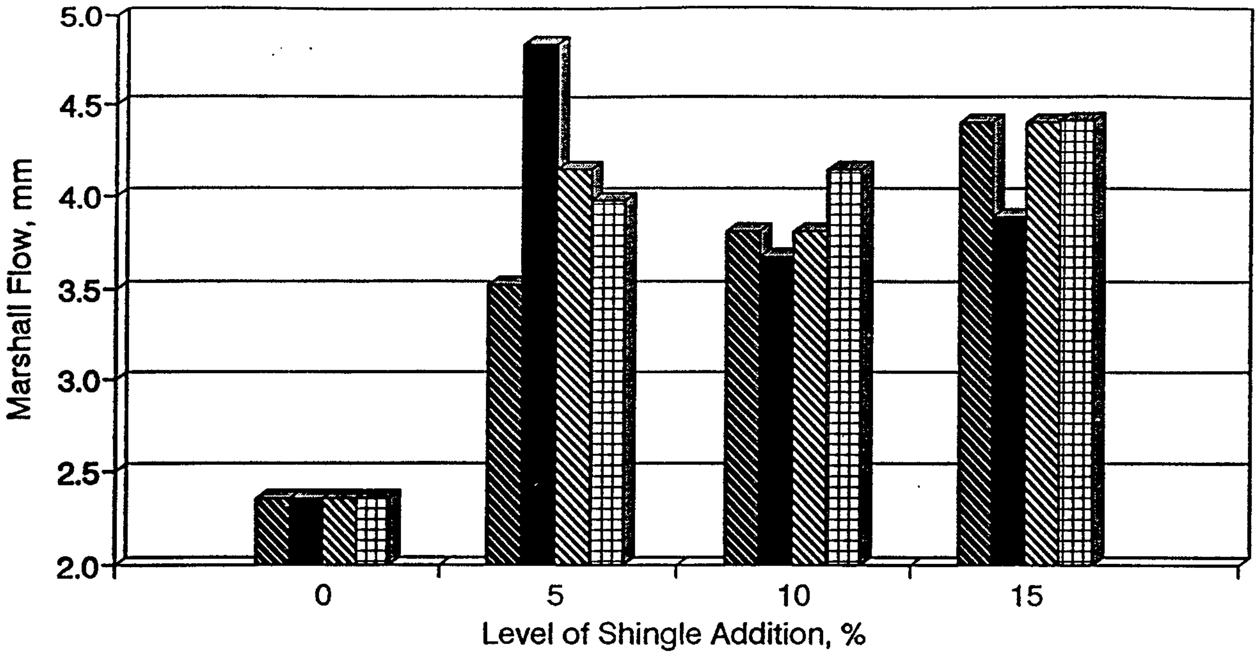
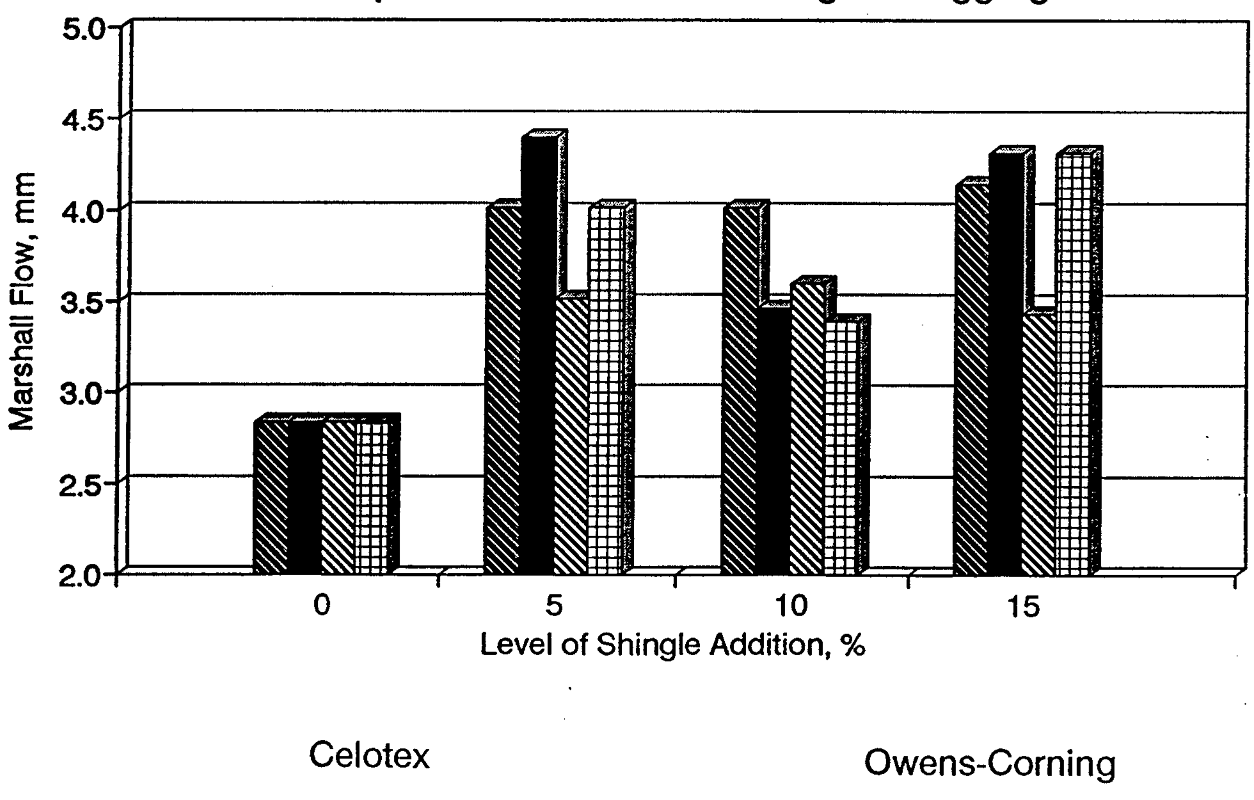



Figure 4.4. Effect of level of shingle addition on Marshall flow of asphalt concrete mixes with gravel aggregate.



had greater stability (10,250 N) than the limestone control mix (9,658 N).

In the Marshall mix design process, flow is used to predict the susceptibility of the asphalt concrete mix to deformation. Mixes with both aggregate types that were tested in this project demonstrated an increased flow after the addition of asphalt roofing shingles. The flow values were 2.36 and 2.84 mm for the limestone and gravel control mixes, respectively. The asphalt concrete mixes containing 5% shredded Celotex shingles showed the highest flow values (4.83 mm for limestone mix and to 4.40 mm for the gravel mix).

### 4.5.4. INDIRECT TENSILE STRENGTH AND DEFORMATION.

The indirect tensile strength test is performed by applying a vertical compressive load to a specimen across its diameter, and measuring the maximum load to failure. The load is applied at a rate of 50 mm/min. The indirect tensile strength is calculated as a function of the ultimate load and the specimen dimensions. The vertical deformation of the specimen is recorded at the maximum load.

Indirect tensile strength and deformation value at the maximum load test results are presented in Tables 4.15 (limestone mixes) and 4.16 (gravel mixes). Figures 4.5 and 4.6 present the indirect tensile strength results graphically.

Table 4.15. Indirect tensile strength and deformation at maximum load for asphalt concrete mixes with limestone aggregate.

| Mix Type | Indirect Tensile Strength (MPa) | Deformation (mm) |
|---|---|---|
| Control | 0.888 | 1.60 |
| 5% Celotex - G | 1.247 | 1.81 |
| 5% Celotex - S | 1.172 | 2.14 |
| 10% Celotex - G | 1.285 | 1.89 |
| 10% Celotex - S | 1.216 | 1.87 |
| 15% Celotex - G | 1.179 | 1.70 |
| 15% Celotex - S | 1.026 | 1.78 |
| 5% Owens-Corning - G | 1.258 | 1.87 |
| 5% Owens-Corning - S | 1.195 | 1.96 |
| 10% Owens-Corning - G | 1.323 | 1.79 |
| 10% Owens-Corning - S | 1.209 | 1.82 |
| 15% Owens-Corning - G | 1.230 | 1.69 |
| 15% Owens-Corning - S | 1.045 | 1.55 |

Table 4.16. **Indirect tensile strength and deformation at the maximum load for asphalt concrete mixes with gravel aggregate.**

| Mix Type | Indirect Tensile Strength (MPa) | Deformation (mm) |
|---|---|---|
| Control | 0.621 | 2.00 |
| 5% Celotex - G | 0.823 | 2.17 |
| 5% Celotex - S | 1.020 | 2.29 |
| 10% Celotex - G | 1.216 | 2.24 |
| 10% Celotex - S | 1.103 | 2.14 |
| 15% Celotex - G | 1.209 | 1.91 |
| 15% Celotex - S | 0.963 | 1.66 |
| 5% Owens-Corning - G | 1.174 | 2.12 |
| 5% Owens-Corning - S | 1.053 | 2.21 |
| 10% Owens-Corning - G | 1.218 | 1.91 |
| 10% Owens-Corning - S | 1.084 | 1.92 |
| 15% Owens-Corning - G | 1.353 | 1.55 |
| 15% Owens-Corning - S | 1.202 | 1.58 |

The indirect tensile strength values for mixes with different levels and types of roofing shingle addition range from 0.888 to 1.323 MPa for limestone mixes, and from 0.621 to 1.353 MPa for gravel mixes. Figures 4.5 and 4.6, and Column 2 in Tables 4.15 and 4.16, show that the asphalt mixes with no shingle addition achieved the lowest value of indirect tensile strength for both types of aggregates. The limestone mixes showed a maximum increase in indirect tensile strength value at 10% shingle addition level. The gravel mixes showed a maximum indirect tensile strength increase at 10% Celotex and at 15% Owens-Corning shingle addition.

Figure 4.5. Effect of level of shingle addition on indirect tensile strength of asphalt concrete mixes with limestone aggregate.

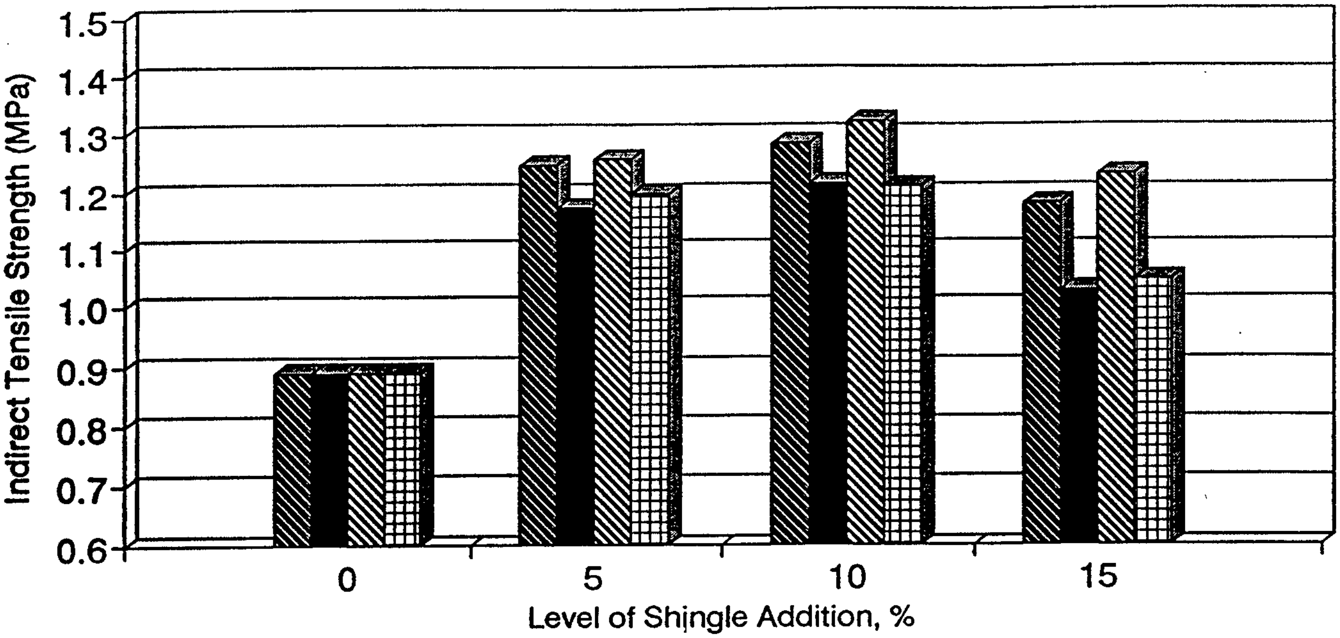
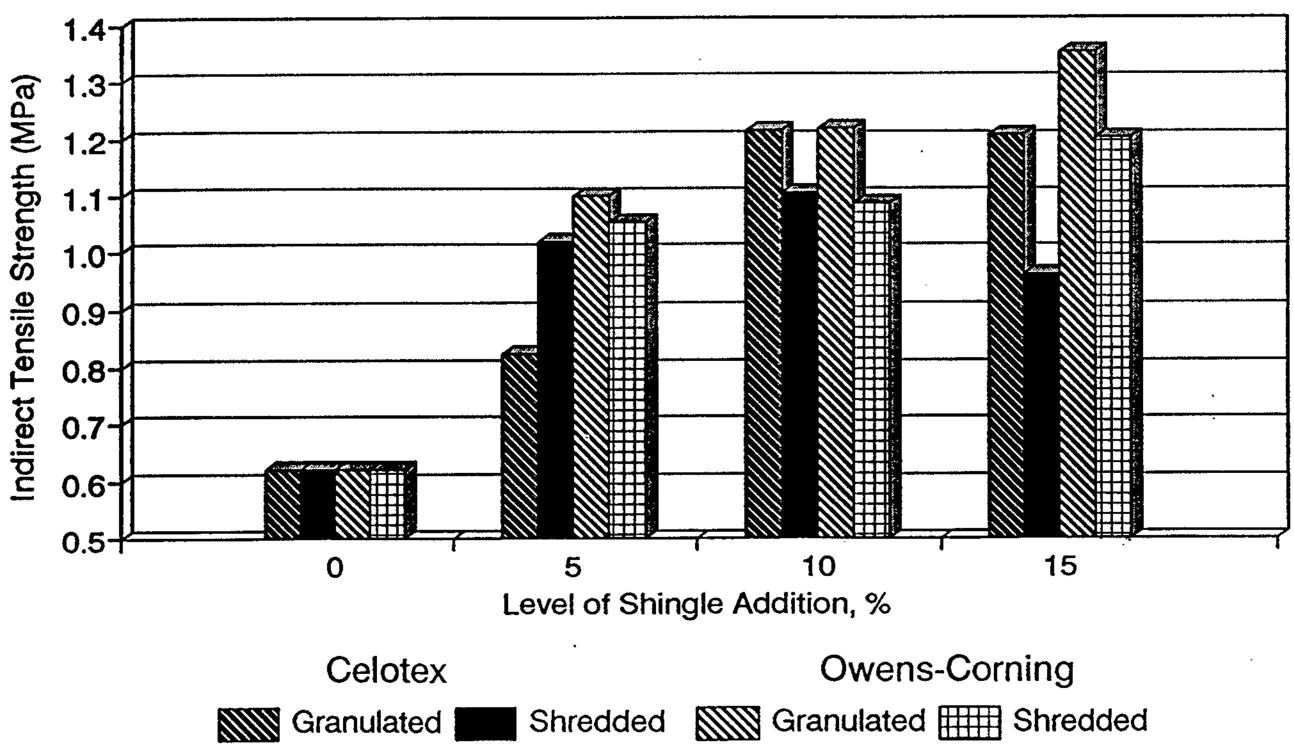



Figure 4.6. Effect of level of shingle addition on indirect tensile strength of asphalt concrete mixes with gravel aggregate.



For both aggregate types the increase in indirect tensile strength was seen to depend on both the shingle source and size reduction method. Indirect tensile strength was seen to increase more for mixes with granulated roofing shingle than for mixes with shredded roofing shingle.

Figures 4.7 (limestone mixes) and 4.8 (gravel mixes) present the magnitude of sample deformation at the maximum indirect tensile strength load in relation to the level of shingle addition. The deformation values range from 1.55 to 2.14 mm for the limestone mixes, and from 1.55 to 2.29 mm for thegravel mixes.

Generally, all of the mixes demonstrated an initial increase in the maximum deformation at 5% shingle addition, followed by a decrease in deformation at higher levels of shingle addition. Figure 4.8 and Column 3 in Table 4.16 show that the gravel mixes with 15% shingle addition had the lowest deformation as measured at the maximum indirect tensile strength load.

Figure 4.7. Effect of level of shingle addition on deformation at maximum load for asphalt concrete mixes with limestone aggregate.

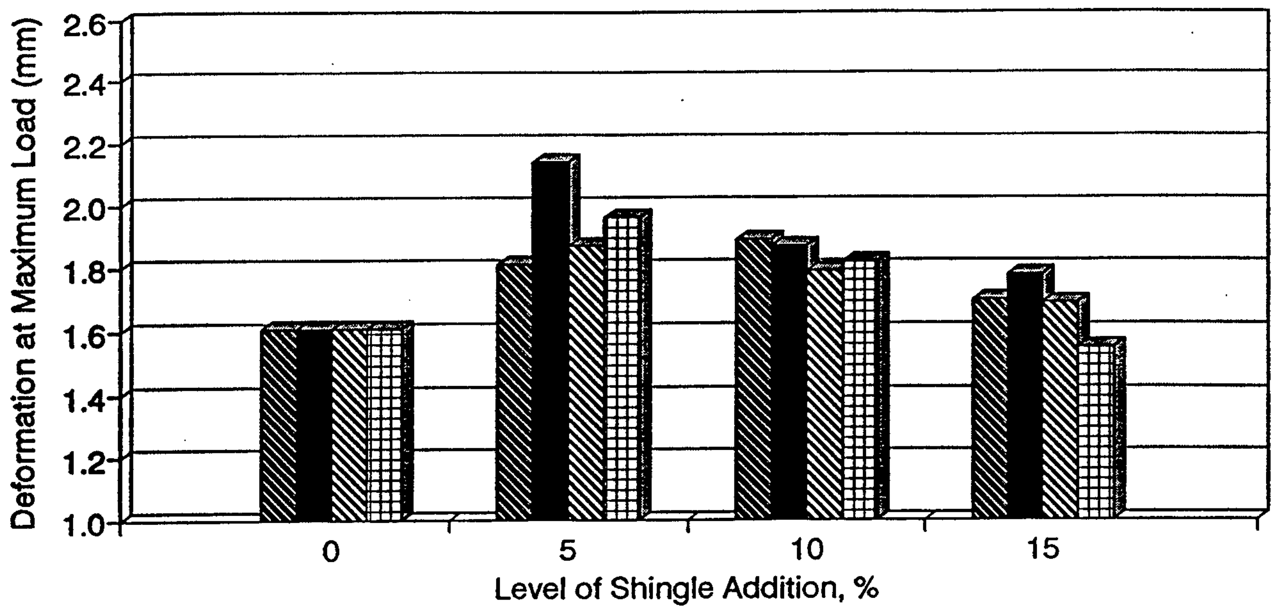
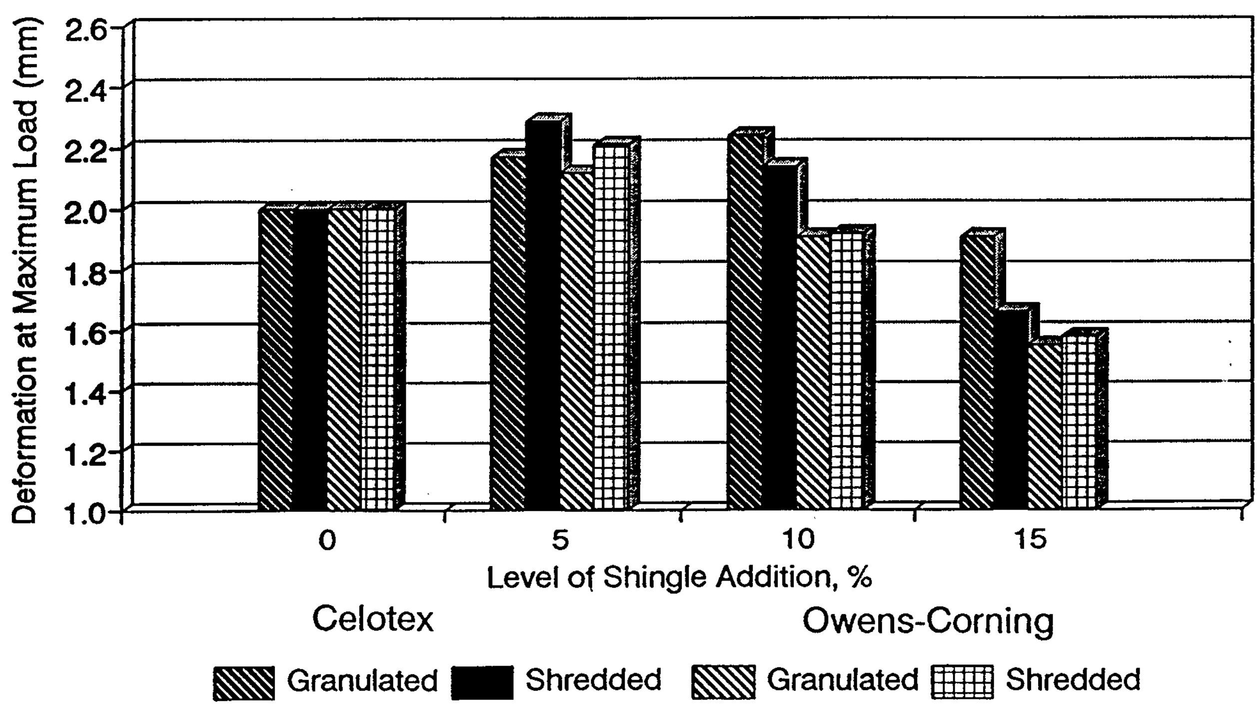



Figure 4.8. Effect of level of shingle addition on deformation at maximum load for asphalt concrete mixes with gravel aggregate.



### 4.5.5. RESILIENT MODULUS.

The modulus of resilience test is performed by application of cyclic vertical compressive loads to a specimen across its diameter, and measuring the total recoverable horizontal deformation. The modulus is calculated as a function of the applied load and resultant measured strain. Testing was conducted under the following conditions:

- Static load applied: 22 - 25 N
- Maximum load applied: 220 ± 5 N
- Load frequency: 1 Hz
- Load duration: 0.1 second
- Test temperature: 0, 22, 40°C

Three specimens were tested for each mix at each temperature. Each specimen was tested in two positions around its cylindrical axis, approximately 90° apart. Fifty loading cycles were applied before measurements were taken when testing at 0 and 22°C. Ten loading cycles were applied before measurements were taken when testing at 40°C. Six to ten measurements were made in each of the two loading positions.

Tables 4.17 and Figures 4.9 through 4.11 and Table 4.18 and Figures 4.12 through 4.14 present the modulus of resilience test data for asphalt concrete mixes with limestone and gravel aggregate, respectively.

Table 4.17. Resilient modulus values for asphalt concrete mixes with limestone aggregate.

| Mix Type | Resilient Modulus (MPa) at Test Temperature (°C) | | |
|---|---|---|---|
| | 0 | 22 | 40 |
| Control | 10,150 | 3,010 | 730 |
| 5% Celotex - G | 9,890 | 2,300 | 560 |
| 5% Celotex - S | 9,660 | 1,830 | 520 |
| 10% Celotex - G | 8,570 | 3,440 | 690 |
| 10% Celotex - S | 8,960 | 2,980 | 780 |
| 15% Celotex - G | 8,590 | 3,710 | 1000 |
| 15% Celotex - S | 9,130 | 3,100 | 860 |
| 5% Owens-Corning - G | 10,880 | 2,750 | 650 |
| 5% Owens-Corning - S | 9,650 | 2,370 | 670 |
| 10% Owens-Corning - G | 9,430 | 3,380 | 1,190 |
| 10% Owens-Corning - S | 9,510 | 2,740 | 610 |
| 15% Owens-Corning - G | 8,380 | 3,260 | 1,430 |
| 15% Owens Corning - S | 8,670 | 3,190 | 1,070 |

The resilient modulus values determined for limestone mixes at 0, 22, and 40°C range from 8,570 to 10,880 MPa, 1,830 to 3,710 MPa, and 520 to 1,430 MPa, respectively. At a test temperature of 0°C, all the limestone shingle mixes, except the 5% granulated Owens-Corning mix, show the lower resilient modulus than the control mix. Lower resilient modulus values indicate less stiffness of the hardened

Figure 4.9. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with limestone aggregate. Test temperature: 0°C.

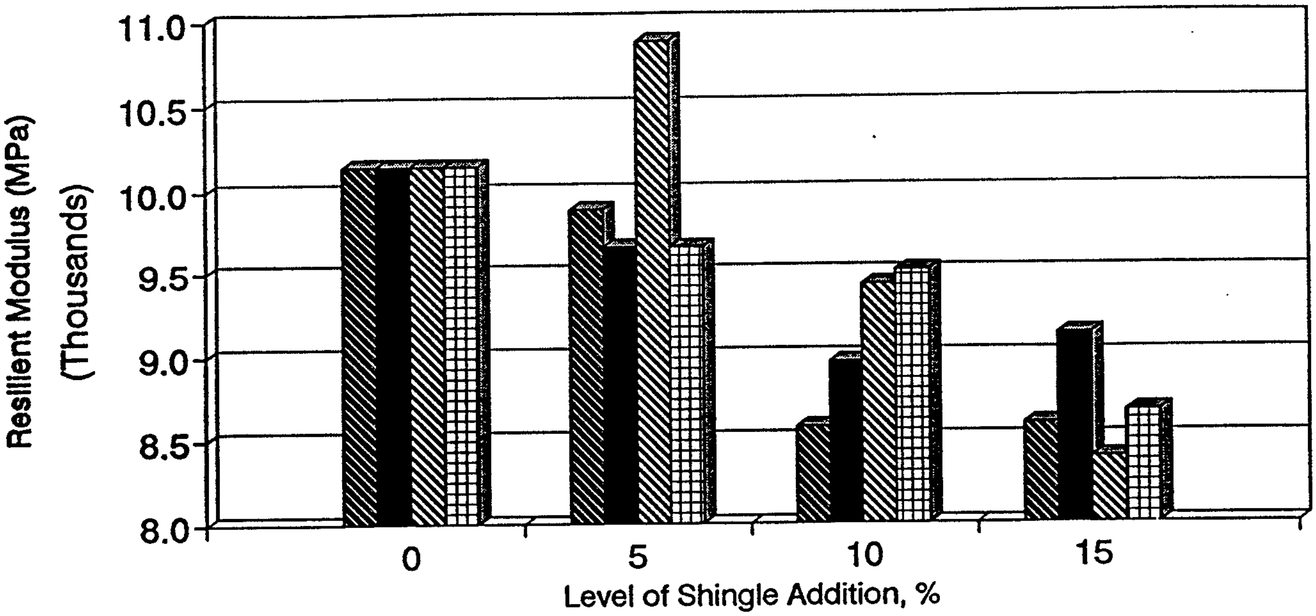



Figure 4.10. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with limestone aggregate. Test temperature: 22°C.

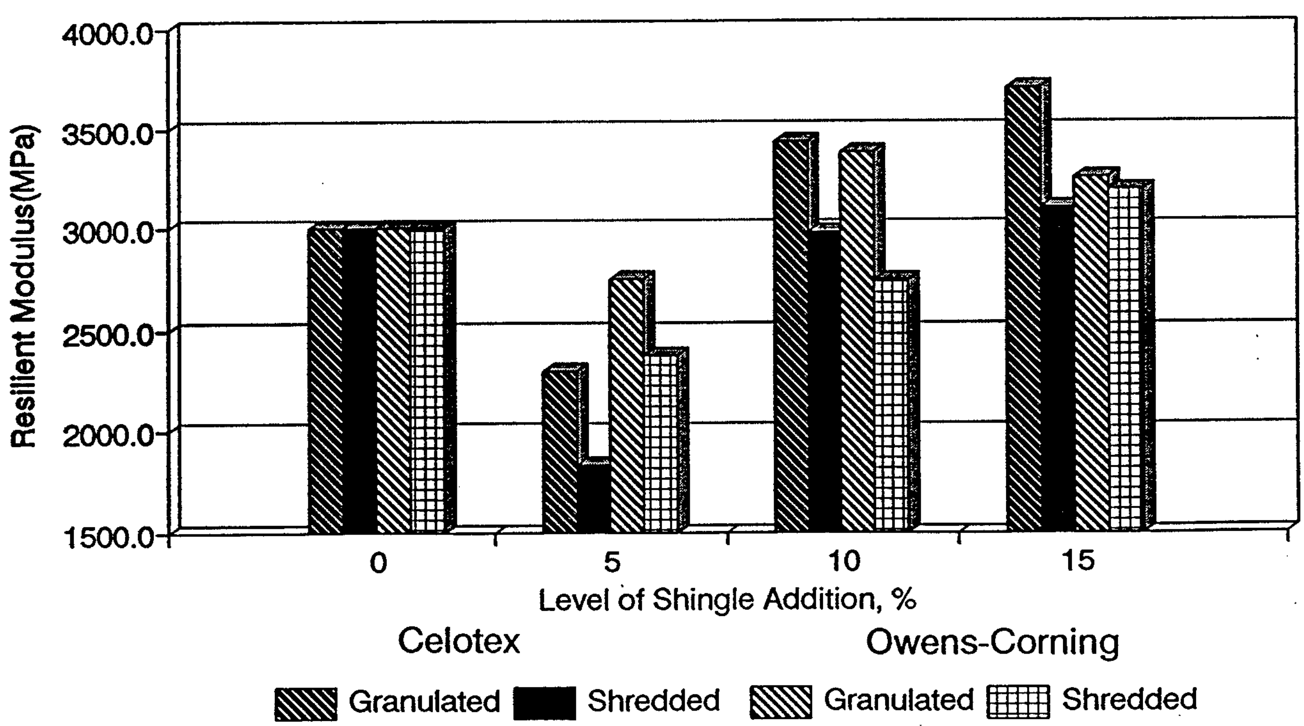


Figure 4.11. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with limestone aggregate. Test temperature: 40°C.

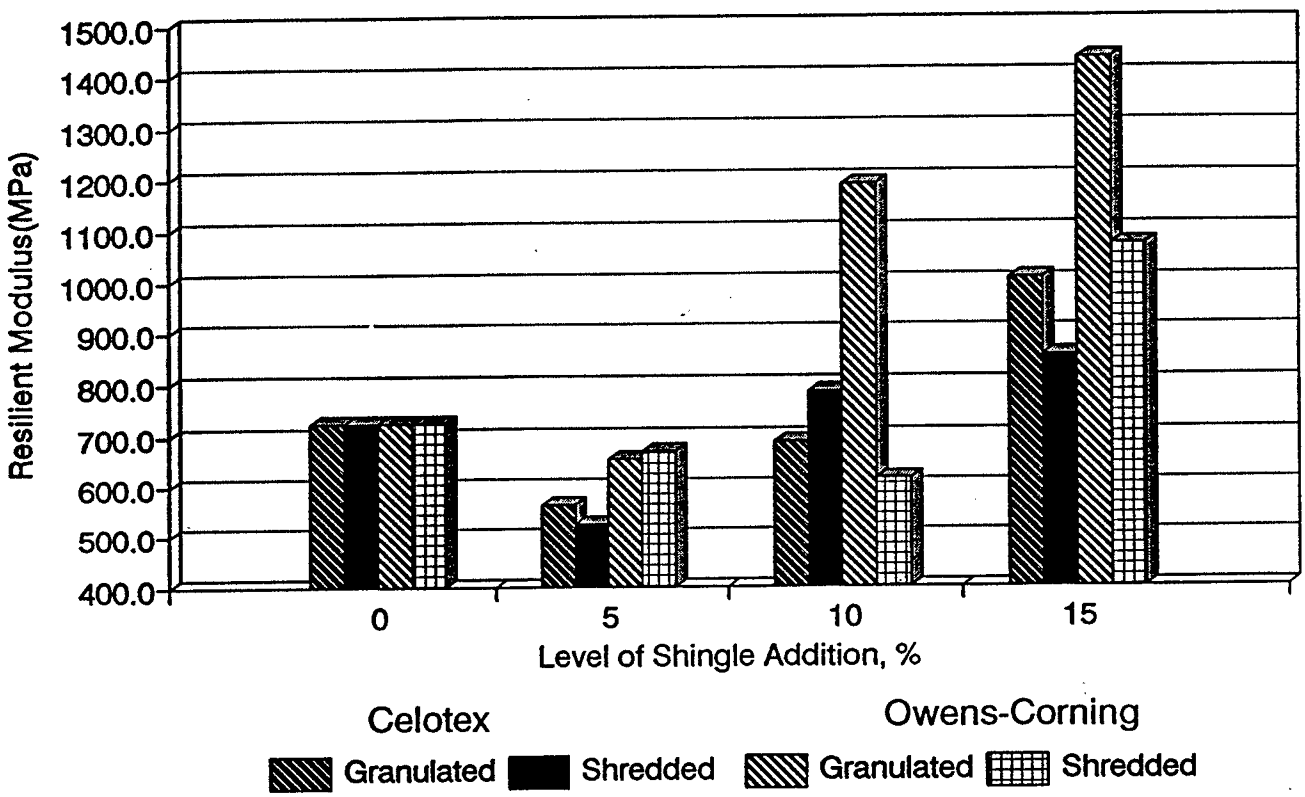


Table 4.18. Resilient modulus values for asphalt concrete mixes with gravel aggregate.

| Mix Type | Resilient Modulus (MPa) at Test Temperature (°C) | | |
|---|---|---|---|
| | 0 | 22 | 40 |
| Control | 8,250 | 2,140 | 330 |
| 5% Celotex - G | 8,630 | 2,880 | 390 |
| 5% Celotex - S | 9,400 | 2,330 | 330 |
| 10% Celotex - G | 8,540 | 2,530 | 730 |
| 10% Celotex - S | 8,250 | 2,480 | 550 |
| 15% Celotex - G | 9,530 | 3,500 | 930 |
| 15% Celotex - S | 7,200 | 2,750 | 650 |
| 5% Owens-Corning - G | 8,880 | 2,620 | 420 |
| 5% Owens-Corning - S | 8,770 | 1,990 | 400 |
| 10% Owens-Corning - G | 9,020 | 2,800 | 710 |
| 10% Owens-Corning - S | 8,160 | 2,400 | 700 |
| 15% Owens-Corning - G | 9,550 | 4,070 | 1,370 |
| 15% Owens Corning - S | 7,580 | 3,230 | 1,010 |

mix. At 22 and 40°C, all of the limestone/shingle mixes at 15% shingle addition show greater resilient modulus values, than the control mix. It is notable that the resilient modulus value for the 15% granulated Owens-Corning mix at 40°C is approximately twice the value for the control mix, which could result in much greater mix stiffness at increased temperatures.

The resilient modulus values determined for the gravel mixes at 0, 22, and 40°C range from 7,200 to 9,550 MPa, 1990 to 4070 MPa, and 330 to 1370 MPa,

Figure 4.12. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with gravel aggregate. Test temperature: $0^{\circ}C$.

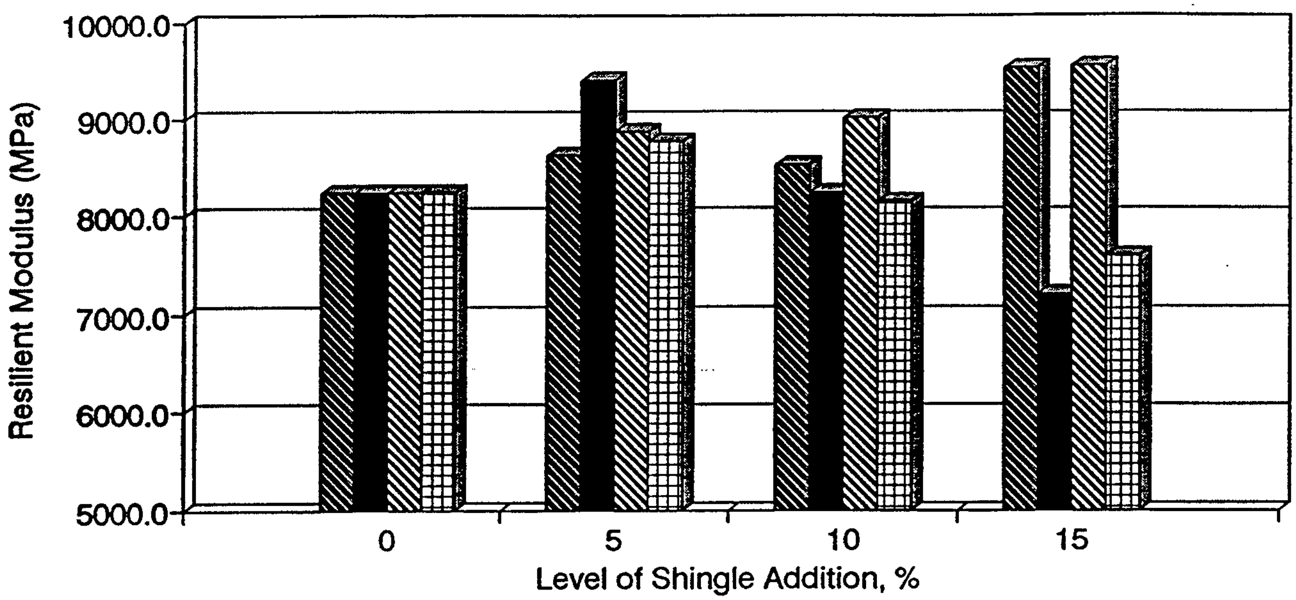



Figure 4.13. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with gravel aggregate. Test temperature: $22^{\circ}C$.

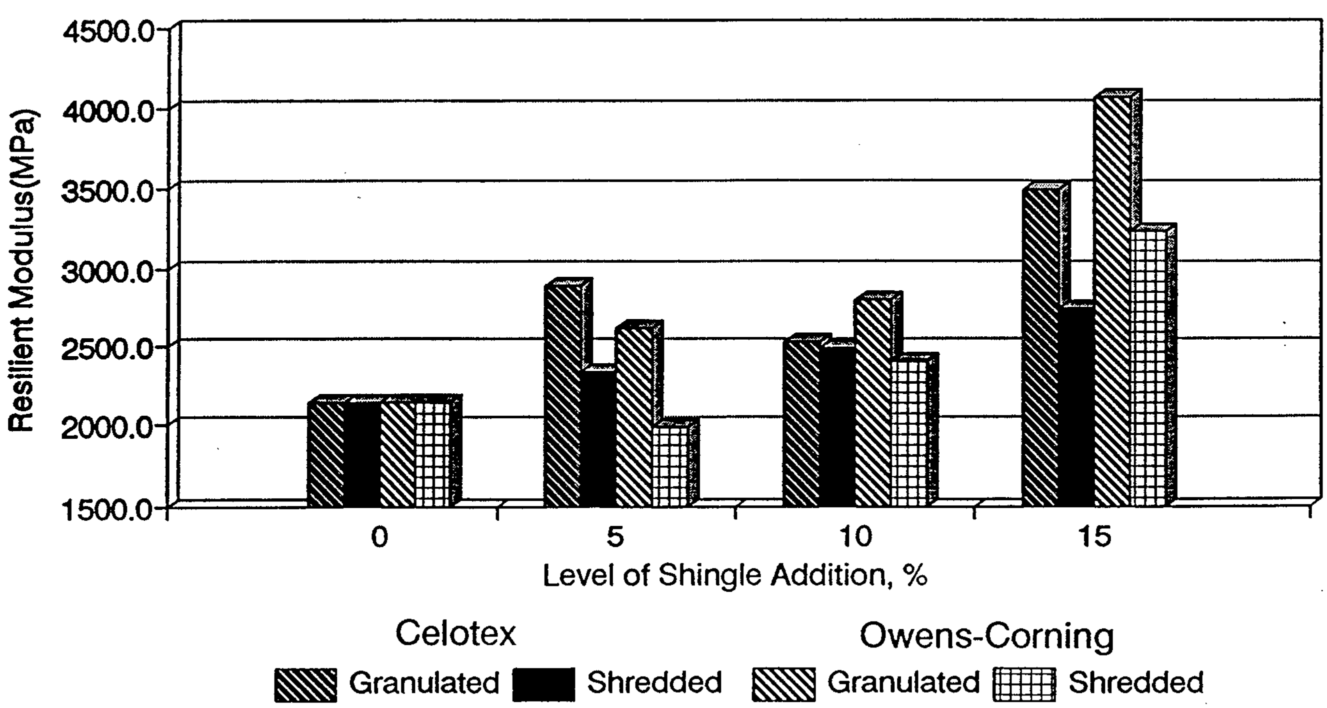
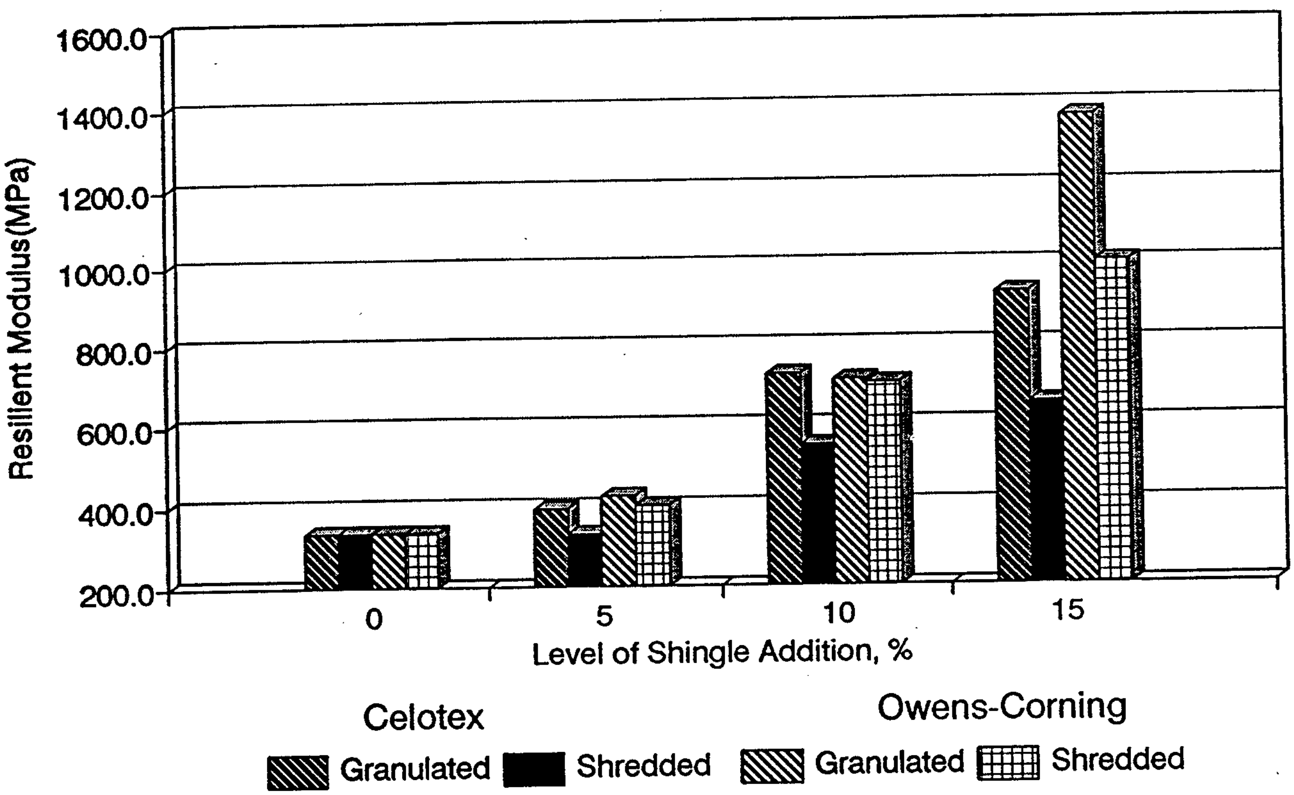


Figure 4.14. Effect of level of shingle addition on resilient modulus for asphalt concrete mixes with gravel aggregate. Test temperature: 40°C.



respectively. At 0°C, all of the gravel/shingle mixes with 5 and 10% shingle addition had greater resilient modulus than the control mix. The 15% shingle addition resulted in an increased resilient modulus for mixes with granulated shingles, and a decreased resilient modulus for mixes with shredded shingles. At 22°C the control mix and the mix with 5% shredded Owens-Corning shingle had the lowest resilient modulus values. The mixes with shredded Celotex and granulated Owens-Corning shingles showed increases in resilient modulus with increased levels of shingle addition. The remaining two mixes, one with granulated Celotex and the other with shredded Owens-Corning, each at one level of shingle addition, yielded resilient modulus values that did not follow the increasing trend. The mix with 5% shredded Owens-Corning shingles had a lower resilient modulus than the control mix, and the mix with granulated Celotex shingles had a lower resilient modulus at 10% than at 5% shingle addition level. The authors believe that this irregularity is attributable to some error in the sample preparation and/or test data collection processes. The resilient modulus values at 40°C for gravel mixes showed an increase with the increased level of shingle addition. At this temperature, mixes with 10 and 15% shingle addition yielded resilient modulus values that were one and a half to four times greater than the values for the control mixes.

### 4.5.6. INDIRECT TENSILE CREEP MODULUS.

The test was performed by applying of a fixed vertical load of 445 Newtons across the diameter of each specimen for 3,600 seconds. Horizontal deformation of the specimen was measured at 1, 3, 10, 30, 100, 300, 1,000, and 3,600 seconds under load application, and at 1, 3, 10, 30, 100, 300, 1,000, and 3,600 seconds following load removal. Testing was conducted at a temperature of 22°C. The indirect tensile creep modulus was calculated as a function of the applied stress and resultant strain. The average indirect tensile creep modulus data is presented in Table 4.19 and Figures 4.15 through 4.18 for the limestone mixes, and in Table 4.20 and Figures 4.19 through 4.22 for the gravel mixes. The indirect tensile creep modulus data for all specimens is presented in Appendix D.

Table 4.19. Average indirect tensile creep modulus data for mixes with limestone aggregate.

| Mix Type | Indirect Tensile Creep Modulus (MPa) at a Loading Time Elapsed (sec) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1,000 | 3,600 |
| Control | 479 | 278 | 156 | 92 | 59 | 40 | 26 | 14 |
| 5% Celotex - G | 749 | 428 | 235 | 129 | 73 | 47 | 31 | 19 |
| 5% Celotex - S | 577 | 329 | 183 | 104 | 65 | 42 | 28 | 17 |
| 10% Celotex - G | 760 | 493 | 294 | 178 | 117 | 80 | 55 | 35 |
| 10% Celotex - S | 660 | 429 | 244 | 148 | 95 | 66 | 46 | 28 |
| 15% Celotex - G | 933 | 630 | 383 | 236 | 148 | 99 | 63 | 38 |
| 15% Celotex - S | 786 | 551 | 326 | 193 | 114 | 71 | 43 | 24 |
| 5% Owens-Corning - G | 728 | 431 | 246 | 146 | 89 | 60 | 41 | 26 |
| 5% Owens-Corning - S | 615 | 362 | 205 | 119 | 72 | 48 | 32 | 19 |
| 10% Owens-Corning - G | 773 | 472 | 288 | 180 | 117 | 85 | 57 | 37 |
| 10% Owens-Corning - S | 802 | 482 | 293 | 181 | 11 | 73 | 49 | 31 |
| 15% Owens-Corning - G | 972 | 675 | 397 | 252 | 160 | 106 | 67 | 39 |
| 15% Owens-Corning - S | 945 | 614 | 386 | 237 | 147 | 95 | 58 | 34 |

Figure 4.15. Average creep modulus data for asphalt mixes with limestone aggregate and granulated Celotex shingles.

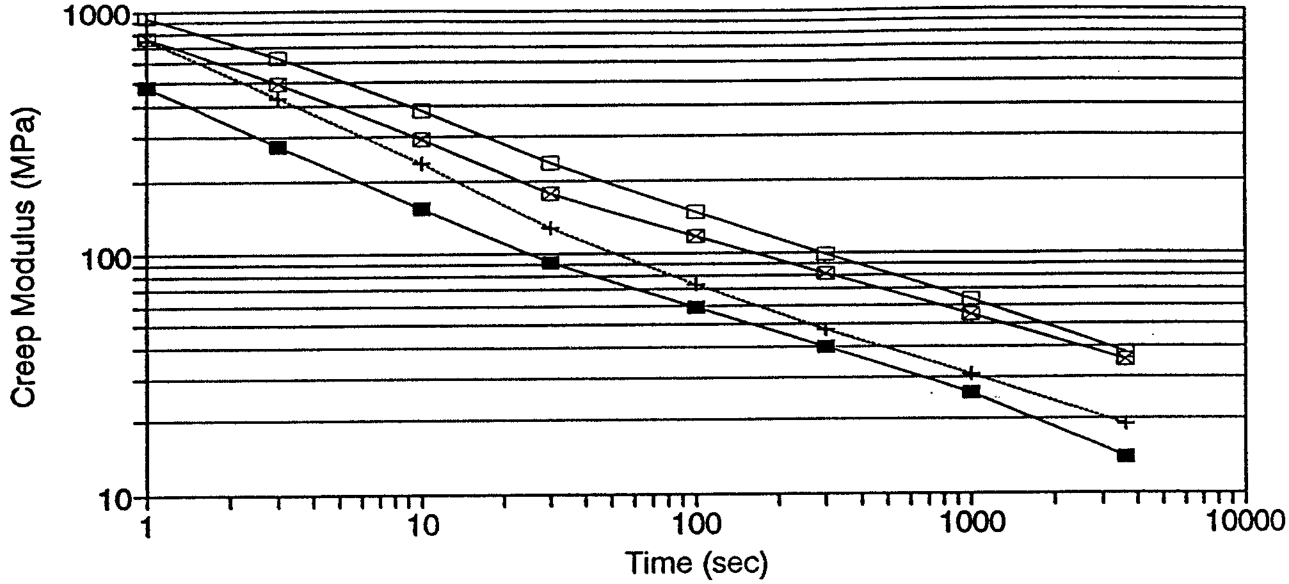
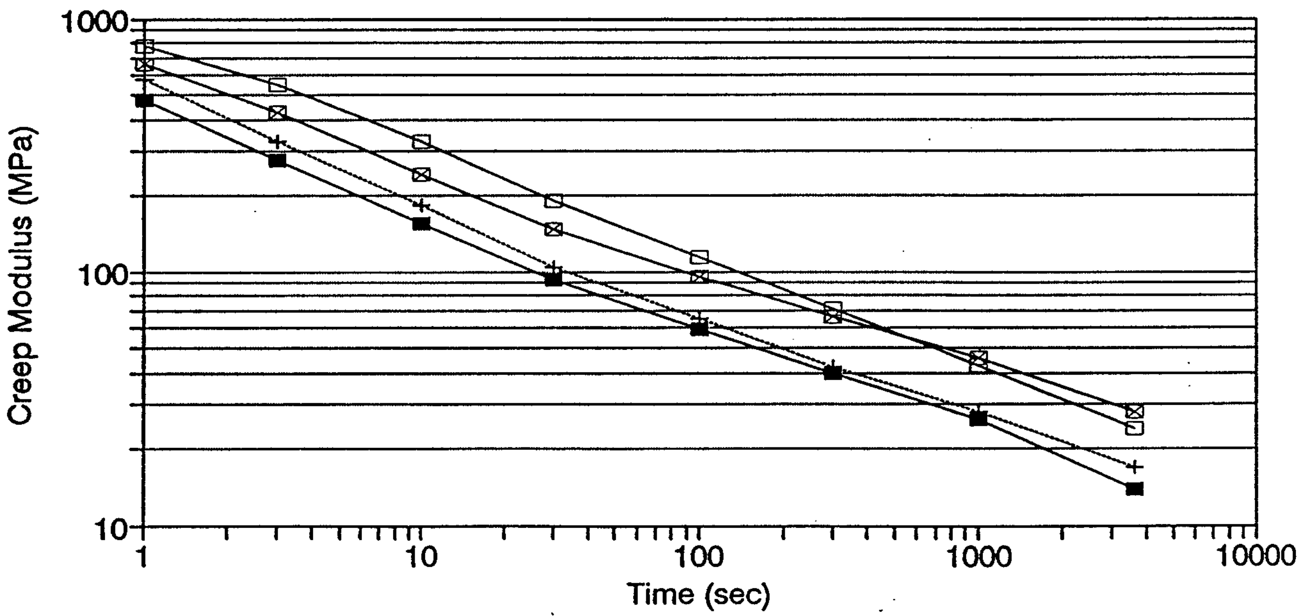



Figure 4.16. Average creep modulus data for asphalt mixes with limestone aggregate and shredded Celotex shingles.




Level of Shingle Addition: 0% 5% 10% 15%

Figure 4.17. Average creep modulus data for asphalt mixes with limestone aggregate and granulated Owens-Corning shingles.

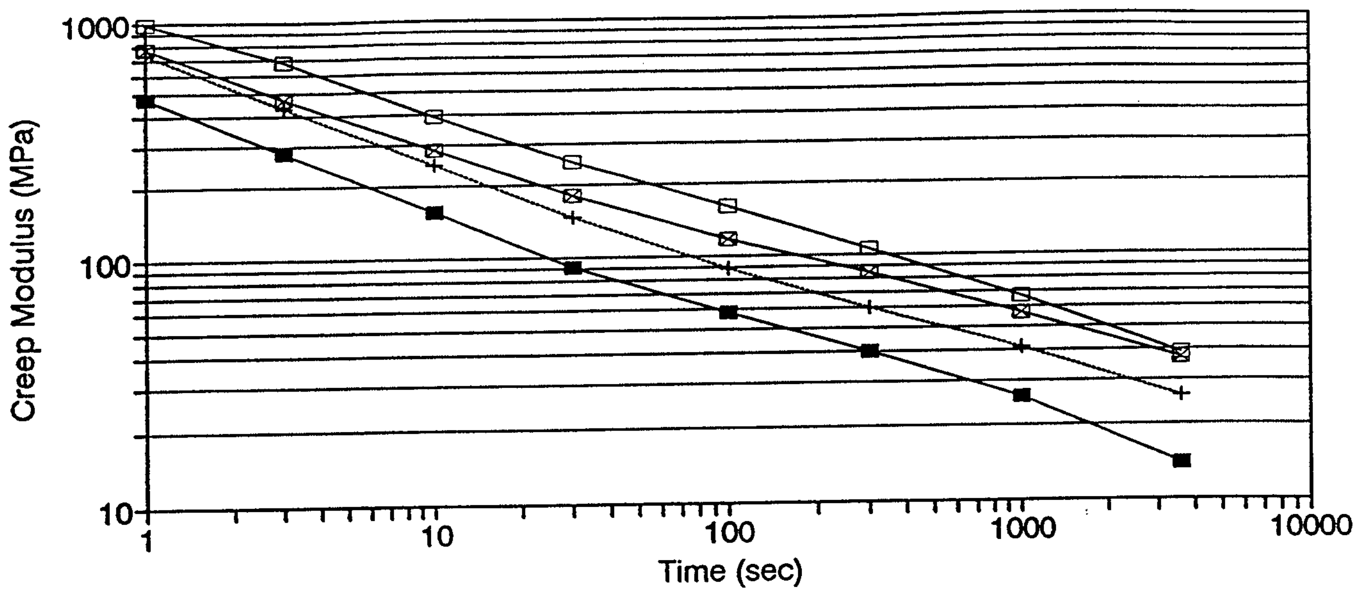



Figure 4.18. Average creep modulus data for asphalt mixes with limestone aggregate and shredded Owens-Corning shingles.

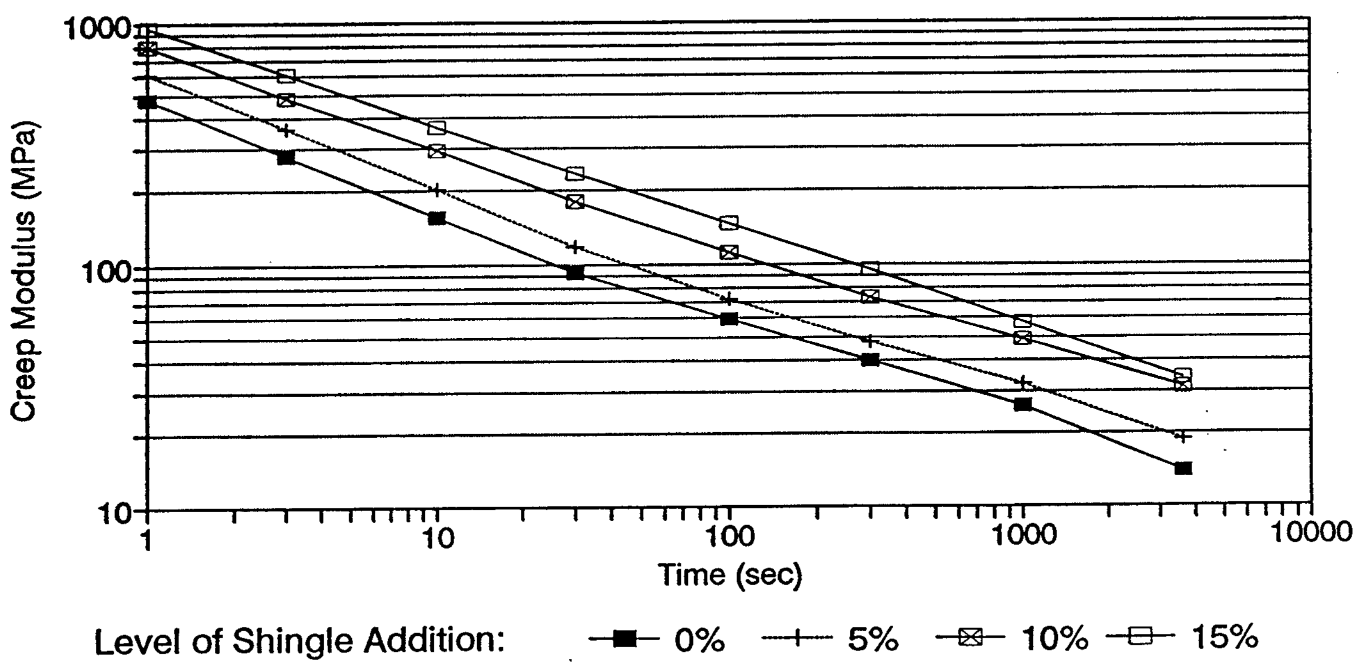


Table 4.20. Average indirect tensile creep modulus data for mixes with gravel aggregate.

| Mix Type | Indirect Tensile Creep Modulus (MPa) at a Loading Time Elapsed (sec) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1,000 | 3,600 |
| Control | 265 | 151 | 77 | 41 | 24 | 15 | 9 | 3 |
| 5% Celotex - G | 310 | 178 | 96 | 55 | 34 | 23 | 14 | 7 |
| 5% Celotex - S | 629 | 359 | 198 | 110 | 62 | 38 | 22 | 11 |
| 10% Celotex - G | 756 | 505 | 267 | 153 | 92 | 59 | 35 | 19 |
| 10% Celotex - S | 551 | 335 | 170 | 113 | 65 | 39 | 23 | 13 |
| 15% Celotex - G | 983 | 611 | 428 | 277 | 182 | 121 | 73 | 41 |
| 15% Celotex - S | 865 | 550 | 333 | 204 | 126 | 82 | 49 | 27 |
| 5% Owens-Corning - G | 696 | 425 | 242 | 136 | 75 | 45 | 27 | 15 |
| 5% Owens-Corning - S | 643 | 382 | 219 | 123 | 70 | 44 | 29 | 15 |
| 10% Owens-Corning - G | 884 | 585 | 361 | 218 | 129 | 81 | 50 | 31 |
| 10% Owens-Corning - S | 635 | 384 | 243 | 146 | 88 | 55 | 32 | 16 |
| 15% Owens-Corning - G | 1121 | 748 | 464 | 317 | 211 | 151 | 100 | 59 |
| 15% Owens-Corning - S | 733 | 500 | 309 | 208 | 136 | 94 | 62 | 37 |

G15% Owens-Corning granulated average of 5 samples
G15% Celotex shredded average of 5 samples.

Figure 4.19. Average creep modulus data for asphalt mixes with gravel aggregate and granulated Celotex shingles.

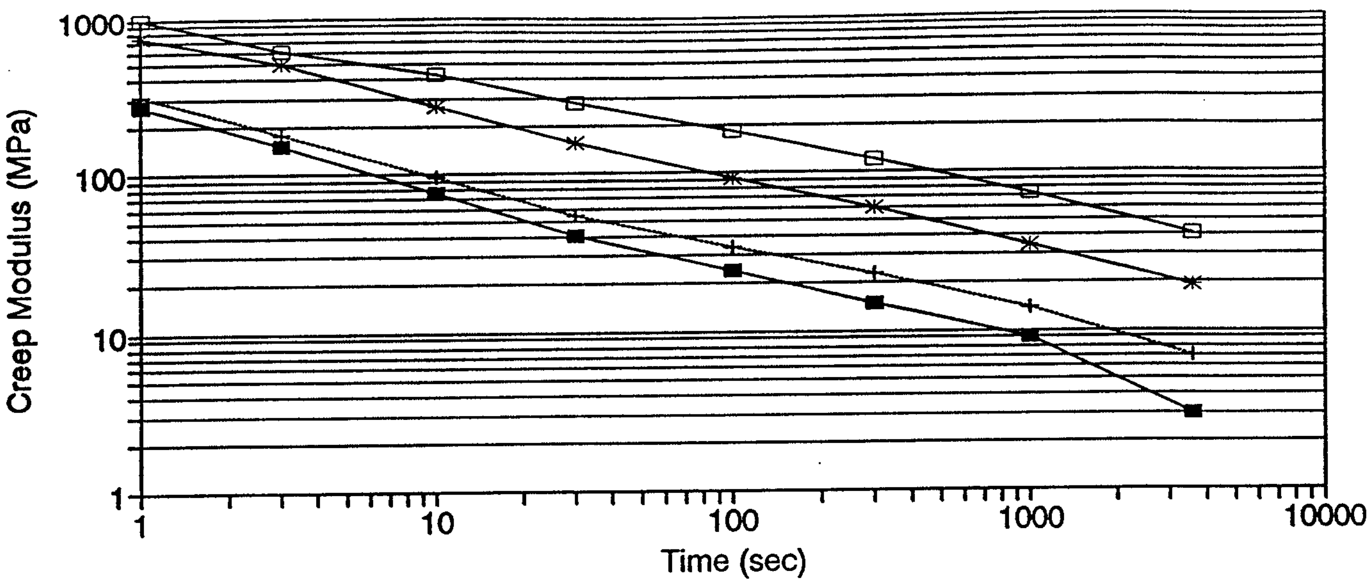



Figure 4.20. Average creep modulus for asphalt mixes with gravel aggregate and shredded Celotex shingles.

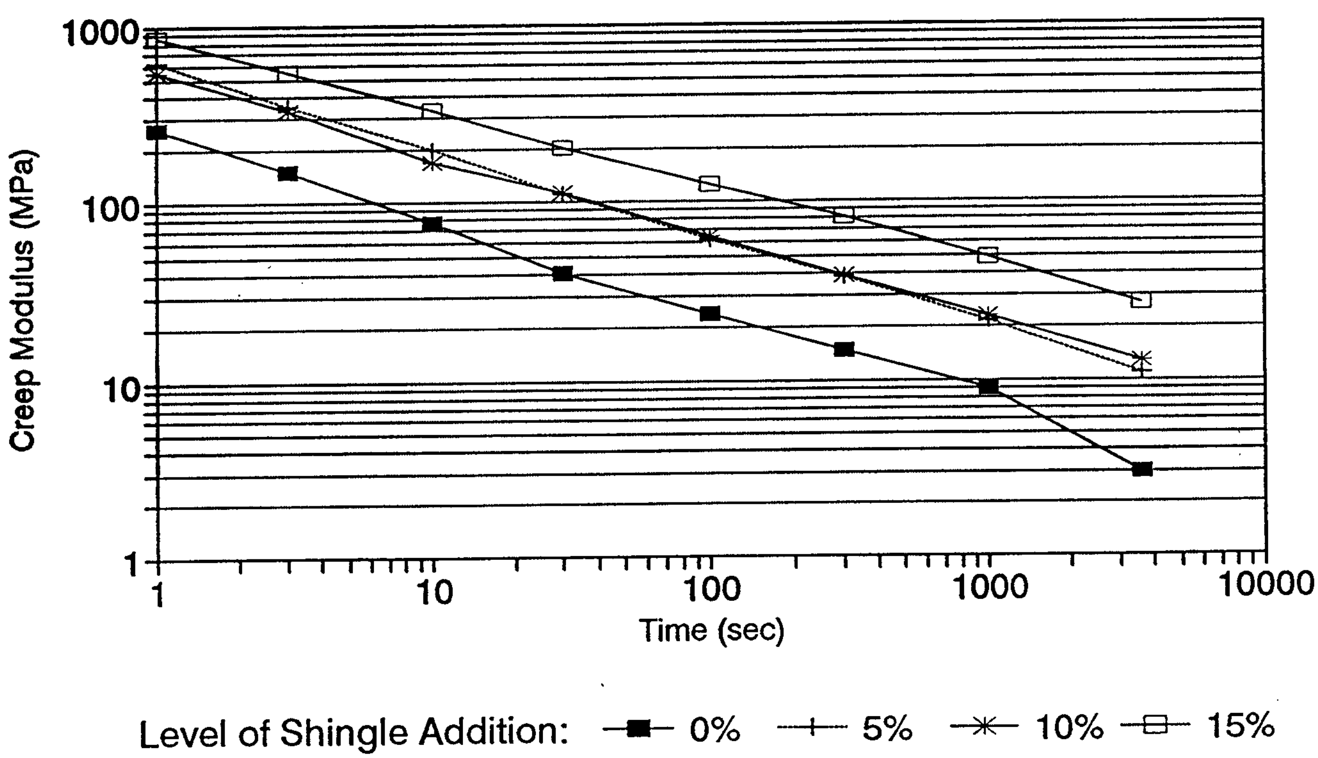


Figure 4.21. Average creep modulus data for asphalt mixes with gravel aggregate and granulated Owens-Corning shingles.

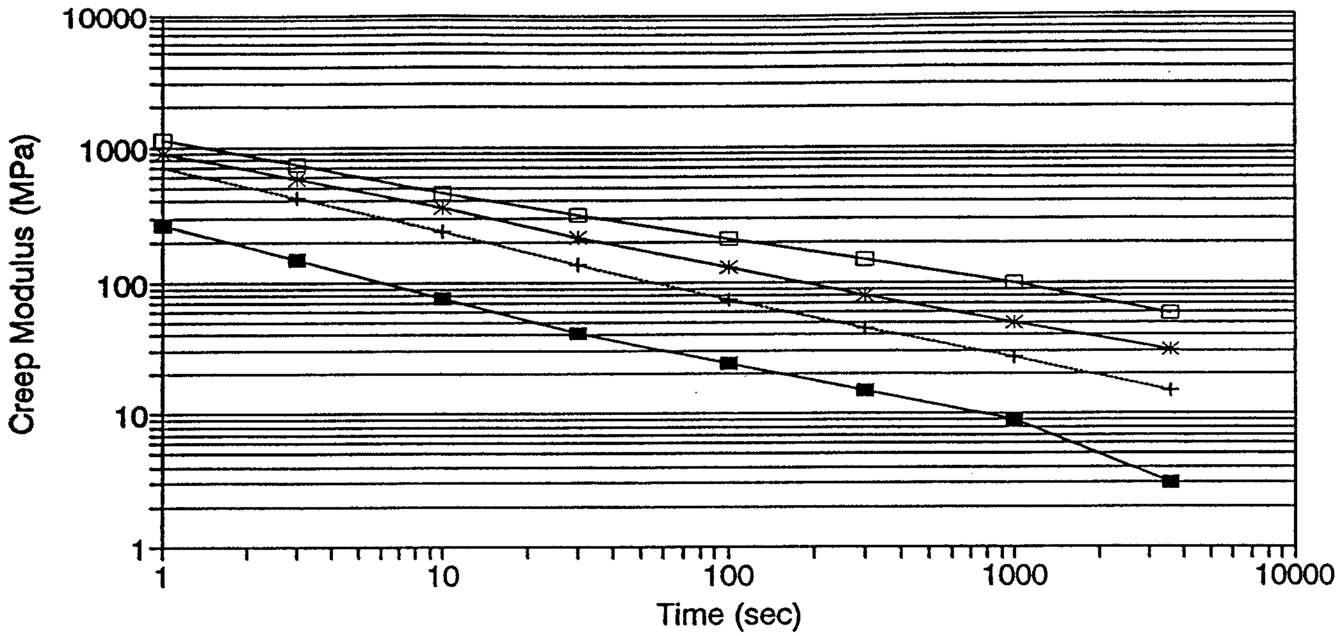
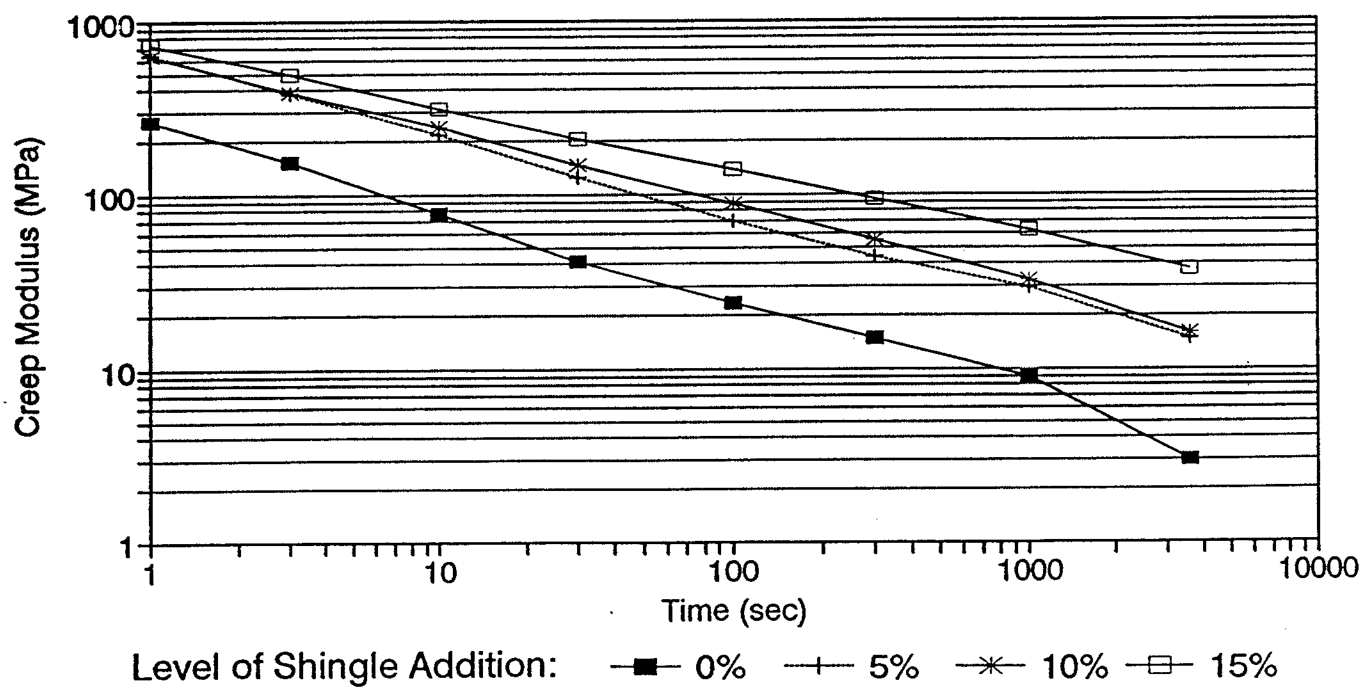



Figure 4.22. Average creep modulus data for asphalt mixes with gravel aggregate and shredded Owens-Corning shingles.



The average indirect tensile creep data for limestone mixes is presented in Figures 4.15 and 4.16 for mixes with granulated and shredded Celotex shingles, and in Figures 4.17 and 4.18 for mixes with granulated and shredded Owens-Corning shingles, respectively. The mixes with no shingle addition showed the lowest modulus values. The indirect tensile creep modulus values increased with an increased level of shingle addition (the only exception is the value of mix with shredded Celotex shingles at 15% shingle addition). Accordingly, the mixes with 15% shingle addition showed the highest indirect tensile creep modulus value.

The average indirect tensile creep data for gravel mixes is shown in Figures 4.19 and 4.20 for mixes with granulated and shredded Celotex shingles, and in Figures 4.21 and 4.22 for mixes with granulated and shredded Owens-Corning shingles, respectively. The mixes with no shingle addition show the lowest modulus values. The indirect tensile creep modulus values increase with an increased level of shingle addition (the only exception is the value of mix with shredded Celotex shingles at 10% shingle addition). Like the limestone mixes, the gravel mixes showed the highest indirect tensile creep data values at 15% shingle addition level.

The results of indirect tensile creep testing give a good indication of the ability of a mix to resist rutting. Figures 4.23 and 4.24 are sample graphs of creep modulus vs. time for gravel mixes and 0 and 15% granulated Owens-Corning shingle addition. Figures 4.25 and 4.26 are sample graphs of creep modulus vs. time for limestone mixes and 0 and 15% granulated Owens-Corning shingle addition.

Figure 4.23 Creep modulus test data for mix with gravel aggregate and 0% waste asphalt roofing shingle addition.

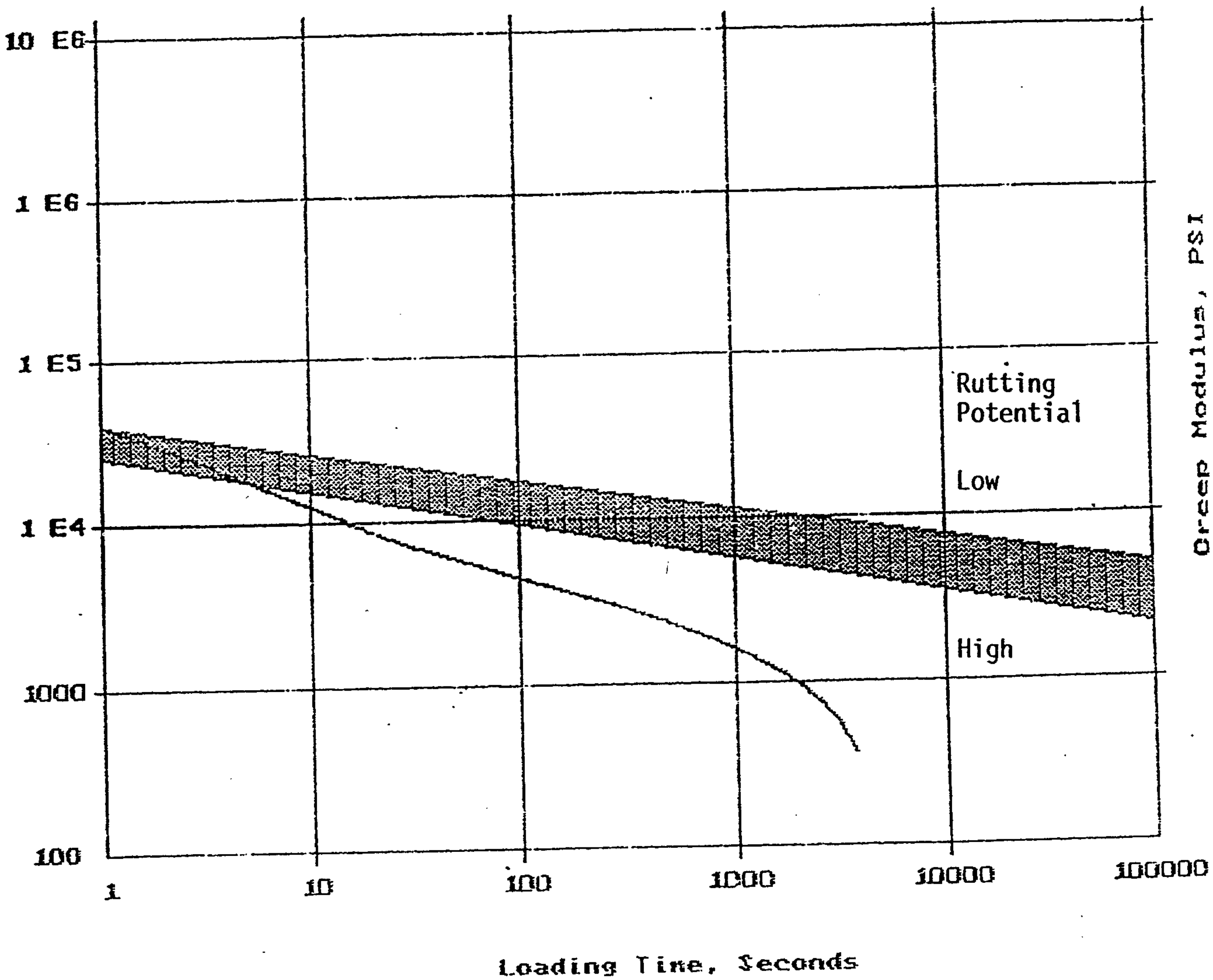


Figure 4.24 Creep modulus test data for mix with gravel aggregate and 15% Owens-Corning shingle addition.

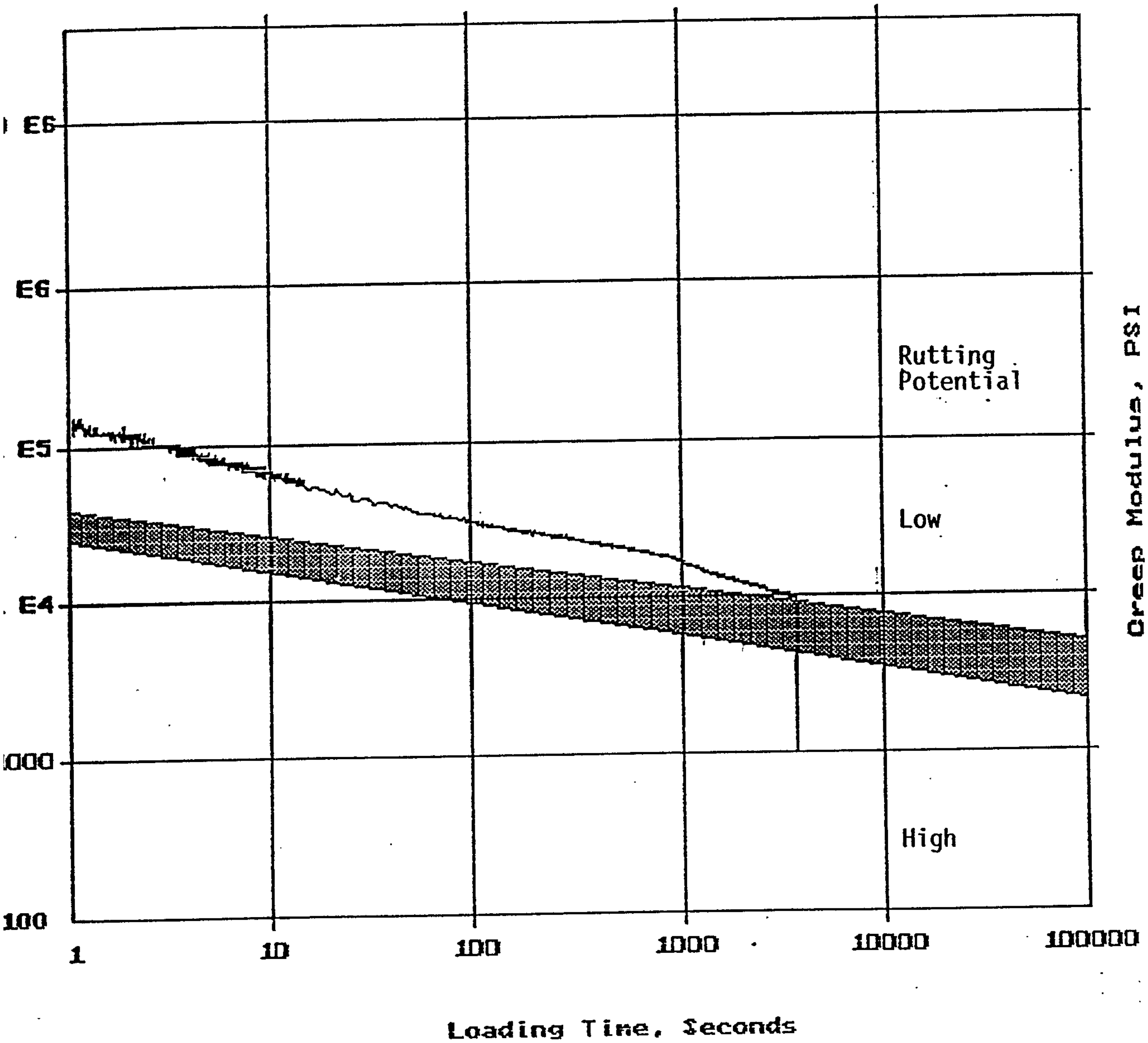


Figure 4.25 Creep modulus test data for mix with limestone aggregate and 0% waste asphalt roofing shingle addition.

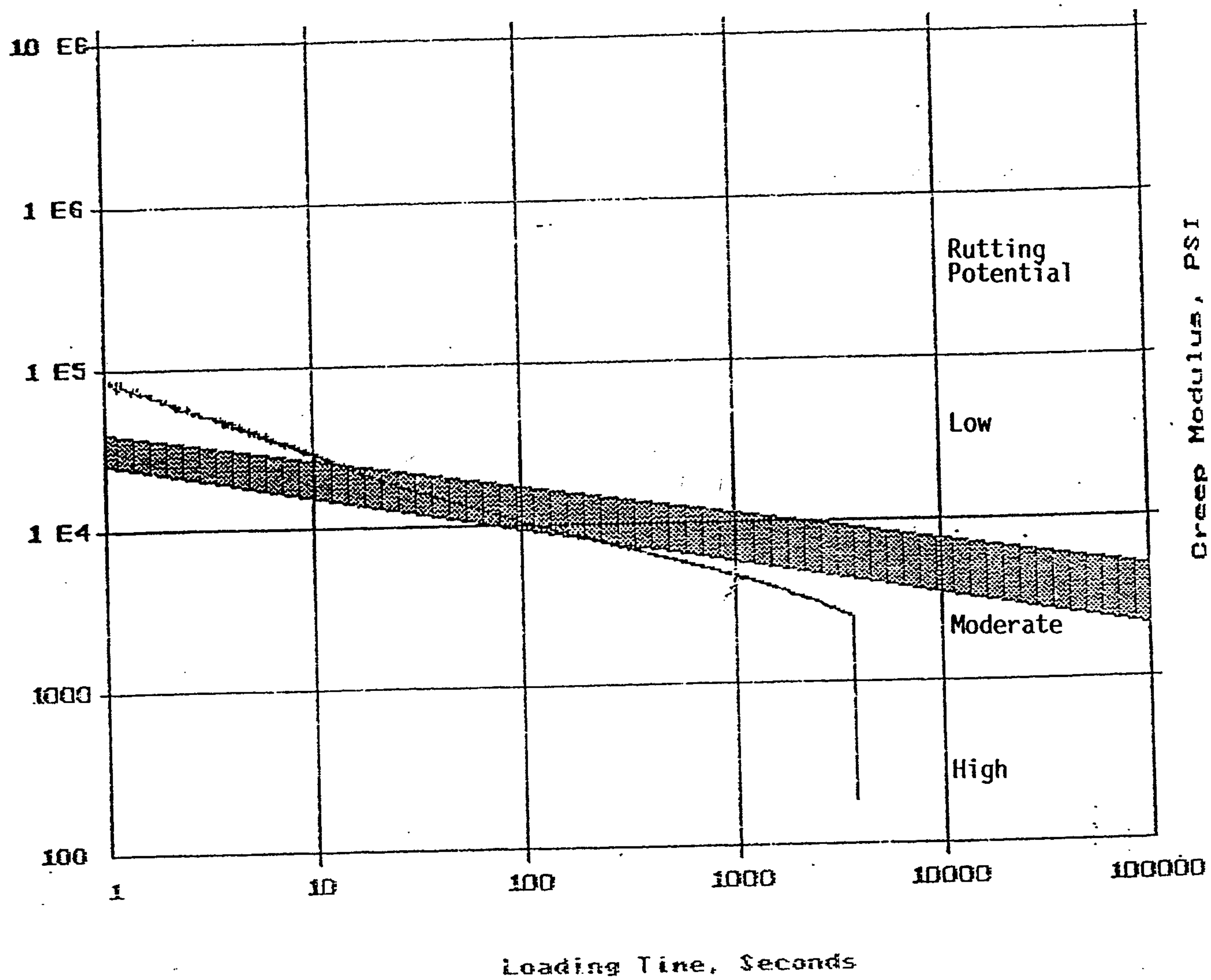
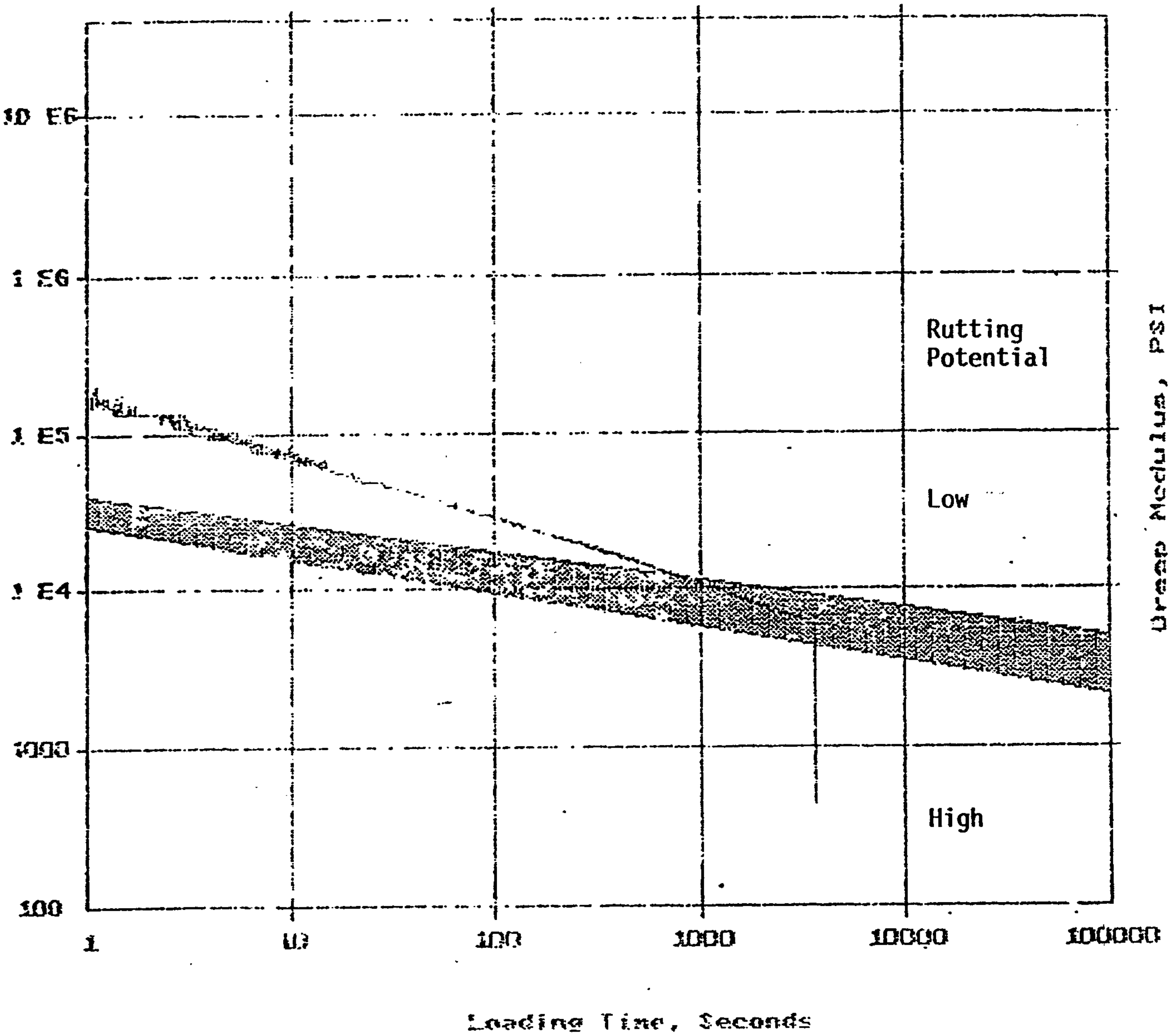


Figure 4.26 Creep modulus test data for mix with limestone aggregate and 15% Owens-Corning shingle addition.



These graphs are presented in the format provided in N.C.H.R.P. Report 338, which classifies three zones of rutting potential: low, moderate, and high, which are located above, within, and below the shaded area, respectively. Figure 4.23 indicates that the gravel mix with 0% shingle addition has moderate (from 1 to approximately 6 seconds) to high (from 6 to 3600 seconds) rutting potential. Figure 4.24 indicates that gravel mix with 15% granulated Owens-Corning shingle addition has low rutting potential. Figure 4.25 shows that the limestone mix and 0% shingle addition has low (from 1 to approximately 15 seconds) to moderate (from 15 to 3,600 seconds) rutting potential. Figure 4.26 shows that the limestone mix with 15% granulated Owens-Corning shingle addition has low (from 1 to approximately 900 seconds) to moderate (from 900 to 3,600 seconds) rutting potential.

Table 4.21 and 4.22, and Figures 4.27 through 4.34, present average measurements of the change in vertical deformation of the test specimens after load removal. With one exception (10% Owens-Corning granulated) the limestone mixes with 10 and 15% shingle addition showed less deformation at 3,600 seconds after load removal than the control mixes. All the gravel mixes with shingle addition showed less deformation at 3,600 seconds after load removal than the control mix. These trends indicate that mixes with 10 and 15% roofing shingle addition perform better than conventional mixes with regard to elastic properties. Under field conditions, these mixes will have less permanent deformation (rutting) than conventional mixes.

Table 4.21. Vertical deformation after removal of indirect tensile creep loading (limestone mixes).

| Mix Type | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1,000 | 3,600 |
| Control | 0.409 | 0.364 | 0.348 | 0.339 | 0.327 | 0.306 | 0.290 | 0.269 | 0.260 |
| 5% Celotex - G | 0.422 | 0.380 | 0.368 | 0.356 | 0.343 | 0.335 | 0.323 | 0.298 | 0.285 |
| 5% Celotex - S | 0.587 | 0.550 | 0.521 | 0.509 | 0.496 | 0.475 | 0.451 | 0.438 | 0.405 |
| 10% Celotex - G | 0.316 | 0.292 | 0.285 | 0.279 | 0.267 | 0.267 | 0.242 | 0.223 | 0.217 |
| 10% Celotex - S | 0.389 | 0.360 | 0.347 | 0.339 | 0.327 | 0.314 | 0.306 | 0.281 | 0.252 |
| 15% Celotex - G | 0.331 | 0.285 | 0.285 | 0.269 | 0.265 | 0.248 | 0.240 | 0.219 | 0.215 |
| 15% Celotex - S | 0.376 | 0.343 | 0.335 | 0.322 | 0.314 | 0.310 | 0.289 | 0.265 | 0.248 |
| 5% Owens-Corning - G | 0.347 | 0.310 | 0.298 | 0.289 | 0.277 | 0.265 | 0.256 | 0.240 | 0.215 |
| 5% Owens-Corning - S | 0.496 | 0.463 | 0.451 | 0.447 | 0.434 | 0.417 | 0.405 | 0.384 | 0.356 |
| 10% Owens-Corning - G | 0.384 | 0.343 | 0.335 | 0.327 | 0.327 | 0.314 | 0.306 | 0.294 | 0.285 |
| 10% Owens-Corning - S | 0.372 | 0.327 | 0.323 | 0.310 | 0.302 | 0.289 | 0.277 | 0.265 | 0.248 |
| 15% Owens-Corning - G | 0.343 | 0.310 | 0.298 | 0.289 | 0.281 | 0.273 | 0.260 | 0.252 | 0.240 |
| 15% Owens-Corning - S | 0.310 | 0.260 | 0.256 | 0.248 | 0.244 | 0.232 | 0.219 | 0.203 | 0.190 |

Figure 4.27. Vertical deformation after load removal for asphalt concrete mixes with limestone aggregate and granulated Celotex shingles.

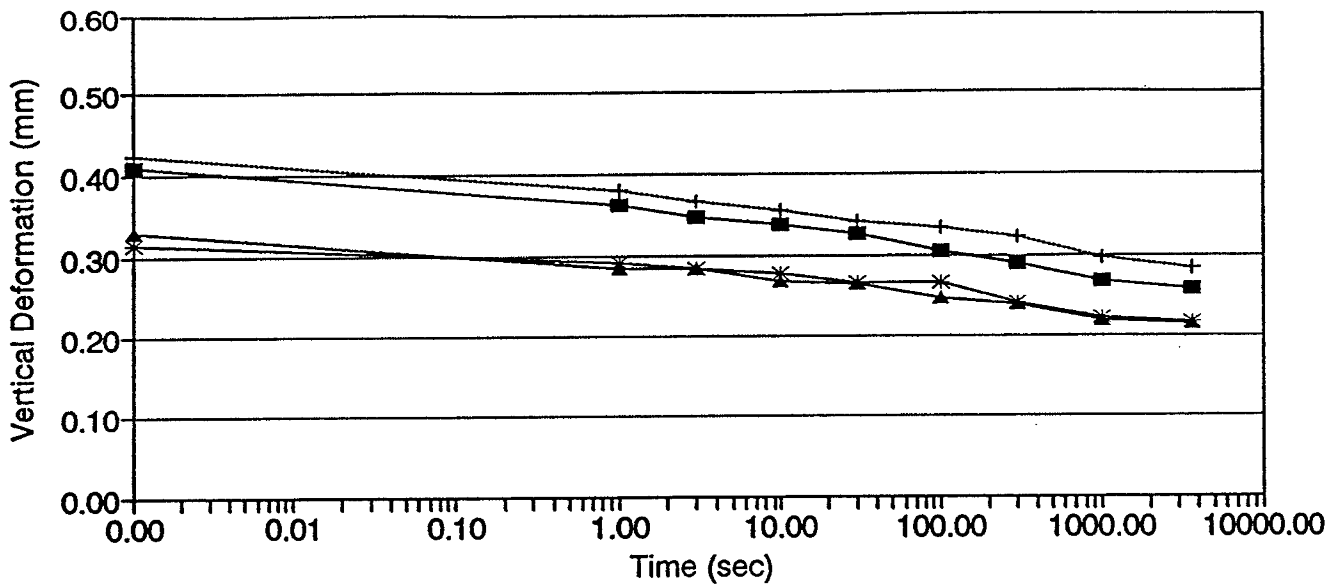



Figure 4.28. Vertical deformation after load removal for asphalt concrete mixes with limestone aggregate and shredded Celotex shingles.

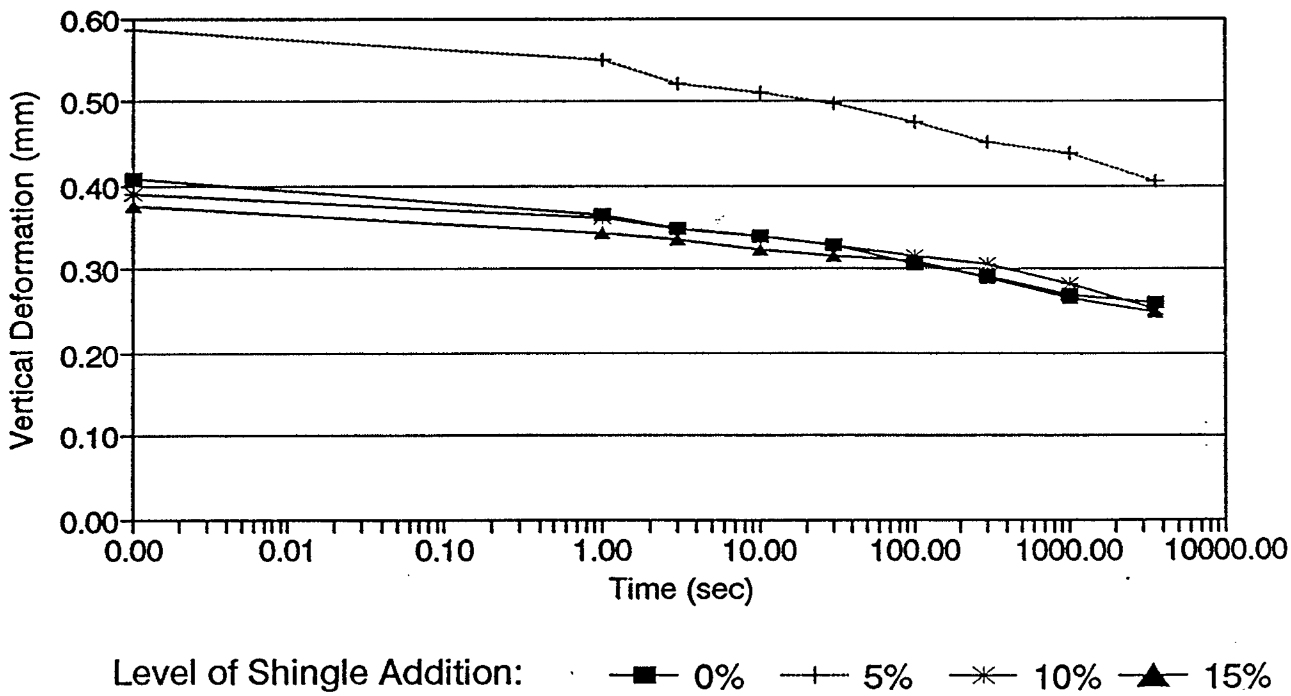


Figure 4.29. Vertical deformation after load removal for asphalt concrete mixes with limestone aggregate and granulated Owens-Corning shingles.

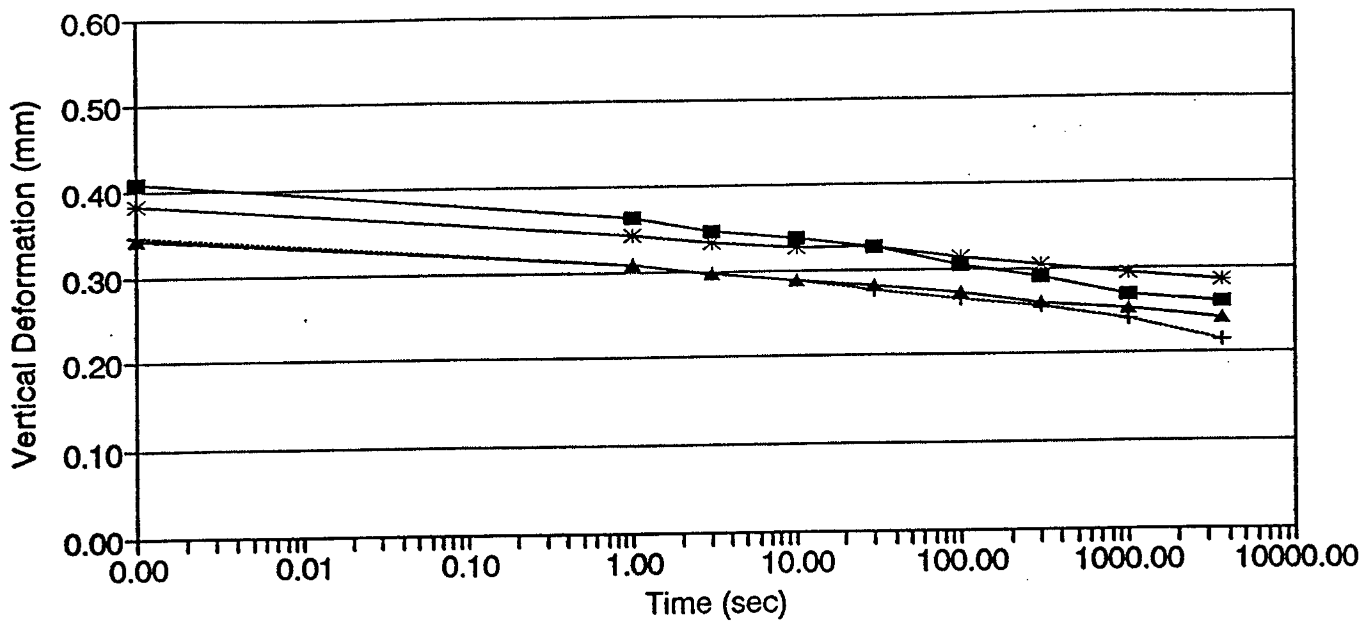



Figure 4.30. Vertical deformation after load removal for asphalt concrete mixes with limestone aggregate and shredded Owens-Corning shingles.

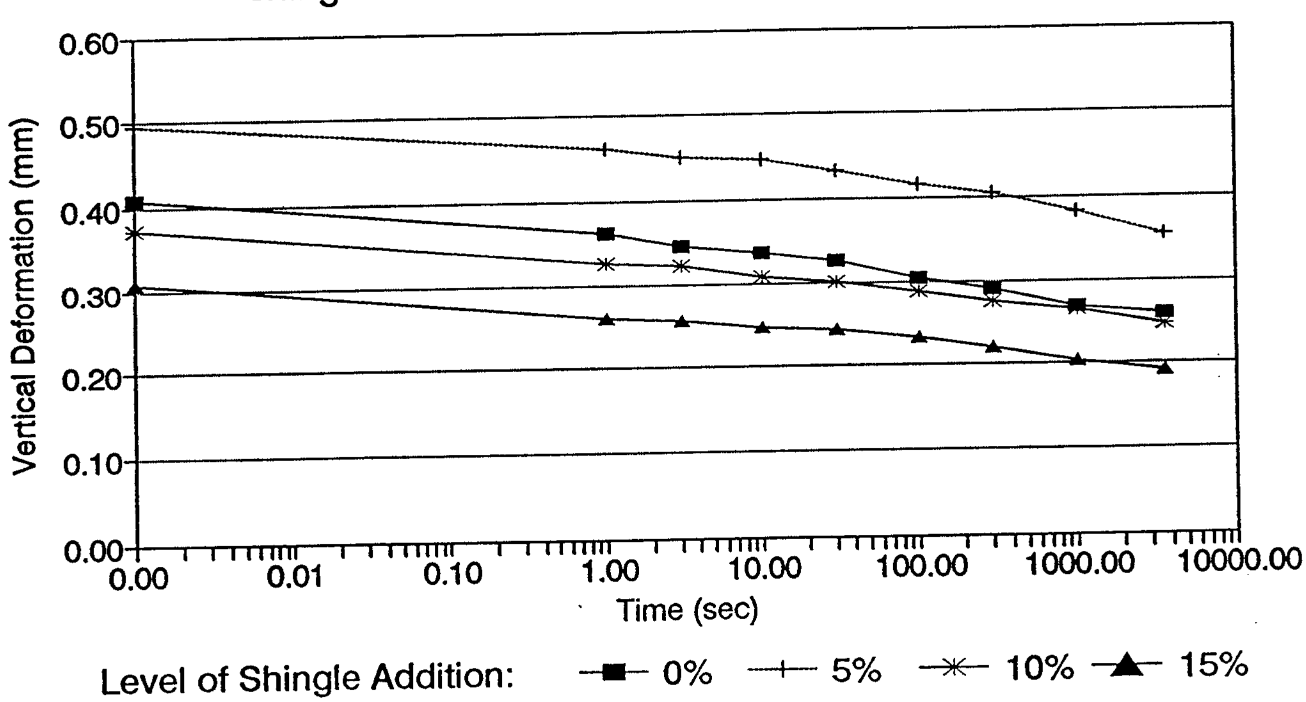


Table 4.22. Vertical deformation after removal of indirect tensile creep loading (gravel mixes).

| Mix Type | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1,000 | 3,600 |
| Control | 1.191 | 1.129 | 1.104 | 1.085 | 1.048 | 1.011 | 0.974 | 0.924 | 0.905 |
| 5% Celotex - G | 0.740 | 0.715 | 0.682 | 0.657 | 0.632 | 0.608 | 0.575 | 0.537 | 0.517 |
| 5% Celotex - S | 0.674 | 0.620 | 0.612 | 0.604 | 0.591 | 0.571 | 0.554 | 0.529 | 0.513 |
| 10% Celotex - G | 0.604 | 0.558 | 0.542 | 0.529 | 0.513 | 0.500 | 0.484 | 0.459 | 0.426 |
| 10% Celotex - S | 0.608 | 0.566 | 0.550 | 0.537 | 0.525 | 0.509 | 0.488 | 0.463 | 0.447 |
| 15% Celotex - G | 0.418 | 0.380 | 0.368 | 0.356 | 0.343 | 0.331 | 0.314 | 0.298 | 0.277 |
| 15% Celotex - S | 0.492 | 0.446 | 0.434 | 0.422 | 0.413 | 0.397 | 0.376 | 0.356 | 0.306 |
| 5% Owens-Corning - G | 0.641 | 0.592 | 0.583 | 0.570 | 0.558 | 0.546 | 0.525 | 0.504 | 0.488 |
| 5% Owens-Corning - S | 0.583 | 0.529 | 0.504 | 0.500 | 0.475 | 0.463 | 0.455 | 0.426 | 0.393 |
| 10% Owens-Corning - G | 0.422 | 0.385 | 0.376 | 0.364 | 0.356 | 0.351 | 0.335 | 0.318 | 0.306 |
| 10% Owens-Corning - S | 0.517 | 0.471 | 0.455 | 0.438 | 0.418 | 0.405 | 0.389 | 0.360 | 0.335 |
| 15% Owens-Corning - G | 0.331 | 0.298 | 0.289 | 0.281 | 0.269 | 0.256 | 0.240 | 0.223 | 0.232 |
| 15% Owens-Corning - S | 0.409 | 0.364 | 0.351 | 0.335 | 0.323 | 0.310 | 0.294 | 0.277 | 0.265 |

Figure 4.31. Vertical deformation after load removal for asphalt concrete mixes with gravel aggregate and granulated Celotex shingles.

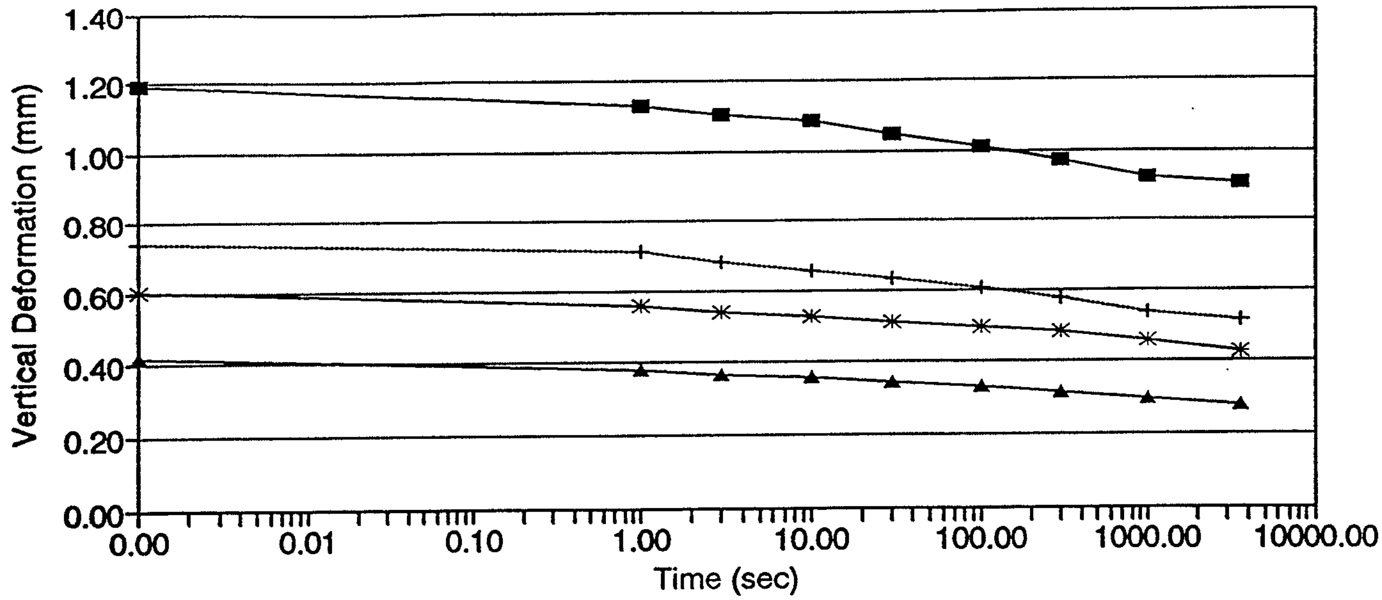



Figure 4.32. Vertical deformation after load removal for asphalt concrete mixes with gravel aggregate and shredded Celotex shingles.

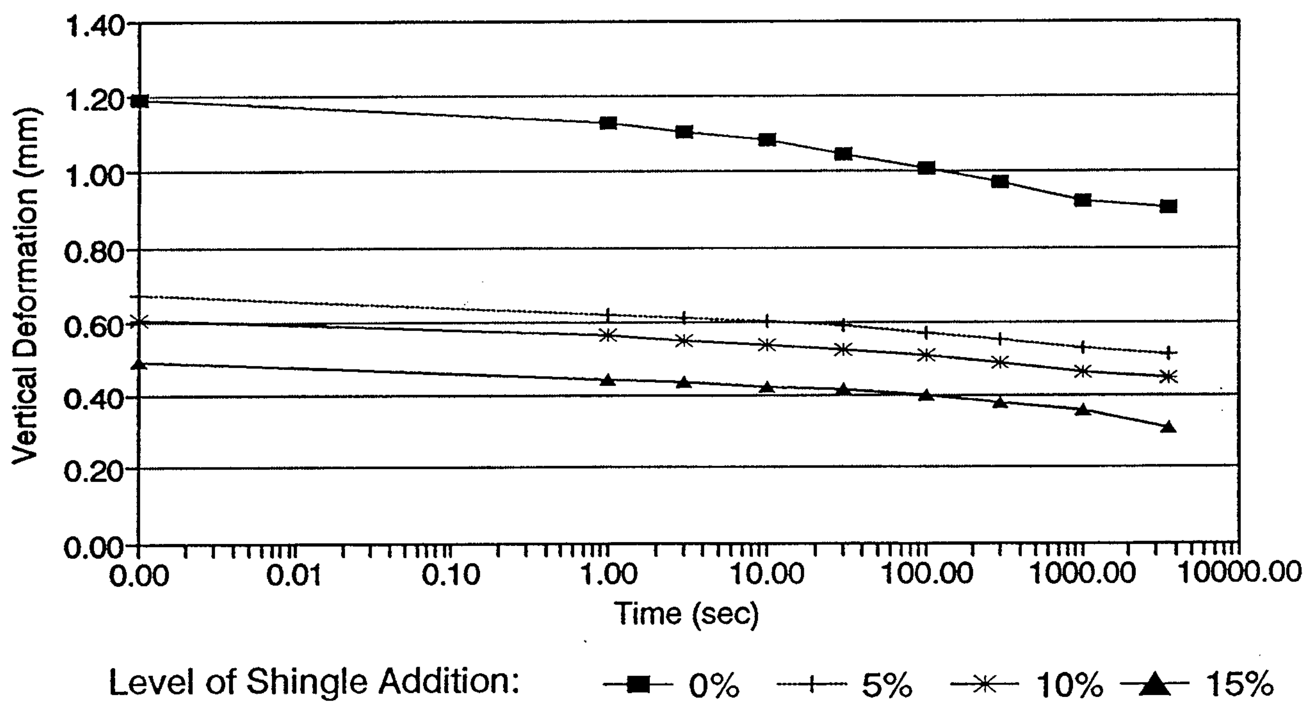


Figure 4.33. Vertical deformation after load removal for asphalt concrete mixes with gravel aggregate and granulated Owens-Corning shingles.

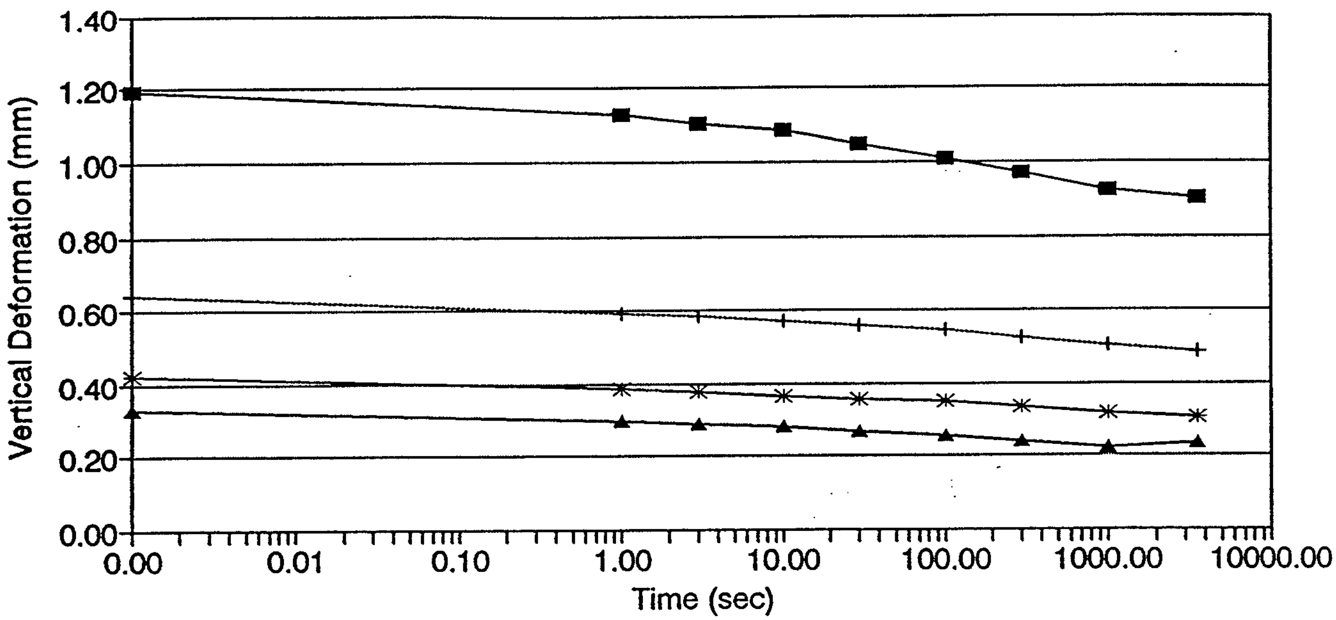
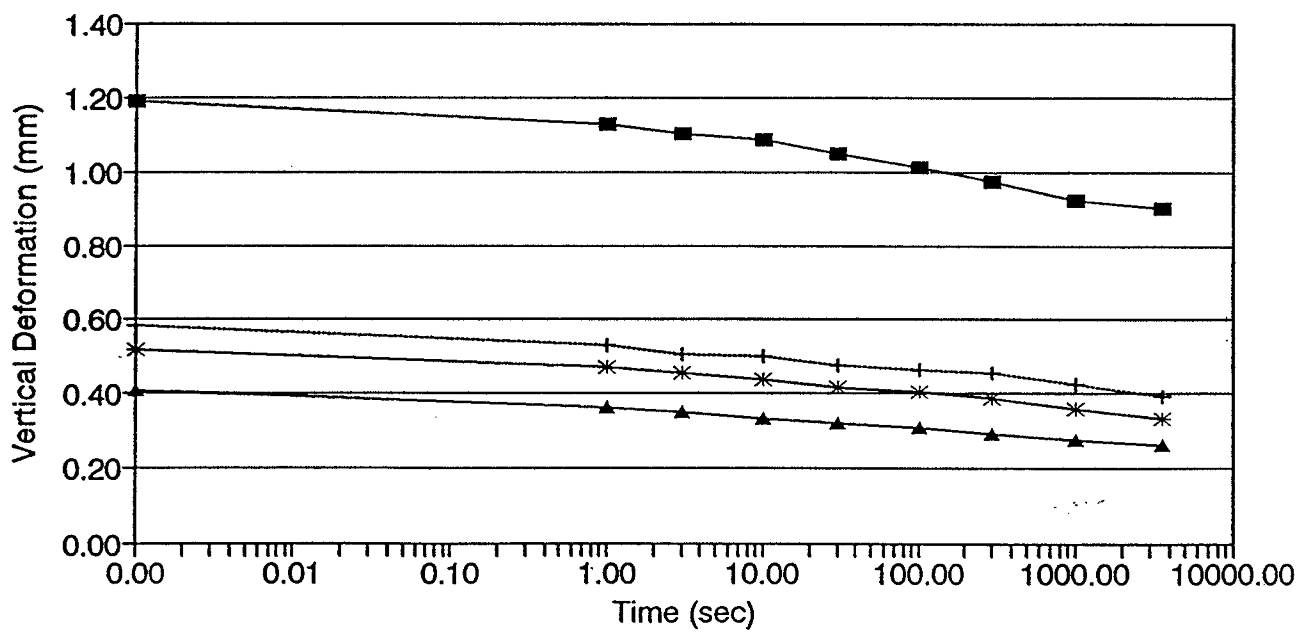



Figure 4.34. Vertical deformation after load removal for asphalt concrete mixes with gravel aggregate and shredded Owens-Corning shingles.




Level of Shingle Addition: 0% 5% 10% 15%

### 4.5.7. RESISTANCE TO MOISTURE-INDUCED DAMAGE.

Asphalt concrete mixes with gravel and limestone aggregate and 0% shingle addition, and mixes with limestone and gravel aggregate and 5, 10, and 15% granulated Owens-Corning shingles, were tested for resistance to moisture-induced damage.

In accordance with AASHTO T 283, six specimens for each mix were prepared and then sorted into two subsets of three specimens each, such that the average air void contents were approximately equal. Three specimens were tested for indirect tensile strength in a dry condition. The other three were first vacuum saturated in water, then frozen at -18 ± 3°C for 16 hours, and then placed in a water bath at 60 ± 1°C for 24 hours. After removal from the hot water bath, the samples were cooled for two hours in a 25 ± 0.5°C water bath and tested for indirect tensile strength. The results of this test are used to predict the susceptibility of an asphalt concrete mix to long-term moisture damage. This susceptibility to moisture damage is expressed as a ratio of the indirect tensile strength of the conditioned to unconditioned specimens. According to the SHRP-A-408 manual [20], the minimum acceptable ratio is 80%.

Table 4.23 and Figures 4.35 and 4.36 present the resistance to moisture-induced damage test results.

Table 4.23. Resistance to moisture-induced damage test results.

| Mix Type | Indirect Tensile Strength (MPa) | | Ratio of Retained Strength |
|---|---|---|---|
| | Control Sample | Conditioned Sample | |
| Limestone-0% | 0.890 | 0.707 | 0.79 |
| Limestone-5% | 1.152 | 1.005 | 0.87 |
| Limestone-10% | 1.263 | 1.120 | 0.89 |
| Limestone-15% | 1.218 | 1.150 | 0.94 |
| Gravel-0% | 0.869 | 0.595 | 0.69 |
| Gravel-5% | 0.818 | 0.560 | 0.69 |
| Gravel-10% | 1.051 | 0.834 | 0.79 |
| Gravel-15% | 1.185 | 0.892 | 0.75 |

The ratios of indirect tensile strength retained for each mix, as shown in the last column of Table 4.23, indicate that the limestone control mix and all of the gravel mixes failed to retain desirable strength, and could be susceptible to moisture-induced damage. Limestone mixes with asphalt shingle addition passed the test, retaining 87 to 94% of the initial indirect tensile strength. None of the mixes with shingle addition showed less retained strength than the control mixes, indicating that the waste shingle material used in this project does not adversely effect the moisture damage susceptibility of the examined mixes.

The moisture damage susceptibility is a function of the source of aggregate and can be controlled by the use of admixtures or additives such as hydrated lime and/or anti-stripping agents.

Figure 4.35. Moisture-induced damage test results for asphalt concrete mixes with limestone aggregate and granulated Owens-Corning shingles.

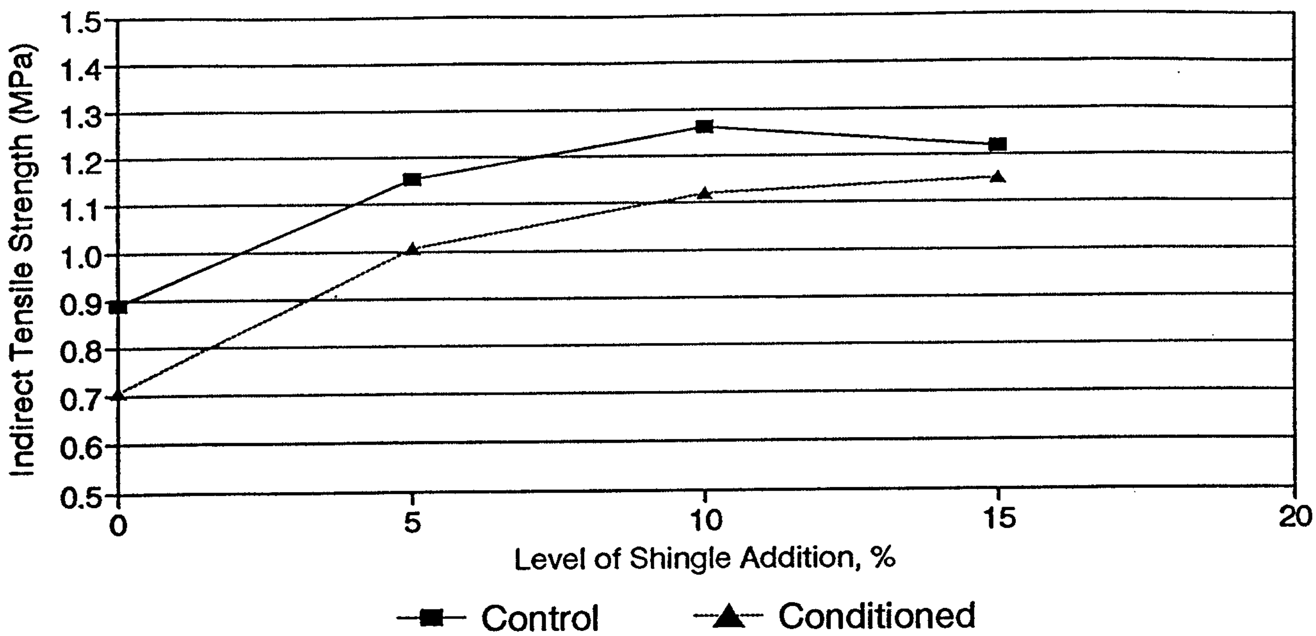
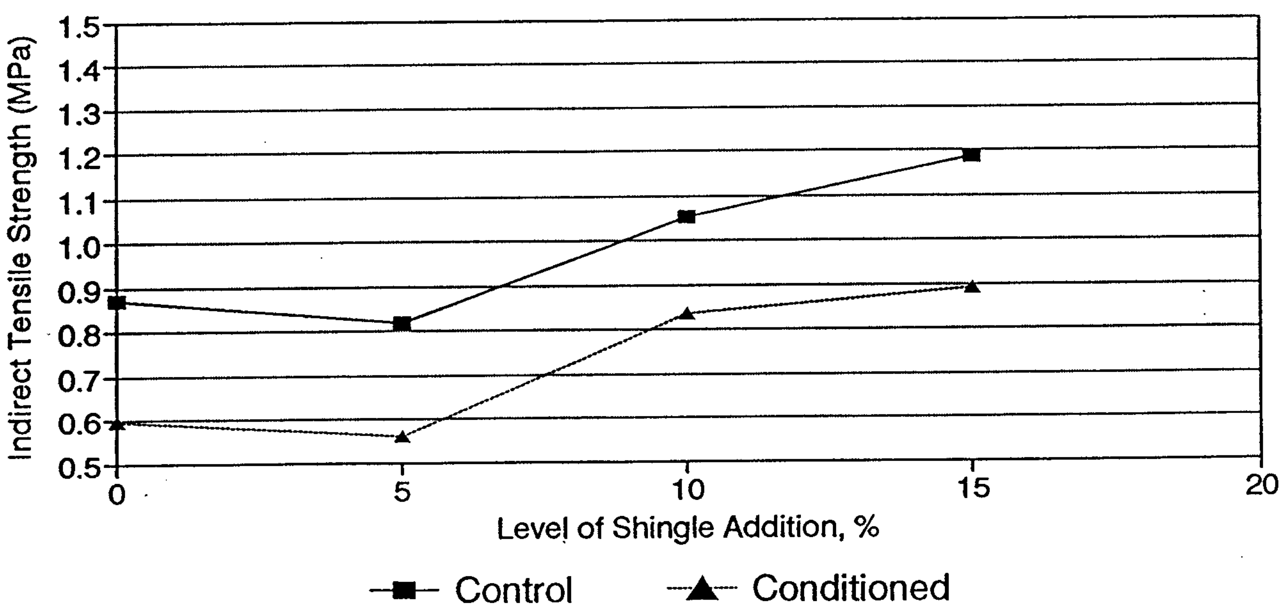



Figure 4.36. Moisture-induced damage test results for asphalt concrete mixes with gravel aggregate and granulated Owens-Corning shingles.



# CHAPTER 5

## RECOMMENDATION FOR MIXTURE DESIGN AND MATERIAL USE GUIDELINES

Based on the findings from this research project, it is proposed that roofing shingle asphalt mixes should adhere to the general requirements of ODOT Item 448, Type 1. The use of shingles should be restricted to fiberglass roofing shingles from manufacturing waste. The recommended size reduction method is granulation. The maximum level of asphalt shingle addition should be restricted to 15%. The Contractor should be required to submit Mix Design data and a Job Mix Formula (JMF) conforming to the criteria presented in Tables 5.1 and 5.2. Changes in the JMF values shall be made only as authorized by the Laboratory.

Table 5.1. Aggregate gradation and new asphalt cement content limits for asphalt concrete mixes made with fiberglass asphalt roofing shingle.

| Sieve Size (mm) | Percent Passing (by Weight) |
|---|---|
| 12.5 | 100 |
| 9.5 | 90 - 100 |
| 4.75 | 50 - 72 |
| 2.36 | 30 - 55 |
| 1.18 | 17 - 40 |
| 0.60 | 12 - 30 |
| 0.30 | 5 - 20 |
| 0.15 | 2 - 12 |
| 75 $\mu$m | 2 - 8 |
| Asphalt Content* | 4 - 8 |

* Total weight basis.

Table 5.2.Mix design criteria.

| Property | Acceptable Range of Values | |
|---|---|---|
| | Minimum | Maximum |
| Bitumen Content of Total Mix (%) | 4 | 8 |
| Design Air Voids (%) | 3.5 | |
| Voids Filled with Asphalt (VFA, %) | 65 | 80 |
| Voids in Mineral Aggregate (VMA, %) | 16 | - |
| Marshall Stability<br>(N)<br>(lbs.) | <br>5,338<br>1,200 | - |
| Flow<br>(mm)<br>(0.01 inches) | <br>2<br>8 | <br>4<br>16 |
| Ratio of Retained Strength (AASHTO T 283, %) | 70 | - |

# CHAPTER 6

# FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

## 6.1. FINDINGS.

The following findings are based on the literature review and the availability survey of waste roofing shingles in Ohio.

1. Waste asphalt roofing shingles have been used in asphalt concrete mixes in several states.

2. Available waste asphalt roofing shingle material requires reduction to a smaller size for proper mixing with virgin asphalt and aggregate.

3. Waste asphalt roofing shingles have been successfully used in asphalt mixes to repair potholes, and in the production of hot asphalt concrete mixes. Several cities and State Departments of Transportation have constructed pavement test sections using hot asphalt concrete mixes containing waste asphalt shingles. The short-term performance of these mixes has been satisfactory; however, the long-term durability needs to be evaluated.

4. The use of waste asphalt roofing shingle in hot asphalt mixes results in a reduced requirement of the amount of virgin asphalt and aggregate, and a reduced burden on landfills. According to Roberts *et al.*, the cost of HMA can be reduced by $ 3.40 per ton by introduction of 5% organic shingles [23]. However, these benefits are a function of a number of variables, including the availability of the waste material, the landfill disposal fees, and the availability of processing facilities.

5. Ohio currently has five plants that produce fiberglass asphalt roofing shingles. The combined manufacturing process waste from these five plants amounts to approximately 10,000 tons per year.

6. Removal of existing rooftops in Ohio generates an estimated 30,000 to 60,000 tons of waste roofing shingle per year.

The following findings are based on the laboratory testing conducted in this project.

1. The waste roofing shingle source and reduction method affected the gradation and asphalt cement content of the produced material.

2. Acceptable air void contents and levels of voids in the mineral aggregate (VMA) were easily maintained in asphalt concrete trial mixes containing waste asphalt roofing shingle.

3. The addition of waste asphalt roofing shingle improved the Marshall stability of the asphalt concrete trial mixes.

4. The addition of waste asphalt roofing shingles improved the indirect tensile strength of tested asphalt concrete trial mixes.

5. The addition of waste asphalt roofing shingle increased the stiffness, as measured by modulus of resilience, of asphalt concrete trail mixes tested at 40°C.

6. The addition of waste asphalt roofing shingle reduced the stiffness, as measured by modulus of resilience, of asphalt concrete trial mixes tested at 0°C. This fact indicates that these mixes will perform better in a low temperature environment.

7. The indirect tensile creep modulus was influenced by the level of waste asphalt roofing shingle addition. The indirect tensile creep increased with an increase in waste asphalt roofing shingle addition. The deformation at the end of the creep test decreased as the level of shingle addition increased, for all trial mixes except the limestone mix having 5% shingle addition. This suggests that the addition of

waste asphalt roofing shingle to asphalt concrete can reduce the rutting potential of the mix.

## 6.2. CONCLUSIONS.

The asphalt concrete trial mixes, made with the addition of fiberglass waste roofing shingle, that were evaluated in this research project showed superior performance to that of conventional asphalt mixes in terms of improved structural capacity, resilient characteristics, and resistance to moisture-induced damage. The use of these shingle mixes would produce pavements having improved serviceability by virtue of reduced temperature susceptibility, improved resilient characteristics, and reduced rutting and deformation. Substantial cost savings to the Ohio Department of Transportation, greater comfort and convenience to highway users, and a reduction in the amount of landfill waste disposal are additional benefits that can be realized. This study, however, was limited in its scope and did not include research on mixtures performance below 0°C (32°F) or aging properties.

## 6.3. RECOMMENDATIONS.

1. It is recommended that a research project be initiated to study aging and low temperature properties (below 0°C) of asphalt concrete mixes containing fiberglass roofing shingles.

2. It is recommended that several test sections of pavement be build using an asphalt mix incorporating fiberglass shingle waste obtained as scrap material from the manufacturing processes as described in this report. The test sections would provide the basis for modifications or adjustments to the proposed mixture design and material use guidelines included in Chapter 5 of this report.

3. It is recommended that a research project be initiated to investigate the use of asphalt concrete mixes incorporating shingle waste obtained as tear-off material from existing rooftops.

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# APPENDIX A

## WEIGHT DETERMINATION

## FOR NEW AGGREGATE AND VIRGIN ASPHALT

Table A1. Aggregate and shingle weight determination for gravel mixes specimens (total weight 1200g)

| Shingle Content | | Sieve Size (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 9.5 | 4.75 | 2.36 | 1.18 | 0.60 | 0.30 | 0.15 | 0.075 | dust |
| % | g | Cummulative Weight of New Aggregate | | | | | | | | |
| 5 | 60 | 34 | 456 | 661 | 787 | 901 | 1049 | 1094 | 1106 | 1140 |
| 10 | 120 | 32 | 432 | 626 | 745 | 853 | 994 | 1037 | 1048 | 1080 |
| 15 | 180 | 31 | 408 | 592 | 704 | 806 | 938 | 979 | 989 | 1020 |

Table A2. Aggregate and shingle weight determination for limestone mixes specimens (total weight 1200g)

| Shingle Content | | Sieve Size (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 9.5 | 4.75 | 2.36 | 1.18 | 0.60 | 0.30 | 0.15 | 0.075 | dust |
| % | g | Cummulative Weight of New Aggregate | | | | | | | | |
| 5 | 60 | 80 | 479 | 651 | 809 | 923 | 1003 | 1060 | 1099 | 1140 |
| 10 | 120 | 76 | 454 | 616 | 767 | 878 | 950 | 1004 | 1041 | 1080 |
| 15 | 180 | 71 | 428 | 581 | 724 | 826 | 898 | 949 | 983 | 1020 |

Table A3. Weight of virgin asphalt for mixes with 5% roofing shingle addition.

| Percent of Total Asphalt Content (%) | Type of Shingle | | | |
|---|---|---|---|---|
| | Celotex | | Owens-Corning | |
| | Granulated | Shredded | Granulated | Shredded |
| | Weight of Virgin Asphalt (g) | | | |
| 5.0 | 1.25 | 49.9 | 50.0 | 46.8 |
| 5.5 | 57.8 | 56.5 | 56.7 | 53.4 |
| 6.0 | 64.5 | 63.2 | 63.2 | 60.1 |
| 6.5 | 71.2 | 70.0 | 70.1 | 66.7 |
| 7.0 | 78.1 | 76.8 | 76.9 | 73.6 |
| 7.5 | 85.1 | 83.6 | 83.9 | 80.5 |
| 8.0 | 92.0 | | | |

Table A4. Weight of virgin asphalt for mixes with 10% roofing shingle addition.

| Percent of Total Asphalt Content (%) | Type of Shingle | | | |
|---|---|---|---|---|
| | Celotex | | Owens-Corning | |
| | Granulated | Shredded | Granulated | Shredded |
| | Weight of Virgin Asphalt (g) | | | |
| 5.5 | 45.7 | 42.3 | 43.4 | 37.0 |
| 6.0 | 52.3 | 49.8 | 50.0 | 42.5 |
| 6.5 | 59.0 | 56.5 | 56.6 | 50.1 |
| 7.0 | 65.9 | 63.2 | 63.4 | 56.9 |
| 7.5 | 72.7 | 70.0 | 70.2 | 63.7 |

Table A5. Weight of virgin asphalt for mixes with 15% roofing shingle addition.

| Percent of Total Asphalt Content (%) | Type of Shingle | | | |
|---|---|---|---|---|
| | Celotex | | Owens-Corning | |
| | Granulated | Shredded | Granulated | Shredded |
| | Weight of Virgin Asphalt (g) | | | |
| 5.0 | 27.2 | 23.4 | 23.7 | 14.1 |
| 5.5 | 33.7 | 29.9 | 30.2 | 20.5 |
| 6.0 | 40.2 | 36.4 | 36.7 | 27.0 |
| 6.5 | 46.8 | 43.0 | 43.4 | 33.6 |
| 7.0 | 53.6 | 49.6 | 50.0 | 40.2 |
| 7.5 | 60.4 | 56.4 | 56.8 | 46.9 |

# APPENDIX B

# DETERMINATION OF THE OPTIMUM ASPHALT CEMENT CONTENT

Table B1. Gravel aggregate; 5% Owens-Corning shingle addition.

| | Sample | Asphalt Content, (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.3 | 6.8 | 7.4 | 7.9 |
| Maximum Specific Gravity | | 2.395 | 2.378 | 2.368 | 2.351 | 2.332 | 2.316 |
| SSD Specific Gravity | 1 | 2.250 | 2.274 | 2.288 | 2.290 | 2.292 | 2.291 |
| | 2 | 2.262 | 2.279 | 2.295 | 2.287 | 2.298 | 2.294 |
| | 3 | 2.268 | 2.264 | 2.282 | 2.293 | 2.293 | 2.284 |
| | Ave | 2.260 | 2.272 | 2.288 | 2.290 | 2.294 | 2.286 |
| Unit Weight (kg/m$^3$) | 1 | 2249 | 2273 | 2286 | 2289 | 2291 | 2280 |
| | 2 | 2262 | 2278 | 2294 | 2286 | 2297 | 2292 |
| | 3 | 2267 | 2264 | 2281 | 2292 | 2292 | 2283 |
| | Ave | 2259 | 2272 | 2287 | 2289 | 2294 | 2285 |
| Air Voids (%) | 1 | 6.04 | 4.38 | 3.39 | 2.62 | 1.70 | 1.50 |
| | 2 | 5.55 | 4.16 | 3.08 | 2.75 | 1.45 | 0.96 |
| | 3 | 5.31 | 4.81 | 3.62 | 2.49 | 1.69 | 1.39 |
| | Ave | 5.63 | 4.45 | 3.36 | 2.62 | 1.61 | 1.28 |
| Voids in Mineral Aggregate (%) | 1 | 17.20 | 16.76 | 16.52 | 16.89 | 17.35 | 18.19 |
| | 2 | 16.76 | 16.58 | 16.26 | 17.00 | 17.14 | 17.73 |
| | 3 | 16.54 | 17.13 | 16.74 | 16.78 | 17.32 | 18.09 |
| | Ave | 16.83 | 16.82 | 16.50 | 16.89 | 17.27 | 18.00 |
| Voids Filled with Asphalt (%) | 1 | 64.9 | 73.9 | 79.5 | 84.5 | 90.1 | 91.8 |
| | 2 | 66.9 | 74.9 | 81.1 | 83.8 | 91.5 | 94.6 |
| | 3 | 67.9 | 71.9 | 78.4 | 85.2 | 90.2 | 92.3 |
| | Ave | 66.6 | 73.6 | 79.6 | 84.5 | 90.7 | 92.9 |
| Indirect Tensile Strenght (MPa) | 1 | 0.820 | 0.870 | 0.906 | 0.807 | 0.728 | 0.583 |
| | 2 | 0.862 | 0.862 | 0.918 | 0.842 | 0.736 | 0.638 |
| | 3 | 0.840 | 0.883 | 0.910 | 0.849 | 0.743 | 0.603 |
| | Ave | 0.840 | 0.868 | 0.911 | 0.833 | 0.736 | 0.608 |
| Deformation (mm) | 1 | 1.676 | 1.676 | 1.905 | 2.134 | 2.565 | 3.124 |
| | 2 | 1.803 | 1.676 | 1.803 | 1.905 | 2.235 | 2.896 |
| | 3 | 1.676 | 1.676 | 1.575 | 1.905 | 2.286 | 3.124 |
| | Ave | 1.719 | 1.676 | 1.761 | 1.981 | 2.362 | 3.048 |

Table B2. Gravel aggregate; 5% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.386 | 2.370 | 2.353 | 2.337 | 2.321 |
| SSD Specific Gravity | 1 | 2.254 | 2.275 | 2.287 | 2.292 | 2.286 |
| | 2 | 2.256 | 2.261 | 2.303 | 2.288 | 2.288 |
| | 3 | 2.252 | 2.266 | 2.280 | 2.291 | 2.284 |
| | Ave | 2.254 | 2.267 | 2.290 | 2.290 | 2.286 |
| Unit Weight ($kg/m^3$) | 1 | 2252 | 2275 | 2286 | 2291 | 2286 |
| | 2 | 2256 | 2260 | 2302 | 2288 | 2288 |
| | 3 | 2251 | 2265 | 2280 | 2291 | 2283 |
| | Ave | 2253 | 2267 | 2289 | 2290 | 2286 |
| Air Voids (%) | 1 | 5.55 | 3.98 | 2.81 | 1.91 | 1.49 |
| | 2 | 5.46 | 4.57 | 2.13 | 2.07 | 1.39 |
| | 3 | 5.62 | 4.38 | 3.09 | 1.94 | 1.56 |
| | Ave | 5.54 | 4.31 | 2.68 | 1.97 | 1.48 |
| Voids in Mineral Aggregate (%) | 1 | 17.22 | 16.89 | 16.89 | 17.16 | 17.82 |
| | 2 | 17.14 | 17.40 | 16.31 | 17.30 | 17.75 |
| | 3 | 17.29 | 17.22 | 17.15 | 17.19 | 17.89 |
| | Ave | 17.22 | 17.17 | 16.78 | 17.22 | 17.82 |
| Voids Filled with Asphalt (%) | 1 | 67.76 | 76.43 | 83.37 | 88.87 | 91.64 |
| | 2 | 68.15 | 73.73 | 86.94 | 88.04 | 92.17 |
| | 3 | 67.49 | 74.56 | 81.98 | 88.72 | 91.28 |
| | Ave | 67.80 | 74.91 | 84.10 | 88.54 | 91.69 |
| Indirect Tensile Strenght (MPa) | 1 | 0.848 | 0.822 | 0.912 | 0.806 | 0.671 |
| | 2 | 0.832 | 0.772 | 0.909 | 0.776 | 0.694 |
| | 3 | 0.823 | 0.793 | 0.861 | 0.833 | 0.682 |
| | Ave | 0.834 | 0.796 | 0.894 | 0.805 | 0.682 |
| Deformation (mm) | 1 | 1.702 | 1.778 | 1.803 | 2.007 | 2.794 |
| | 2 | 1.575 | 1.676 | 1.803 | 2.007 | 2.464 |
| | 3 | 1.626 | 1.676 | 1.930 | 1.803 | 2.337 |
| | Ave | 1.634 | 1.710 | 1.761 | 1.939 | 2.532 |

Table B3. Limestone aggregate; 5% Owens-Corning shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.542 | 2.523 | 2.503 | 2.484 | 2.465 |
| SSD Specific Gravity | 1 | 2.323 | 2.350 | 2.358 | 2.371 | 2.377 |
| | 2 | 2.320 | 2.339 | 2.351 | 2.367 | 2.383 |
| | 3 | 2.323 | 2.338 | 2.354 | 2.373 | 2.370 |
| | Ave | 2.323 | 2.342 | 2.354 | 2.370 | 2.377 |
| Unit Weight ($kg/m^3$) | 1 | 2322 | 2349 | 2357 | 2370 | 2376 |
| | 2 | 2319 | 2338 | 2350 | 2366 | 2382 |
| | 3 | 2324 | 2337 | 2353 | 2372 | 2369 |
| | Ave | 2322 | 2342 | 2354 | 2369 | 2376 |
| Air Voids (%) | 1 | 8.61 | 6.84 | 5.81 | 4.52 | 3.55 |
| | 2 | 8.75 | 7.28 | 6.09 | 4.69 | 3.32 |
| | 3 | 8.53 | 7.31 | 5.94 | 4.45 | 3.84 |
| | Ave | 8.63 | 7.14 | 5.95 | 4.55 | 3.57 |
| Voids in Mineral Aggregate (%) | 1 | 17.84 | 17.33 | 17.49 | 17.48 | 17.71 |
| | 2 | 17.95 | 17.71 | 17.73 | 17.62 | 17.50 |
| | 3 | 17.77 | 17.75 | 17.63 | 17.41 | 17.95 |
| | Ave | 17.85 | 17.60 | 17.62 | 17.50 | 17.72 |
| Voids Filled with Asphalt (%) | 1 | 51.75 | 60.53 | 66.78 | 74.14 | 79.96 |
| | 2 | 51.25 | 58.90 | 65.66 | 73.38 | 81.03 |
| | 3 | 52.00 | 58.82 | 66.30 | 74.44 | 78.61 |
| | Ave | 51.69 | 59.42 | 66.25 | 73.98 | 79.97 |
| Indirect Tensile Strenght (MPa) | 1 | 0.960 | 1.031 | 0.912 | 1.056 | 0.874 |
| | 2 | 1.010 | 0.927 | 0.925 | 0.928 | 0.916 |
| | 3 | 0.963 | 0.993 | 0.967 | 0.954 | 0.885 |
| | Ave | 0.978 | 0.984 | 0.935 | 0.979 | 0.891 |
| Deformation (mm) | 1 | 1.448 | 1.473 | 1.448 | 1.575 | 2.159 |
| | 2 | 1.473 | 1.524 | 1.575 | 1.676 | 1.905 |
| | 3 | 1.346 | 1.473 | 1.473 | 1.473 | 1.930 |
| | Ave | 1.422 | 1.490 | 1.499 | 1.575 | 1.998 |

Table B4. Limestone aggregate; 5% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 |
| Maximum Specific Gravity | | 2.524 | 2.504 | 2.485 | 2.466 | 2.448 | 2.429 |
| SSD Specific Gravity | 1 | 2.319 | 2.333 | 2.356 | 2.363 | 2.379 | 2.381 |
| | 2 | 2.321 | 2.327 | 2.343 | 2.373 | 2.387 | 2.380 |
| | 3 | 2.312 | 2.333 | 2.353 | 2.368 | 2.387 | 2.381 |
| | Ave | 2.317 | 2.331 | 2.351 | 2.368 | 2.384 | 2.381 |
| Unit Weight ($kg/m^3$) | 1 | 2318 | 2332 | 2355 | 2362 | 2378 | 2381 |
| | 2 | 2320 | 2326 | 2342 | 2373 | 2386 | 2379 |
| | 3 | 2311 | 2332 | 2352 | 2367 | 2386 | 2381 |
| | Ave | 2317 | 2330 | 2350 | 2367 | 2383 | 2380 |
| Air Voids (%) | 1 | 8.09 | 6.83 | 5.17 | 4.17 | 2.80 | 1.98 |
| | 2 | 8.02 | 7.08 | 5.73 | 3.78 | 2.47 | 2.02 |
| | 3 | 8.39 | 6.85 | 5.29 | 3.97 | 2.46 | 1.97 |
| | Ave | 8.17 | 6.92 | 5.40 | 3.97 | 2.58 | 1.99 |
| Voids in Mineral Aggregate (%) | 1 | 18.11 | 18.05 | 17.68 | 17.88 | 17.77 | 18.14 |
| | 2 | 18.04 | 18.26 | 18.14 | 17.53 | 17.49 | 18.18 |
| | 3 | 18.35 | 18.05 | 17.79 | 17.70 | 17.49 | 18.14 |
| | Ave | 18.17 | 18.12 | 17.87 | 17.70 | 17.58 | 18.15 |
| Voids Filled with Asphalt (%) | 1 | 55.32 | 62.16 | 70.76 | 76.67 | 84.24 | 89.09 |
| | 2 | 55.53 | 61.23 | 68.40 | 78.44 | 85.88 | 88.89 |
| | 3 | 54.29 | 62.05 | 70.26 | 77.58 | 85.93 | 89.14 |
| | Ave | 55.05 | 61.81 | 69.81 | 77.56 | 85.35 | 89.04 |
| Indirect Tensile Strenght (MPa) | 1 | 0.938 | 0.980 | 1.045 | 1.025 | 0.956 | 0.871 |
| | 2 | 0.948 | 1.014 | 0.983 | 1.007 | 1.022 | 0.886 |
| | 3 | 0.973 | 1.006 | 1.017 | 0.988 | 0.943 | 0.914 |
| | Ave | 0.953 | 1.000 | 1.015 | 1.007 | 0.974 | 0.890 |
| Deformation (mm) | 1 | 1.448 | 1.575 | 1.600 | 1.600 | 2.235 | 2.235 |
| | 2 | 1.676 | 1.448 | 1.524 | 1.651 | 1.803 | 2.134 |
| | 3 | 1.346 | 1.422 | 1.600 | 1.727 | 1.930 | 2.134 |
| | Ave | 1.490 | 1.482 | 1.575 | 1.659 | 1.990 | 2.167 |

Table B5. Gravel aggregate; 10% Owens-Corning shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.430 | 2.412 | 2.395 | 2.378 | 2.361 |
| SSD Specific Gravity | 1 | 2.255 | 2.252 | 2.281 | 2.309 | 2.301 |
| | 2 | 2.262 | 2.259 | 2.273 | 2.304 | 2.298 |
| | 3 | 2.254 | 2.262 | 2.284 | 2.295 | 2.305 |
| | Ave | 2.257 | 2.258 | 2.279 | 2.303 | 2.301 |
| Unit Weight ($kg/m^3$) | 1 | 2254 | 2251 | 2280 | 2308 | 2300 |
| | 2 | 2261 | 2258 | 2272 | 2303 | 2297 |
| | 3 | 2253 | 2261 | 2283 | 2294 | 2304 |
| | Ave | 2256 | 2257 | 2279 | 2302 | 2301 |
| Air Voids (%) | 1 | 7.21 | 6.63 | 4.74 | 2.90 | 2.55 |
| | 2 | 6.90 | 6.37 | 5.08 | 3.13 | 2.65 |
| | 3 | 7.25 | 6.25 | 4.65 | 3.49 | 2.36 |
| | Ave | 7.12 | 6.42 | 4.82 | 3.17 | 2.52 |
| Voids in Mineral Aggregate (%) | 1 | 16.82 | 17.37 | 16.76 | 16.18 | 16.92 |
| | 2 | 16.57 | 17.12 | 17.05 | 16.37 | 17.03 |
| | 3 | 16.86 | 17.01 | 16.65 | 16.69 | 16.78 |
| | Ave | 16.75 | 17.17 | 16.82 | 16.41 | 16.91 |
| Voids Filled with Asphalt (%) | 1 | 57.1 | 61.8 | 71.7 | 82.1 | 84.9 |
| | 2 | 58.3 | 62.8 | 70.2 | 80.9 | 84.4 |
| | 3 | 57.0 | 63.3 | 72.1 | 79.1 | 85.9 |
| | Ave | 57.5 | 62.5 | 71.3 | 80.7 | 85.1 |
| Indirect Tensile Strenght (MPa) | 1 | 0.900 | 0.764 | 0.885 | 0.917 | 0.735 |
| | 2 | 0.927 | 0.866 | 0.795 | 0.898 | 0.818 |
| | 3 | 0.812 | 0.859 | 0.881 | 0.852 | 0.769 |
| | Ave | 0.880 | 0.830 | 0.854 | 0.889 | 0.774 |
| Deformation (mm) | 1 | 1.575 | 1.676 | 1.930 | 1.702 | 2.235 |
| | 2 | 1.473 | 1.803 | 1.803 | 2.032 | 1.930 |
| | 3 | 1.676 | 1.676 | 1.803 | 2.032 | 2.235 |
| | Ave | 1.575 | 1.719 | 1.803 | 1.922 | 2.134 |

Table B6. Gravel aggregate; 10% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.426 | 2.408 | 2.391 | 2.374 | 2.357 |
| SSD Specific Gravity | 1 | 2.273 | 2.267 | 2.297 | 2.297 | 2.306 |
| | 2 | 2.255 | 2.282 | 2.282 | 2.297 | 2.300 |
| | 3 | 2.259 | 2.276 | 2.291 | 2.302 | 2.301 |
| | Ave | 2.262 | 2.275 | 2.290 | 2.299 | 2.302 |
| Unit Weight ($kg/m^3$) | 1 | 2272 | 2266 | 2296 | 2296 | 2305 |
| | 2 | 2254 | 2281 | 2281 | 2296 | 2299 |
| | 3 | 2258 | 2275 | 2290 | 2301 | 2300 |
| | Ave | 2262 | 2274 | 2289 | 2298 | 2302 |
| Air Voids (%) | 1 | 6.29 | 5.86 | 3.93 | 3.25 | 2.16 |
| | 2 | 7.06 | 5.26 | 4.56 | 3.25 | 2.42 |
| | 3 | 6.87 | 5.50 | 4.18 | 3.05 | 2.37 |
| | Ave | 6.74 | 5.54 | 4.22 | 3.18 | 2.32 |
| Voids in Mineral Aggregate (%) | 1 | 16.39 | 17.05 | 16.40 | 16.85 | 16.97 |
| | 2 | 17.05 | 16.50 | 16.95 | 16.85 | 17.19 |
| | 3 | 16.90 | 16.72 | 16.62 | 16.67 | 17.15 |
| | Ave | 16.78 | 16.76 | 16.65 | 16.79 | 17.10 |
| Voids Filled with Asphalt (%) | 1 | 61.6 | 65.6 | 76.0 | 80.7 | 87.3 |
| | 2 | 58.6 | 68.1 | 73.1 | 80.7 | 85.9 |
| | 3 | 59.4 | 67.1 | 74.8 | 81.7 | 86.2 |
| | Ave | 59.9 | 67.0 | 74.7 | 81.0 | 86.6 |
| Indirect Tensile Strenght (MPa) | 1 | 1.158 | 0.987 | 1.059 | 1.029 | 0.896 |
| | 2 | 1.025 | 1.100 | 1.054 | 1.038 | 0.965 |
| | 3 | 1.027 | 1.016 | 1.050 | 1.027 | 0.872 |
| | Ave | 1.070 | 1.034 | 1.054 | 1.032 | 0.911 |
| Deformation (mm) | 1 | 1.473 | 1.930 | 1.930 | 2.057 | 2.540 |
| | 2 | 1.575 | 1.702 | 1.930 | 2.057 | 2.261 |
| | 3 | 1.575 | 1.600 | 1.702 | 1.930 | 2.362 |
| | Ave | 1.541 | 1.744 | 1.854 | 2.015 | 2.388 |

Table B7. Limestone aggregate; 10% Owens-Corning shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.533 | 2.513 | 2.494 | 2.475 | 2.456 |
| SSD Specific Gravity | 1 | 2.294 | 2.327 | 2.339 | 2.366 | 2.379 |
| | 2 | 2.305 | 2.324 | 2.339 | 2.360 | 2.366 |
| | 3 | 2.294 | 2.309 | 2.343 | 2.364 | 2.372 |
| | Ave | 2.298 | 2.320 | 2.340 | 2.363 | 2.372 |
| Unit Weight ($kg/m^3$) | 1 | 2293 | 2326 | 2338 | 2365 | 2378 |
| | 2 | 2304 | 2323 | 2338 | 2359 | 2365 |
| | 3 | 2293 | 2308 | 2342 | 2363 | 2371 |
| | Ave | 2297 | 2319 | 2340 | 2363 | 2371 |
| Air Voids (%) | 1 | 9.45 | 7.41 | 6.21 | 4.39 | 3.15 |
| | 2 | 9.00 | 7.55 | 6.23 | 4.63 | 3.69 |
| | 3 | 9.42 | 8.11 | 6.07 | 4.48 | 3.41 |
| | Ave | 9.29 | 7.69 | 6.17 | 4.50 | 3.42 |
| Voids in Mineral Aggregate (%) | 1 | 18.47 | 17.74 | 17.75 | 17.25 | 17.24 |
| | 2 | 18.08 | 17.84 | 17.75 | 17.46 | 17.69 |
| | 3 | 18.47 | 18.37 | 17.61 | 17.32 | 17.48 |
| | Ave | 18.34 | 17.98 | 17.71 | 17.34 | 17.47 |
| Voids Filled with Asphalt (%) | 1 | 48.8 | 58.2 | 65.0 | 74.5 | 81.7 |
| | 2 | 50.2 | 57.7 | 64.9 | 73.5 | 79.1 |
| | 3 | 49.0 | 55.9 | 65.5 | 74.1 | 80.5 |
| | Ave | 49.4 | 57.3 | 65.2 | 74.1 | 80.5 |
| Indirect Tensile Strenght (MPa) | 1 | 0.962 | 1.116 | 1.008 | 1.087 | 1.029 |
| | 2 | 1.016 | 1.029 | 1.085 | 1.133 | 1.005 |
| | 3 | 0.911 | 0.999 | 1.136 | 1.122 | 1.054 |
| | Ave | 0.963 | 1.048 | 1.076 | 1.114 | 1.029 |
| Deformation (mm) | 1 | 1.346 | 1.372 | 1.575 | 1.473 | 1.702 |
| | 2 | 1.473 | 1.575 | 1.273 | 1.473 | 1.575 |
| | 3 | 1.448 | 1.600 | 1.600 | 1.702 | 1.803 |
| | Ave | 1.422 | 1.516 | 1.549 | 1.549 | 1.693 |

Table B8. Limestone aggregate; 10% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 |
| Maximum Specific Gravity | | 2.510 | 2.491 | 2.472 | 2.453 | 2.435 |
| SSD Specific Gravity | 1 | 2.339 | 2.364 | 2.356 | 2.382 | 2.382 |
| | 2 | 2.334 | 2.338 | 2.366 | 2.378 | 2.382 |
| | 3 | 2.326 | 2.325 | 2.365 | 2.384 | 2.388 |
| | Ave | 2.333 | 2.342 | 2.362 | 2.381 | 2.384 |
| Unit Weight (kg/m$^3$) | 1 | 2338 | 2363 | 2355 | 2381 | 2381 |
| | 2 | 2333 | 2337 | 2365 | 2377 | 2381 |
| | 3 | 2325 | 2324 | 2364 | 2383 | 2387 |
| | Ave | 2332 | 2342 | 2362 | 2380 | 2381 |
| Air Voids (%) | 1 | 6.83 | 5.11 | 4.68 | 2.92 | 2.18 |
| | 2 | 7.04 | 6.13 | 4.29 | 3.08 | 2.15 |
| | 3 | 7.34 | 6.65 | 4.32 | 2.83 | 1.94 |
| | Ave | 7.07 | 5.96 | 4.43 | 2.94 | 2.09 |
| Voids in Mineral Aggregate (%) | 1 | 17.98 | 18.00 | 17.50 | 17.49 | 17.83 |
| | 2 | 18.09 | 18.00 | 17.71 | 17.94 | 17.83 |
| | 3 | 18.62 | 17.86 | 17.57 | 17.73 | 17.62 |
| | Ave | 18.23 | 17.95 | 17.59 | 17.72 | 17.76 |
| Voids Filled with Asphalt (%) | 1 | 62.0 | 71.6 | 73.3 | 83.3 | 87.8 |
| | 2 | 61.1 | 65.9 | 75.8 | 82.8 | 87.9 |
| | 3 | 60.6 | 62.8 | 75.4 | 84.0 | 89.0 |
| | Ave | 61.2 | 66.8 | 74.8 | 83.4 | 88.2 |
| Indirect Tensile Strenght (MPa) | 1 | 1.078 | 1.144 | 0.976 | 0.983 | 0.966 |
| | 2 | 1.076 | 1.067 | 1.069 | 1.094 | 0.980 |
| | 3 | 1.056 | 1.008 | 1.092 | 1.044 | 0.835 |
| | Ave | 1.070 | 1.073 | 1.046 | 1.040 | 0.927 |
| Deformation (mm) | 1 | 1.575 | 1.575 | 1.575 | 1.829 | 1.803 |
| | 2 | 1.905 | 1.575 | 1.600 | 1.702 | 1.930 |
| | 3 | 1.473 | 1.575 | 1.803 | 2.032 | 2.134 |
| | Ave | 1.651 | 1.575 | 1.744 | 1.846 | 2.146 |

Table B9. Gravel aggregate; 15% Owens-Corning shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.7 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.397 | 2.380 | 2.356 | 2.347 | 2.330 |
| SSD Specific Gravity | 1 | 2.267 | 2.290 | 2.281 | 2.292 | 2.287 |
| | 2 | 2.287 | 2.282 | 2.281 | 2.286 | 2.275 |
| | 3 | 2.280 | 2.296 | 2.381 | 2.285 | 2.281 |
| | Ave | 2.278 | 2.289 | 2.281 | 2.288 | 2.281 |
| Unit Weight (kg/m$^3$) | 1 | 2267 | 2289 | 2280 | 2292 | 2286 |
| | 2 | 2286 | 2281 | 2280 | 2284 | 2275 |
| | 3 | 2280 | 2296 | 2280 | 2284 | 2280 |
| | Ave | 2278 | 2289 | 2280 | 2287 | 2280 |
| Air Voids (%) | 1 | 5.40 | 3.76 | 3.2 | 2.3 | 1.84 |
| | 2 | 4.57 | 4.12 | 3.18 | 2.59 | 2.38 |
| | 3 | 4.97 | 3.52 | 3.22 | 2.61 | 2.14 |
| | Ave | 4.98 | 3.80 | 3.20 | 2.50 | 2.12 |
| Voids in Mineral Aggregate (%) | 1 | 16.15 | 15.75 | 16.71 | 16.57 | 17.85 |
| | 2 | 15.41 | 16.04 | 16.71 | 16.79 | 18.28 |
| | 3 | 15.67 | 15.53 | 16.71 | 16.83 | 18.03 |
| | Ave | 15.75 | 15.77 | 16.71 | 16.73 | 18.06 |
| Voids Filled with Asphalt (%) | 1 | 66.57 | 76.13 | 80.84 | 86.12 | 89.69 |
| | 2 | 70.35 | 74.32 | 80.96 | 84.58 | 86.98 |
| | 3 | 68.29 | 77.33 | 80.72 | 84.49 | 88.15 |
| | Ave | 68.40 | 75.93 | 80.84 | 85.06 | 88.27 |
| Indirect Tensile Strenght (MPa) | 1 | 1.094 | 1.280 | 1.320 | 1.049 | 0.940 |
| | 2 | 1.271 | 1.220 | 1323 | 1.029 | 0.903 |
| | 3 | 1.260 | 1.302 | 1.248 | 1.089 | 0.869 |
| | Ave | 1.209 | 1.267 | 1.297 | 1.056 | 0.904 |
| Deformation (mm) | 1 | 1.575 | 1.473 | 1.702 | 2.134 | 2.235 |
| | 2 | 1.651 | 1.651 | 1.702 | 2.362 | 2.032 |
| | 3 | 1.600 | 1.600 | 1.854 | 1.930 | 2.261 |
| | Ave | 1.609 | 1.575 | 1.753 | 2.142 | 2.176 |

Table B10. Gravel aggregate; 15% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | |
|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 |
| Maximum Specific Gravity | | 2.425 | 2.407 | 2.390 | 2.373 | 2.356 |
| SSD Specific Gravity | 1 | 2.229 | 2.276 | 2.264 | 2.296 | 2.298 |
| | 2 | 2.251 | 2.265 | 2.280 | 2.293 | 2.306 |
| | 3 | 2.246 | 2.272 | 2.268 | 2.293 | 2.301 |
| | Ave | 2.242 | 2.271 | 2.271 | 2.294 | 2.302 |
| Unit Weight ($kg/m^3$) | 1 | 2228 | 2275 | 2263 | 2295 | 2297 |
| | 2 | 2250 | 2264 | 2279 | 2292 | 2305 |
| | 3 | 2245 | 2271 | 2267 | 2292 | 2300 |
| | Ave | 2241 | 2270 | 2270 | 2293 | 2301 |
| Air Voids (%) | 1 | 6.56 | 5.83 | 5.26 | 3.24 | 2.48 |
| | 2 | 6.58 | 5.93 | 4.62 | 3.37 | 2.14 |
| | 3 | 7.40 | 6.02 | 5.10 | 3.36 | 2.33 |
| | Ave | 6.85 | 5.93 | 4.99 | 3.32 | 2.32 |
| Voids in Mineral Aggregate (%) | 1 | 17.94 | 16.66 | 17.54 | 16.82 | 17.19 |
| | 2 | 17.13 | 17.06 | 16.95 | 16.93 | 16.90 |
| | 3 | 17.32 | 16.80 | 17.39 | 16.93 | 17.09 |
| | Ave | 17.46 | 16.84 | 17.29 | 16.89 | 17.06 |
| Voids Filled with Asphalt (%) | 1 | 63.4 | 65.0 | 70.0 | 80.7 | 85.6 |
| | 2 | 61.6 | 65.2 | 72.7 | 80.1 | 87.3 |
| | 3 | 57.3 | 64.2 | 70.7 | 80.1 | 86.4 |
| | Ave | 60.8 | 64.8 | 71.1 | 80.3 | 86.4 |
| Indirect Tensile Strenght (MPa) | 1 | 0.816 | 1.070 | 0.919 | 0.974 | 0.854 |
| | 2 | 0.971 | 0.959 | 0.954 | 0.919 | 0.881 |
| | 3 | 0.984 | 0.981 | 0.929 | 1.014 | 0.947 |
| | Ave | 0.924 | 1.003 | 0.934 | 0.969 | 0.894 |
| Deformation (mm) | 1 | 1.473 | 1.702 | 1.803 | 1.803 | 2.362 |
| | 2 | 1.346 | 1.600 | 1.803 | 1.803 | 2.235 |
| | 3 | 1.346 | 1.499 | 1.803 | 1.676 | 2.261 |
| | Ave | 1.389 | 1.600 | 1.803 | 1.761 | 2.286 |

Table B11. Limestone aggregate; 15% Owens-Corning shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 |
| Maximum Specific Gravity | | 2.522 | 2.502 | 2.483 | 2.464 | 2.446 | 2.427 |
| SSD Specific Gravity | 1 | 2.313 | 2.331 | 2.349 | 2.370 | 2.379 | 2.375 |
| | 2 | 2.304 | 2.322 | 2.342 | 2.362 | 2.387 | 2.382 |
| | 3 | 2.320 | 2.320 | 2.336 | 2.367 | 2.368 | 2.372 |
| | Ave | 2.312 | 2.324 | 2.342 | 2.366 | 2.378 | 2.376 |
| Unit Weight ($kg/m^3$) | 1 | 2312 | 2330 | 2348 | 2369 | 2378 | 2374 |
| | 2 | 2303 | 2321 | 2341 | 2361 | 2386 | 2381 |
| | 3 | 2319 | 2319 | 2335 | 2366 | 2367 | 2371 |
| | Ave | 2312 | 2324 | 2342 | 2366 | 2377 | 2375 |
| Air Voids (%) | 1 | 8.28 | 6.84 | 5.39 | 3.84 | 2.72 | 2.17 |
| | 2 | 8.63 | 7.19 | 5.69 | 4.15 | 2.38 | 1.89 |
| | 3 | 7.98 | 7.27 | 5.94 | 3.93 | 3.17 | 2.28 |
| | Ave | 8.30 | 7.10 | 5.67 | 3.97 | 2.76 | 2.11 |
| Voids in Mineral Aggregate (%) | 1 | 17.39 | 17.19 | 16.99 | 16.70 | 16.83 | 17.42 |
| | 2 | 17.71 | 17.51 | 17.24 | 16.98 | 16.55 | 17.18 |
| | 3 | 17.14 | 17.58 | 17.45 | 16.81 | 17.22 | 17.53 |
| | Ave | 17.42 | 17.43 | 17.23 | 16.83 | 16.87 | 17.38 |
| Voids Filled with Asphalt (%) | 1 | 52.4 | 60.2 | 68.3 | 77.0 | 83.8 | 87.5 |
| | 2 | 51.3 | 58.9 | 67.0 | 75.6 | 85.6 | 89.0 |
| | 3 | 53.5 | 58.6 | 66.0 | 76.6 | 81.8 | 87.0 |
| | Ave | 52.4 | 59.3 | 67.1 | 76.4 | 83.7 | 87.8 |
| Indirect Tensile Strenght (MPa) | 1 | 1.209 | 1.236 | 1.291 | 1.251 | 1.136 | 0.940 |
| | 2 | 1.174 | 1.091 | 1.193 | 1.233 | 1.200 | 0.949 |
| | 3 | 1.263 | 1.172 | 1.114 | 1.269 | 1.042 | 0.898 |
| | Ave | 1.215 | 1.167 | 1.199 | 1.251 | 1.126 | 0.929 |
| Deformation (mm) | 1 | 1.346 | 1.270 | 1.473 | 1.473 | 2.032 | 1.803 |
| | 2 | 1.346 | 1.575 | 1.372 | 1.600 | 1.702 | 1.803 |
| | 3 | 1.600 | 1.600 | 1.473 | 1.702 | 1.930 | 1.905 |
| | Ave | 1.431 | 1.482 | 1.439 | 1.592 | 1.888 | 1.837 |

Table B12. Limestone aggregate; 15% Celotex shingle addition.

| Property | Sample | Asphalt Content, (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5.7 | 6.2 | 6.7 | 7.2 | 7.7 | 8.5 |
| Maximum Specific Gravity | | 2.513 | 2.494 | 2.475 | 2.456 | 2.438 | 2.409 |
| SSD Specific Gravity | 1 | 2.287 | 2.316 | 2.336 | 2.364 | 2.379 | 2.379 |
| | 2 | 2.294 | 2.336 | 2.335 | 2.351 | 2.371 | |
| | 3 | 2.294 | 2.318 | 2.332 | 2.369 | 2.371 | |
| | Ave | 2.292 | 2.323 | 2.334 | 2.361 | 2.374 | 2.379 |
| Unit Weight (kg/m$^3$) | 1 | 2286 | 2315 | 2335 | 2363 | 2378 | 2378 |
| | 2 | 2293 | 2335 | 2334 | 2350 | 2370 | |
| | 3 | 2293 | 2317 | 2331 | 2368 | 2370 | |
| | Ave | 2291 | 2323 | 2334 | 2361 | 2373 | 2378 |
| Air Voids (%) | 1 | 9.01 | 7.13 | 5.61 | 3.76 | 2.41 | 1.23 |
| | 2 | 8.72 | 6.32 | 5.68 | 4.27 | 2.72 | |
| | 3 | 8.73 | 7.05 | 5.77 | 3.57 | 2.75 | |
| | Ave | 8.82 | 6.83 | 5.69 | 3.87 | 2.63 | 1.23 |
| Voids in Mineral Aggregate (%) | 1 | 18.86 | 18.27 | 18.00 | 17.46 | 17.39 | 18.10 |
| | 2 | 18.61 | 17.56 | 18.04 | 17.92 | 17.67 | |
| | 3 | 18.61 | 18.20 | 18.14 | 17.29 | 17.67 | |
| | Ave | 18.70 | 18.01 | 18.06 | 17.56 | 17.57 | 18.10 |
| Voids Filled with Asphalt (%) | 1 | 52.2 | 61.0 | 68.8 | 78.5 | 86.1 | 93.2 |
| | 2 | 53.2 | 64.0 | 68.5 | 76.2 | 86.4 | |
| | 3 | 53.1 | 61.3 | 68.2 | 79.4 | 84.4 | |
| | Ave | 52.8 | 62.1 | 68.5 | 78.0 | 85.1 | 93.2 |
| Indirect Tensile Strenght (MPa) | 1 | 1.029 | 1.065 | 1.139 | 1.176 | 1.105 | 0.849 |
| | 2 | 1.049 | 1.209 | 1.151 | 1.109 | 1.058 | |
| | 3 | 1.069 | 1.012 | 1.070 | 1.142 | 1.071 | |
| | Ave | 1.049 | 1.095 | 1.120 | 1.143 | 1.078 | 0.849 |
| Deformation (mm) | 1 | 1.524 | 1.372 | 1.600 | 1.727 | 1.676 | 2.032 |
| | 2 | 1.473 | 1.372 | 1.702 | 1.600 | 1.930 | |
| | 3 | 1.473 | 1.600 | 1.473 | 1.600 | 1.930 | |
| | Ave | 1.490 | 1.448 | 1.592 | 1.643 | 1.846 | 2.032 |

# APPENDIX C

# INDIVIDUAL TEST RESULTS

Table C1 . Test results for asphalt concrete specimens produced with limestone aggregate.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.320 | 5.81 | 18.75 | 69.0 | 11121 | 3034 | 600 | - | - | 0.885 | 1.59 |
| 2 | 2.324 | 5.64 | 18.61 | 69.7 | 10425 | 3199 | 745 | - | - | 0.910 | 1.67 |
| 3 | 2.319 | 5.85 | 18.78 | 68.8 | 8908 | 2785 | 834 | - | - | 0.868 | 1.57 |
| 4 | 2.324 | 5.64 | 18.61 | 69.7 | - | - | - | - | - | - | - |
| 5 | 2.317 | 5.93 | 18.85 | 68.5 | - | - | - | - | - | - | - |
| 6 | 2.314 | 6.05 | 18.96 | 68.1 | - | - | - | - | - | - | - |
| 7 | 2.311 | 6.17 | 19.06 | 67.6 | - | - | - | 9105 | 2.54 | - | - |
| 8 | 2.317 | 5.93 | 18.85 | 68.5 | - | - | - | 10293 | 2.16 | - | - |
| 9 | 2.317 | 5.93 | 18.85 | 68.5 | - | - | - | 9599 | 2.41 | - | - |
| Ave | 2.318 | 5.88 | 18.81 | 68.7 | 10151 | 3006 | 726 | 9666 | 2.41 | 0.888 | 1.61 |

Table C2 . Test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.371 | 3.85 | 17.60 | 78.1 | - | - | - | | | - | - |
| 2 | 2.372 | 3.8 | 17.57 | 78.4 | - | - | - | | | - | - |
| 3 | 2.371 | 3.86 | 17.60 | 78.1 | - | - | - | - | - | - | - |
| 4 | 2.369 | 3.95 | 17.68 | 77.7 | - | - | - | - | - | - | - |
| 5 | 2.368 | 3.96 | 17.71 | 77.6 | 9198 | 2523 | 576 | - | - | 1.310 | 1.90 |
| 6 | 2.361 | 4.27 | 17.96 | 76.2 | 10528 | 2399 | 669 | - | - | 1.257 | 1.60 |
| 7 | 2.357 | 4.42 | 18.09 | 75.6 | - | - | - | | | - | - |
| 8 | 2.363 | 4.19 | 17.89 | 76.6 | - | - | - | - | - | - | - |
| 9 | 2.371 | 3.84 | 17.60 | 78.2 | 9935 | 1986 | 441 | - | - | 1.173 | 1.93 |
| Ave | 2.367 | 4.02 | 17.74 | 77.4 | 9887 | 2302 | 562 | - | - | 1.247 | 1.81 |

Table C3 . Test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.348 | 5.63 | 18.40 | 69.4 | - | - | - | 11089 | 5.08 | - | - |
| 2 | 2.355 | 5.35 | 18.16 | 70.5 | - | - | - | - | - | - | - |
| 3 | 2.361 | 5.10 | 17.96 | 71.6 | - | - | - | - | - | - | - |
| 4 | 2.356 | 5.31 | 18.13 | 70.7 | - | - | - | - | - | - | - |
| 5 | 2.367 | 4.86 | 17.75 | 72.6 | - | - | - | 10599 | 4.57 | - | - |
| 6 | 2.357 | 5.27 | 18.09 | 70.9 | - | - | - | 10969 | 4.83 | - | - |
| 7 | 2.355 | 5.35 | 18.16 | 70.5 | 9294 | 1793 | 503 | - | - | 1.251 | 1.90 |
| 8 | 2.351 | 5.51 | 18.30 | 69.9 | 9922 | 1965 | 571 | - | - | 1.162 | 2.18 |
| 9 | 2.365 | 4.94 | 17.82 | 72.3 | 9749 | 1737 | 498 | | | 1.102 | 2.34 |
| Ave | 2.357 | 5.26 | 18.09 | 70.9 | 9655 | 1832 | 524 | 10886 | 4.83 | 1.172 | 2.14 |

Table C4 . Test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.374 | 3.81 | 17.31 | 78.0 | - | - | - | 11831 | 3.81 | - | - |
| 2 | 2.370 | 3.98 | 17.45 | 77.2 | 9494 | 3654 | 778 | - | - | 1.335 | 1.75 |
| 3 | 2.368 | 4.06 | 17.52 | 76.8 | 7998 | 3247 | 671 | - | - | 1.267 | 1.96 |
| 4 | 2.366 | 4.14 | 17.59 | 76.5 | - | - | - | - | - | - | - |
| 5 | 2.360 | 4.37 | 17.80 | 75.5 | 8219 | 3406 | 615 | - | - | 1.252 | 1.96 |
| 6 | 2.364 | 4.20 | 17.66 | 76.2 | - | - | - | - | - | - | - |
| 7 | 2.364 | 4.22 | 17.66 | 76.1 | - | - | - | 11376 | 3.81 | - | - |
| 8 | 2.360 | 4.38 | 17.80 | 75.4 | - | - | - | 11335 | 3.81 | - | - |
| 9 | 2.365 | 4.16 | 17.62 | 76.4 | - | - | - | - | - | - | - |
| Ave | 2.366 | 4.15 | 17.60 | 76.5 | 8570 | 3636 | 688 | 11514 | 3.81 | 1.285 | 1.89 |

Table C5 . Test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.328 | 4.59 | 18.91 | 75.7 | - | - | - | 9768 | 3.81 | - | - |
| 2 | 2.327 | 4.63 | 18.95 | 75.6 | 8453 | 3034 | 914 | - | - | 1.251 | 1.83 |
| 3 | 2.340 | 4.10 | 18.50 | 77.8 | - | - | - | 11281 | 3.56 | - | - |
| 4 | 2.332 | 4.43 | 18.78 | 76.4 | - | - | - | - | - | - | - |
| 5 | 2.332 | 4.43 | 18.78 | 76.4 | 10004 | 3061 | 772 | - | - | 1.196 | 1.83 |
| 6 | 2.325 | 4.71 | 19.02 | 75.2 | - | - | - | 10253 | 3.68 | - | - |
| 7 | 2.332 | 4.43 | 18.78 | 76.4 | - | - | - | - | - | - | - |
| 8 | 2.335 | 4.30 | 18.67 | 77.0 | 8425 | 2848 | 670 | - | - | 1.202 | 1.96 |
| 9 | 2.331 | 4.47 | 18.81 | 76.2 | - | - | - | - | - | - | - |
| Ave | 2.331 | 4.45 | 18.80 | 76.3 | 8961 | 2981 | 785 | 10101 | 3.68 | 1.216 | 1.87 |

Table C6 . Test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.349 | 4.34 | 17.99 | 75.9 | 8101 | 3537 | 938 | - | - | 1.175 | 1.70 |
| 2 | 2.356 | 4.08 | 17.75 | 77.0 | - | - | - | 11665 | 4.57 | - | - |
| 3 | 2.350 | 4.33 | 17.96 | 75.9 | 9729 | 3833 | 1100 | - | - | 1.170 | 1.70 |
| 4 | 2.357 | 4.03 | 17.72 | 77.3 | - | - | - | - | - | - | - |
| 5 | 2.339 | 4.78 | 18.35 | 73.9 | - | - | - | 11213 | 3.94 | - | - |
| 6 | 2.360 | 3.90 | 17.61 | 77.8 | 7929 | 3744 | 975 | - | - | 1.193 | 1.70 |
| 7 | 2.367 | 3.64 | 17.37 | 79.0 | - | - | - | 12418 | 4.70 | - | - |
| 8 | 2.348 | 4.39 | 18.03 | 75.6 | - | - | - | - | - | - | - |
| 9 | 2.349 | 4.34 | 17.99 | 75.9 | - | - | - | - | - | - | - |
| Ave | 2.353 | 4.20 | 17.86 | 76.5 | 8586 | 3705 | 1004 | 11765 | 4.40 | 1.179 | 1.70 |

Table C7 . Test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor mation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.306 | 4.83 | 19.95 | 75.8 | - | - | - | - | - | - | - |
| 2 | 2.304 | 4.91 | 19.57 | 74.9 | - | - | - | 10924 | 3.43 | - | - |
| 3 | 2.301 | 5.04 | 19.67 | 74.4 | 9694 | 3244 | 736 | - | - | 1.011 | 1.70 |
| 4 | 2.312 | 4.58 | 19.29 | 76.3 | - | - | - | 10768 | 3.30 | - | - |
| 5 | 2.301 | 5.04 | 19.67 | 74.4 | - | - | - | - | - | - | - |
| 6 | 2.302 | 4.99 | 19.64 | 74.6 | - | - | - | 10134 | 4.95 | - | - |
| 7 | 2.307 | 4.79 | 19.46 | 75.4 | - | - | - | - | - | - | - |
| 8 | 2.306 | 4.83 | 19.95 | 75.8 | 9018 | 3196 | 757 | - | - | 1.024 | 1.80 |
| 9 | 2.309 | 4.70 | 19.39 | 75.8 | 8676 | 3102 | 1071 | - | - | 1.042 | 1.83 |
| Ave | 2.305 | 4.86 | 19.39 | 75.3 | 9130 | 3102 | 855 | 10609 | 3.89 | 1.026 | 1.78 |

Table C8. Test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.369 | 4.61 | 17.55 | 73.7 | 11473 | 3110 | 669 | - | - | 1.289 | 1.85 |
| 2 | 2.368 | 4.66 | 17.57 | 73.5 | 10459 | 2572 | 689 | - | - | 1.229 | 1.93 |
| 3 | 2.376 | 4.34 | 17.29 | 74.9 | 10694 | 2572 | 600 | - | - | 1.256 | 1.83 |
| 4 | 2.368 | 4.68 | 17.57 | 73.4 | - | - | - | - | - | - | - |
| 5 | 2.373 | 4.45 | 17.40 | 74.4 | - | - | - | 12658 | 4.57 | - | - |
| 6 | 2.364 | 4.81 | 17.71 | 72.8 | - | - | - | 11499 | 3.56 | - | - |
| 7 | 2.381 | 4.16 | 17.12 | 75.7 | - | - | - | - | - | - | - |
| 8 | 2.375 | 4.39 | 17.33 | 74.7 | - | - | - | 12548 | 4.32 | - | - |
| 9 | 2.369 | 4.64 | 17.54 | 73.5 | - | - | - | - | - | - | - |
| Ave | 2.371 | 4.53 | 17.45 | 74.1 | 10875 | 2751 | 653 | 12235 | 4.15 | 1.258 | 1.87 |

Table C9. Test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.348 | 4.36 | 18.28 | 76.2 | - | - | - | 11249 | 3.94 | - | - |
| 2 | 2.344 | 4.52 | 18.41 | 75.4 | 9922 | 2455 | 772 | - | - | 1.244 | 1.70 |
| 3 | 2.359 | 3.91 | 17.88 | 78.1 | - | - | - | 11867 | 3.94 | - | - |
| 4 | 2.355 | 4.07 | 18.02 | 77.4 | - | - | - | - | - | - | - |
| 5 | 2.353 | 4.15 | 18.09 | 77.1 | 10053 | 2434 | 598 | - | - | 1.165 | 2.16 |
| 6 | 2.356 | 4.03 | 17.99 | 77.6 | - | - | - | - | - | - | - |
| 7 | 2.349 | 4.32 | 18.23 | 76.3 | - | - | - | - | - | - | - |
| 8 | 2.360 | 3.87 | 17.85 | 78.3 | 8991 | 2227 | 641 | - | - | 1.175 | 2.01 |
| 9 | 2.348 | 4.36 | 18.28 | 76.1 | - | - | - | 11164 | 3.98 | - | - |
| Ave | 2.352 | 4.18 | 18.11 | 76.9 | 9655 | 2392 | 670 | 11427 | 3.95 | 1.195 | 1.96 |

Table C10. Test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Deform ation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.376 | 3.64 | 17.12 | 78.7 | - | - | - | - | - | - | - |
| 2 | 2.376 | 3.63 | 17.12 | 78.8 | 9398 | 3468 | 1268 | - | - | 1.356 | 1.70 |
| 3 | 2.372 | 3.82 | 17.26 | 77.9 | - | - | - | - | - | - | - |
| 4 | 2.375 | 3.70 | 17.16 | 78.4 | - | - | - | - | - | - | - |
| 5 | 2.377 | 3.60 | 17.09 | 78.9 | 8425 | 3392 | 1220 | - | - | 1.324 | 1.98 |
| 6 | 2.369 | 3.95 | 17.37 | 77.3 | 10466 | 3289 | 1073 | - | - | 1.290 | 1.70 |
| 7 | 2.379 | 3.51 | 17.02 | 79.4 | - | - | - | 11541 | 3.56 | - | - |
| 8 | 2.378 | 3.55 | 17.06 | 79.2 | - | - | - | 11789 | 4.32 | - | - |
| 9 | 2.363 | 4.17 | 17.58 | 76.3 | - | - | - | 10962 | 3.56 | - | - |
| Ave | 2.374 | 3.73 | 17.20 | 78.3 | 9430 | 3383 | 1187 | 11431 | 3.81 | 1.323 | 1.79 |

Table C11. Test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.327 | 5.18 | 18.83 | 72.5 | - | - | - | 10847 | 4.06 | - | - |
| 2 | 2.319 | 5.50 | 19.11 | 71.2 | - | - | - | - | - | - | - |
| 3 | 2.318 | 5.54 | 19.15 | 71.2 | 9163 | 2896 | 584 | - | - | 1.225 | 1.65 |
| 4 | 2.327 | 5.18 | 18.83 | 72.5 | 9432 | 2834 | 694 | - | - | 1.244 | 1.93 |
| 5 | 2.323 | 5.34 | 18.97 | 71.8 | - | - | - | - | - | - | - |
| 6 | 2.314 | 5.70 | 19.29 | 70.5 | - | - | - | 9818 | 3.68 | - | - |
| 7 | 2.321 | 5.42 | 19.04 | 71.5 | 9935 | 2503 | 569 | - | - | 1.158 | 1.88 |
| 8 | 2.324 | 5.30 | 18.94 | 72.0 | - | - | - | 9238 | 4.70 | - | - |
| 9 | 2.324 | 5.30 | 18.94 | 72.0 | - | - | - | - | - | - | - |
| Ave | 2.322 | 5.38 | 19.01 | 71.7 | 9510 | 2744 | 615 | 9968 | 4.15 | 1.209 | 1.82 |

Table C12. Test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.357 | 4.06 | 17.34 | 76.6 | - | - | - | 12930 | 4.06 | - | - |
| 2 | 2.356 | 4.13 | 17.38 | 76.2 | - | - | - | - | - | - | - |
| 3 | 2.355 | 4.16 | 17.41 | 76.1 | - | - | - | - | - | | |
| 4 | 2.351 | 4.31 | 17.55 | 75.4 | 7998 | 2999 | 1391 | - | - | 1.193 | 1.60 |
| 5 | 2.347 | 4.48 | 17.69 | 74.7 | - | - | - | 12236 | 4.45 | - | - |
| 6 | 2.359 | 3.97 | 17.34 | 77.1 | - | - | - | - | - | | |
| 7 | 2.364 | 3.79 | 17.09 | 77.8 | - | - | - | 12244 | 4.70 | | |
| 8 | 2.365 | 3.74 | 17.06 | 78.1 | 10108 | 3316 | 1611 | - | - | 1.282 | 1.70 |
| 9 | 2.351 | 4.33 | 17.55 | 75.3 | 7040 | 3256 | 1304 | - | - | 1.216 | 1.78 |
| Ave | 2.356 | 4.11 | 17.38 | 76.4 | 8382 | 3257 | 1435 | 12470 | 4.40 | 1.230 | 1.69 |

Table C13. Test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Deform ation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.296 | 6.17 | 19.51 | 68.4 | - | - | - | - | - | - | - |
| 2 | 2.288 | 6.50 | 19.78 | 67.1 | - | - | - | - | - | - | - |
| 3 | 2.286 | 6.58 | 19.85 | 66.9 | - | - | - | 10530 | 4.45 | - | - |
| 4 | 2.295 | 6.21 | 19.54 | 68.2 | 9403 | 3363 | 1114 | - | - | 1.025 | 1.57 |
| 5 | 2.288 | 6.50 | 19.78 | 67.1 | - | - | - | 10134 | 4.83 | - | - |
| 6 | 2.301 | 5.97 | 19.33 | 69.1 | - | - | - | 10969 | 3.94 | - | - |
| 7 | 2.285 | 6.62 | 19.89 | 66.7 | 9371 | 3179 | 993 | - | - | 1.084 | 1.60 |
| 8 | 2.292 | 6.33 | 19.64 | 67.8 | 7225 | 3029 | 1108 | - | - | 1.026 | 1.47 |
| 9 | 2.288 | 6.50 | 19.78 | 67.1 | - | - | - | - | - | - | - |
| Ave | 2.291 | 6.38 | 19.68 | 67.6 | 8666 | 3190 | 1071 | 10544 | 4.41 | 1.045 | 1.55 |

Table C14. Test results for asphalt concrete specimens produced with gravel aggregate.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.255 | 4.25 | 17.42 | 75.6 | 8977 | 2358 | 276 | - | - | 0.552 | 2.13 |
| 2 | 2.247 | 4.59 | 17.71 | 74.1 | 8088 | 2048 | 427 | - | - | 0.669 | 2.01 |
| 3 | 2.250 | 4.46 | 17.60 | 74.7 | 7674 | 2020 | 303 | - | - | 0.641 | 1.87 |
| 4 | 2.254 | 4.29 | 17.45 | 75.4 | - | - | - | - | - | - | - |
| 5 | 2.249 | 4.50 | 17.64 | 74.5 | - | - | - | - | - | - | - |
| 6 | 2.246 | 4.63 | 17.75 | 73.9 | - | - | - | - | - | - | - |
| 7 | 2.263 | 3.91 | 17.13 | 77.2 | - | - | - | 7166 | 2.41 | - | - |
| 8 | 2.258 | 4.12 | 17.31 | 76.2 | - | - | - | 6810 | 3.05 | - | - |
| 9 | 2.249 | 4.50 | 17.64 | 74.5 | - | - | - | 6160 | 3.05 | | |
| Ave | 2.252 | 4.36 | 17.52 | 75.1 | 8246 | 2142 | 335 | 6712 | 2.84 | - | - |

Table C15 . Test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Deform ation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.283 | 2.97 | 16.95 | 82.5 | - | - | - | 7326 | 3.68 | - | - |
| 2 | 2.285 | 2.9 | 16.87 | 82.8 | 9149 | 2979 | 330 | - | - | 0.805 | 2.37 |
| 3 | 2.280 | 3.09 | 17.05 | 81.9 | - | - | - | 7120 | 4.06 | - | - |
| 4 | 2.281 | 3.05 | 17.02 | 62.1 | - | - | - | - | - | - | - |
| 5 | 2.286 | 2.85 | 16.84 | 83.1 | 8088 | 3156 | 421 | - | - | 0.908 | 2.03 |
| 6 | 2.280 | 3.11 | 17.05 | 81.8 | - | - | - | - | - | - | - |
| 7 | 2.289 | 2.72 | 16.73 | 83.7 | 8639 | 2517 | 427 | - | - | 0.907 | 2.12 |
| 8 | 2.295 | 2.46 | 16.51 | 85.1 | - | - | - | 6967 | 4.32 | - | - |
| 9 | 2.291 | 2.40 | 16.44 | 85.4 | - | - | - | - | - | - | - |
| Ave | 2.286 | 2.84 | 16.83 | 83.2 | 8625 | 2884 | 393 | 7138 | 4.02 | 0.873 | 2.17 |

Table C16. Test results for asphalt concrete specimens produced with gravel aggregate and 5% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Defor matio n (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.260 | 3.17 | 17.78 | 82.2 | - | - | - | 5951 | 5.46 | - | - |
| 2 | 2.263 | 3.04 | 17.67 | 82.8 | 9218 | 2358 | 379 | - | - | 0.993 | 2.36 |
| 3 | 2.283 | 2.19 | 16.94 | 87.1 | - | - | - | 7361 | 4.06 | - | - |
| 4 | 2.274 | 2.57 | 17.27 | 85.1 | - | - | - | - | - | - | - |
| 5 | 2.272 | 2.66 | 17.34 | 84.7 | - | - | - | - | - | - | - |
| 6 | 2.276 | 2.49 | 17.20 | 85.5 | - | - | - | 7006 | 3.68 | - | - |
| 7 | 2.274 | 2.57 | 17.27 | 85.1 | - | - | - | - | - | - | - |
| 8 | 2.280 | 2.31 | 17.05 | 86.4 | 10280 | 2503 | 268 | - | - | 1.014 | 2.34 |
| 9 | 2.278 | 2.40 | 17.13 | 86.0 | 8715 | 2144 | 338 | - | - | 1.053 | 2.16 |
| Ave | 2.273 | 2.60 | 17.27 | 85.0 | 9404 | 2335 | 328 | 6773 | 4.40 | 1.020 | 2.29 |

Table C17. Test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.298 | 3.92 | 16.54 | 78.1 | Tested for Creep | | | | | | |
| 2 | 2.298 | 3.91 | 16.54 | 78.2 | Tested for Creep | | | | | | |
| 3 | 2.298 | 3.59 | 16.54 | 78.3 | - | - | - | 7206 | 4.45 | - | - |
| 4 | 2.298 | 3.62 | 16.54 | 78.1 | Tested for Creep | | | | | | |
| 5 | 2.298 | 3.55 | 16.50 | 78.5 | - | - | - | 7126 | 3.56 | - | - |
| 6 | 2.298 | 3.59 | 16.54 | 78.3 | 8540 | 2544 | 622 | - | - | 1.241 | 2.16 |
| 7 | 2.298 | 3.63 | 16.54 | 78.1 | 8977 | 2654 | 738 | - | - | 1.193 | 2.41 |
| 8 | 2.298 | 4.56 | 17.37 | 73.8 | - | - | - | 6107 | 4.06 | - | - |
| 9 | 2.298 | 3.61 | 16.54 | 78.2 | 8108 | 2654 | 820 | - | - | 1.214 | 2.16 |
| Average | 2.298 | 3.71 | 16.63 | 77.7 | 8540 | 2530 | 727 | 6813 | 4.02 | 1.216 | 2.24 |

Table C18. Test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.272 | 2.57 | 17.48 | 85.3 | 9425 | 2599 | 503 | - | - | 1.183 | 2.29 |
| 2 | 2.261 | 3.04 | 17.88 | 83.0 | Tested for Creep | | | | | | |
| 3 | 2.251 | 3.47 | 18.24 | 79.3 | Tested for Creep | | | | | | |
| 4 | 2.245 | 3.73 | 18.46 | 79.8 | - | - | - | 6196 | 3.18 | - | - |
| 5 | 2.247 | 3.64 | 18.39 | 80.2 | 9094 | 2255 | 538 | - | - | 1.036 | 2.11 |
| 6 | 2.262 | 3.00 | 17.84 | 83.2 | 6226 | 2599 | 605 | - | - | 1.091 | 2.01 |
| 7 | 2.266 | 2.83 | 17.70 | 84.0 | - | - | - | 6890 | 3.81 | - | - |
| 8 | 2.271 | 2.62 | 17.52 | 85.1 | - | - | - | 7246 | 3.43 | - | - |
| 9 | 2.269 | 2.70 | 17.59 | 84.7 | Tested for Creep | | | | | | |
| Average | 2.260 | 3.10 | 17.90 | 82.7 | 8248 | 2484 | 549 | 6777 | 3.47 | 1.103 | 2.14 |

Table C19. Test results for asphalt concrete specimens produced with gravel aggregate and 15% granulated Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.304 | 3.21 | 16.30 | 80.3 | - | - | - | 9448 | 4.57 | - | - |
| 2 | 2.285 | 4.05 | 16.99 | 76.2 | - | - | - | 8749 | 3.56 | - | - |
| 3 | 2.301 | 3.35 | 16.40 | 79.6 | Tested for Creep | | | | | | |
| 4 | 2.296 | 3.55 | 16.59 | 78.6 | Tested for Creep | | | | | | |
| 5 | 2.302 | 3.32 | 16.37 | 79.7 | Tested for Creep | | | | | | |
| 6 | 2.310 | 2.97 | 16.08 | 81.5 | - | - | - | 9577 | 4.32 | - | - |
| 7 | 2.294 | 3.65 | 16.66 | 78.1 | 10880 | 3475 | 887 | - | - | 1.169 | 1.96 |
| 8 | 2.302 | 3.34 | 16.37 | 79.6 | 8591 | 3537 | 974 | - | - | 1.224 | 1.93 |
| 9 | 2.303 | 3.28 | 16.33 | 79.9 | 9115 | 3475 | 921 | - | - | 1.234 | 1.83 |
| Average | 2.300 | 3.41 | 16.45 | 79.3 | 9529 | 3496 | 927 | 9258 | 4.15 | 1.209 | 1.91 |

Table C20. Test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Celotex shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.235 | 4.45 | 18.80 | 76.3 | - | - | - | 6961 | 3.68 | - | - |
| 2 | 2.242 | 4.15 | 18.55 | 77.6 | 8225 | 2710 | 643 | - | - | 0.955 | 1.70 |
| 3 | 2.231 | 4.62 | 18.95 | 75.6 | Tested for Creep | | | | | | |
| 4 | 2.254 | 3.63 | 18.11 | 80.0 | 6867 | 2965 | 672 | - | - | 1.038 | 1.57 |
| 5 | 2.248 | 3.89 | 18.33 | 78.8 | Tested for Creep | | | | | | |
| 6 | 2.257 | 3.51 | 18.00 | 80.5 | - | - | - | 7161 | 4.45 | - | - |
| 7 | 2.228 | 4.75 | 19.06 | 75.1 | 6509 | 2565 | 638 | - | - | 0.896 | 1.70 |
| 8 | 2.234 | 4.49 | 18.84 | 76.2 | - | - | - | 6890 | 4.83 | - | - |
| 9 | 2.248 | 3.89 | 18.33 | 78.8 | Tested for Creep | | | | | | |
| Average | 2.242 | 4.15 | 18.55 | 77.7 | 7200 | 2746 | 651 | 7004 | 4.32 | 0.963 | 1.66 |

Table C21. Test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.283 | 3.47 | 16.78 | 79.3 | 8839 | 2992 | 476 | - | - | 1.196 | 2.06 |
| 2 | 2.284 | 3.51 | 16.75 | 79.0 | - | - | - | 7321 | 3.81 | - | - |
| 3 | 2.281 | 3.54 | 16.86 | 79.0 | 9018 | 2530 | 365 | - | - | 1.195 | 2.29 |
| 4 | 2.283 | 3.46 | 16.78 | 79.4 | Tested for Creep | | | | | | |
| 5 | 2.276 | 3.78 | 17.04 | 77.8 | - | - | - | 6889 | 3.18 | - | - |
| 6 | 2.283 | 3.47 | 1678 | 79.3 | 8770 | 2337 | 427 | - | - | 1.130 | 2.01 |
| 7 | 2.279 | 3.65 | 16.93 | 78.4 | Tested for Creep | | | | | | |
| 8 | 2.290 | 3.18 | 16.53 | 80.8 | - | - | - | 8064 | 3.56 | - | - |
| 9 | 2.285 | 3.38 | 16.71 | 79.8 | Tested for Creep | | | | | | |
| Average | 2.282 | 3.49 | 16.80 | 79.2 | 8876 | 2620 | 423 | 7425 | 3.52 | 1.174 | 2.12 |

Table C22. Test results for asphalt concrete specimens produced with gravel aggregate and 5% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.269 | 4.26 | 17.30 | 75.4 | Tested for Creep | | | | | | |
| 2 | 2.296 | 4.26 | 17.30 | 75.4 | 8039 | 1737 | 448 | - | - | 1.055 | 2.18 |
| 3 | 2.280 | 3.80 | 16.89 | 77.5 | - | - | - | 8300 | 3.81 | - | - |
| 4 | 2.273 | 4.09 | 17.15 | 76.2 | 8605 | 2020 | 345 | - | - | 1.049 | 2.21 |
| 5 | 2.270 | 4.22 | 17.26 | 75.6 | Tested for Creep | | | | | | |
| 6 | 2.270 | 4.22 | 17.26 | 75.6 | Tested for Creep | | | | | | |
| 7 | 2.255 | 4.85 | 17.81 | 72.8 | - | - | - | 6890 | 4.45 | - | - |
| 8 | 2.268 | 4.30 | 17.33 | 75.2 | 9660 | 2199 | 400 | - | - | 1.056 | 2.24 |
| 9 | 2.275 | 4.01 | 17.08 | 76.5 | - | - | - | 7201 | 3.81 | - | - |
| Average | 2.270 | 4.22 | 17.26 | 75.6 | 8768 | 1986 | 398 | 7464 | 4.02 | 1.053 | 2.21 |

Table C23. Test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stabi lity (N) | Flow (mm) | ITS (MPa) | Deform ation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.298 | 3.77 | 16.31 | 76.9 | 8446 | 3041 | 769 | - | - | 1.214 | 1.88 |
| 2 | 2.284 | 4.35 | 16.82 | 74.1 | Tested for Creep | | | | | | |
| 3 | 2.290 | 4.10 | 16.60 | 75.1 | 9370 | 2710 | 776 | - | - | 1.246 | 1.83 |
| 4 | 2.302 | 3.62 | 16.16 | 77.6 | - | - | - | 7766 | 3.30 | - | - |
| 5 | 2.288 | 4.21 | 16.67 | 74.8 | Tested for Creep | | | | | | |
| 6 | 2.301 | 3.62 | 16.20 | 77.6 | - | - | - | 7771 | 3.43 | - | - |
| 7 | 2.278 | 4.60 | 17.04 | 73.0 | 9246 | 2648 | 583 | - | - | 1.193 | 2.01 |
| 8 | 2.294 | 3.95 | 16.45 | 76.0 | Tested for Creep | | | | | | |
| 9 | 2.266 | 5.12 | 17.47 | 70.7 | - | - | - | 6574 | 4.06 | - | - |
| Average | 2.289 | 4.15 | 16.64 | 75.1 | 9021 | 2799 | 709 | 7370 | 3.60 | 1.218 | 1.91 |

Table C24. Test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.260 | 4.07 | 17.73 | 77.0 | - | - | - | 7508 | 2.92 | - | - |
| 2 | 2.257 | 4.20 | 17.85 | 76.5 | - | - | - | 6966 | 3.43 | - | - |
| 3 | 2.261 | 4.03 | 17.70 | 77.2 | Tested for Creep | | | | | | |
| 4 | 2.251 | 4.46 | 18.06 | 75.3 | 8467 | 2585 | 803 | - | - | 1.076 | 1.68 |
| 5 | 2.256 | 4.24 | 17.88 | 76.3 | 7219 | 2475 | 610 | - | - | 1.134 | 2.16 |
| 6 | 2.241 | 4.88 | 18.43 | 73.5 | Tested for Creep | | | | | | |
| 7 | 2.241 | 4.88 | 18.43 | 73.5 | 8784 | 2130 | 690 | - | - | 1.042 | 1.93 |
| 8 | 2.244 | 4.75 | 18.32 | 74.1 | Tested for Creep | | | | | | |
| 9 | 2.232 | 5.26 | 18.65 | 71.8 | - | - | - | 6307 | 3.81 | - | - |
| Average | 2.249 | 4.53 | 18.12 | 75.0 | 8156 | 2397 | 701 | 6927 | 3.39 | 1.084 | 1.92 |

Table C25. Test results for asphalt concrete specimens produced with gravel aggregate and 15% granulated Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.286 | 3.01 | 16.52 | 81.8 | - | - | - | 10319 | 3.05 | - | - |
| 2 | 2.289 | 2.89 | 16.41 | 82.4 | Tested for Creep | | | | | | |
| 3 | 2.286 | 3.01 | 16.52 | 81.8 | 8876 | 2620 | 1298 | - | - | 1.369 | 1.55 |
| 4 | 2.285 | 3.05 | 16.56 | 81.6 | 9021 | 2799 | 1388 | - | - | 1.366 | 1.45 |
| 5 | 2.276 | 3.44 | 16.89 | 79.6 | 9549 | 4068 | 1438 | - | - | 1.325 | 1.66 |
| 6 | 2.290 | 2.84 | 16.38 | 82.7 | - | - | - | 10604 | 3.43 | - | - |
| 7 | 2.285 | 3.05 | 16.56 | 81.6 | Tested for Creep | | | | | | |
| 8 | 2.269 | 3.73 | 17.14 | 78.2 | - | - | - | 9817 | 3.81 | - | - |
| 9 | 2.273 | 3.56 | 17.00 | 79.1 | Tested for Creep | | | | | | |
| Ave | 2.282 | 3.18 | 16.66 | 81.0 | 9549 | 4069 | 1375 | 10247 | 3.43 | 1.353 | 1.55 |

Table C26. Test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Owens-Corning shingles.

| Sample Number | SSD | AV % | VMA % | VFWA % | Resilient Modulus (MPa) | | | Stability (N) | Flow (mm) | ITS (MPa) | Deformation (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | @0°C | @22°C | @40°C | | | | |
| 1 | 2.207 | 5.48 | 19.44 | 71.8 | - | - | - | 7940 | 4.06 | - | - |
| 2 | 2.214 | 5.18 | 19.18 | 73.0 | 6918 | 3119 | 985 | - | - | 1.132 | 1.55 |
| 3 | 2.240 | 4.07 | 18.23 | 77.7 | 7100 | 3510 | 1068 | - | - | 1.267 | 1.54 |
| 4 | 2.244 | 4.75 | 18.82 | 74.8 | Tested for Creep | | | | | | |
| 5 | 2.231 | 4.45 | 18.56 | 76.0 | Tested for Creep | | | | | | |
| 6 | 2.233 | 4.80 | 18.85 | 74.5 | 8736 | 3063 | 965 | - | - | 8976 | 4.57 |
| 7 | 2.229 | 4.54 | 18.64 | 75.6 | - | - | - | 8976 | 4.57 | - | - |
| 8 | 2.241 | 4.03 | 18.20 | 77.9 | - | - | - | 8940 | 4.32 | - | - |
| 9 | 2.221 | 4.88 | 18.93 | 74.2 | Tested for Creep | | | | | | |
| Ave | 2.226 | 4.69 | 18.76 | 75.1 | 7585 | 3231 | 1006 | 8619 | 4.32 | 1.202 | 1.58 |

# APPENDIX D

## INDIRECT TENSILE CREEP

## INDIVIDUAL TEST RESULTS

Table D1. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 0% shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 594 | 351 | 197 | 117 | 73 | 49 | 32 | 18 |
| 5 | 452 | 246 | 140 | 81 | 52 | 37 | 24 | 13 |
| 6 | 392 | 238 | 132 | 79 | 51 | 35 | 22 | 12 |
| Average | 479 | 248 | 156 | 92 | 59 | 40 | 26 | 14 |

Table D2. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 0% shingles addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 285 | 163 | 87 | 50 | 31 | 20 | 11 | 3 |
| 6 | 245 | 138 | 67 | 33 | 17 | 10 | 6 | 3 |
| Average | 265 | 151 | 77 | 41 | 24 | 15 | 9 | 3 |

Table D3. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Celotex shingles addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 668 | 385 | 220 | 121 | 70 | 44 | 29 | 17 |
| 3 | 826 | 459 | 250 | 133 | 74 | 45 | 28 | 16 |
| 4 | 753 | 441 | 237 | 133 | 76 | 51 | 35 | 25 |
| Average | 749 | 428 | 235 | 129 | 73 | 47 | 31 | 19 |

Table D4. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Celotex shingles addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 694 | 377 | 209 | 120 | 72 | 47 | 34 | 23 |
| 3 | 562 | 333 | 186 | 105 | 61 | 39 | 24 | 14 |
| 4 | 475 | 278 | 155 | 88 | 62 | 40 | 25 | 15 |
| Average | 577 | 329 | 183 | 104 | 65 | 42 | 28 | 17 |

Table D5. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Celotex shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 6 | 785 | 509 | 288 | 173 | 115 | 79 | 56 | 38 |
| 9 | 735 | 477 | 299 | 183 | 119 | 82 | 55 | 32 |
| Average | 760 | 493 | 294 | 178 | 117 | 80 | 55 | 35 |

Average in Table D5 was calculated based on two test results.

Table D6. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Celotex shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 616 | 401 | 220 | 131 | 83 | 57 | 39 | 24 |
| 7 | 702 | 458 | 268 | 160 | 105 | 74 | 52 | 31 |
| 9 | 663 | 427 | 243 | 153 | 99 | 68 | 48 | 30 |
| Average | 660 | 429 | 244 | 148 | 95 | 66 | 46 | 28 |

Table D7. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Celotex shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 1044 | 702 | 405 | 243 | 149 | 98 | 60 | 34 |
| 5 | 911 | 595 | 363 | 230 | 144 | 95 | 62 | 38 |
| 8 | 844 | 594 | 382 | 236 | 150 | 103 | 68 | 42 |
| Average | 933 | 630 | 383 | 236 | 148 | 99 | 63 | 38 |

Table D8. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Celotex shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 784 | 609 | 356 | 224 | 136 | 87 | 55 | 33 |
| 5 | 818 | 584 | 341 | 192 | 109 | 67 | 40 | 21 |
| 7 | 755 | 459 | 281 | 162 | 96 | 60 | 34 | 18 |
| Average | 786 | 551 | 326 | 193 | 114 | 71 | 43 | 24 |

Table D9. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 687 | 391 | 221 | 128 | 78 | 50 | 33 | 19 |
| 7 | 789 | 478 | 269 | 165 | 97 | 64 | 41 | 24 |
| 9 | 708 | 423 | 248 | 147 | 92 | 65 | 50 | 35 |
| Average | 728 | 431 | 246 | 146 | 89 | 60 | 41 | 26 |

Table D10. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 633 | 358 | 201 | 115 | 69 | 45 | 29 | 18 |
| 6 | 627 | 368 | 215 | 120 | 71 | 45 | 26 | 16 |
| 7 | 585 | 359 | 198 | 122 | 76 | 55 | 40 | 24 |
| Average | 615 | 362 | 205 | 119 | 72 | 48 | 32 | 19 |

Table D11. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 794 | 467 | 277 | 169 | 106 | 77 | 46 | 29 |
| 3 | 648 | 400 | 221 | 131 | 85 | 58 | 39 | 24 |
| 4 | 877 | 550 | 367 | 239 | 161 | 120 | 86 | 57 |
| Average | 773 | 472 | 228 | 180 | 117 | 85 | 57 | 37 |

Table D12. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 757 | 459 | 281 | 167 | 101 | 63 | 41 | 24 |
| 2 | 735 | 477 | 288 | 172 | 105 | 66 | 42 | 25 |
| 9 | 914 | 509 | 311 | 204 | 128 | 90 | 65 | 45 |
| Average | 802 | 482 | 293 | 181 | 111 | 73 | 49 | 31 |

Table D13. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 739 | 517 | 295 | 187 | 113 | 73 | 49 | 36 |
| 6 | 980 | 671 | 404 | 259 | 168 | 118 | 76 | 40 |
| 7 | 1199 | 836 | 493 | 311 | 199 | 126 | 75 | 41 |
| Average | 972 | 675 | 397 | 252 | 160 | 106 | 67 | 39 |

Table D14. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 1035 | 694 | 435 | 259 | 165 | 107 | 65 | 36 |
| 2 | 949 | 611 | 355 | 219 | 135 | 81 | 48 | 26 |
| 9 | 849 | 536 | 368 | 232 | 142 | 96 | 61 | 38 |
| Average | 945 | 614 | 386 | 237 | 147 | 95 | 58 | 34 |

Table D15. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Celotex shingles addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 310 | 180 | 95 | 55 | 33 | 22 | 14 | 6 |
| 2 | 283 | 158 | 86 | 49 | 30 | 20 | 13 | 7 |
| 8 | 337 | 195 | 105 | 60 | 38 | 26 | 16 | 7 |
| Average | 310 | 178 | 96 | 55 | 34 | 23 | 14 | 7 |

Table D16. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 5% shredded Celotex shingles addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 597 | 353 | 190 | 104 | 58 | 34 | 20 | 10 |
| 5 | 728 | 404 | 225 | 126 | 68 | 40 | 23 | 13 |
| 7 | 564 | 319 | 178 | 102 | 61 | 40 | 24 | 11 |
| Average | 629 | 359 | 198 | 110 | 62 | 38 | 22 | 11 |

Table D17. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Celotex shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 835 | 547 | 293 | 179 | 111 | 74 | 45 | 22 |
| 2 | 804 | 571 | 288 | 152 | 88 | 54 | 31 | 16 |
| 4 | 628 | 397 | 220 | 130 | 78 | 49 | 28 | 17 |
| Average | 756 | 505 | 267 | 153 | 92 | 59 | 35 | 19 |

Table D18. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Celotex shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 548 | 321 | 184 | 114 | 67 | 39 | 22 | 11 |
| 3 | 583 | 369 | 209 | 120 | 69 | 42 | 25 | 14 |
| 8 | 521 | 315 | 115 | 104 | 59 | 36 | 22 | 13 |
| Average | 551 | 335 | 170 | 113 | 65 | 39 | 23 | 13 |

Table D19. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 15% granulated Celotex shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 3 | 1184 | 840 | 546 | 375 | 255 | 173 | 97 | 47 |
| 4 | 623 | 271 | 271 | 173 | 109 | 75 | 48 | 31 |
| 5 | 1143 | 723 | 469 | 284 | 182 | 114 | 73 | 44 |
| Average | 983 | 611 | 428 | 277 | 182 | 121 | 73 | 41 |

Table D20. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Celotex shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 902 | 612 | 365 | 220 | 137 | 94 | 63 | 38 |
| 3 | 745 | 455 | 266 | 159 | 90 | 52 | 27 | 13 |
| 5 | 1007 | 625 | 381 | 251 | 164 | 115 | 77 | 45 |
| 8 | 667 | 440 | 265 | 163 | 102 | 63 | 36 | 17 |
| 9 | 1003 | 321 | 386 | 226 | 139 | 87 | 44 | 24 |
| Average | 865 | 550 | 333 | 204 | 126 | 82 | 49 | 27 |

Table D21. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 640 | 375 | 212 | 119 | 62 | 36 | 22 | 13 |
| 7 | 807 | 500 | 298 | 172 | 101 | 60 | 36 | 20 |
| 9 | 641 | 399 | 216 | 117 | 64 | 38 | 23 | 11 |
| Average | 696 | 425 | 242 | 136 | 75 | 45 | 27 | 15 |

Table D22. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 5% shredded Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 610 | 398 | 231 | 130 | 75 | 50 | 35 | 16 |
| 5 | 622 | 371 | 207 | 123 | 69 | 44 | 27 | 16 |
| 6 | 696 | 378 | 220 | 117 | 65 | 39 | 29 | 15 |
| Average | 643 | 382 | 219 | 123 | 70 | 44 | 29 | 15 |

Table D23. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 902 | 570 | 347 | 210 | 118 | 73 | 44 | 26 |
| 5 | 910 | 586 | 372 | 227 | 130 | 80 | 45 | 25 |
| 8 | 839 | 597 | 363 | 218 | 137 | 91 | 60 | 43 |
| Average | 884 | 585 | 361 | 218 | 129 | 81 | 50 | 31 |

Table D24. Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Owens-Corning shingle addition.

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 3 | 695 | 435 | 284 | 179 | 113 | 70 | 38 | 18 |
| 6 | 678 | 387 | 246 | 141 | 80 | 49 | 30 | 17 |
| 8 | 531 | 330 | 199 | 118 | 72 | 47 | 28 | 14 |
| Average | 635 | 384 | 243 | 146 | 88 | 55 | 32 | 16 |

Table D25. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 15% granulated Owens-Corning shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 1070 | 707 | 449 | 315 | 215 | 165 | 116 | 67 |
| 2 | 1039 | 689 | 438 | 298 | 199 | 158 | 125 | 94 |
| 6 | 1263 | 812 | 524 | 359 | 252 | 173 | 106 | 57 |
| 7 | 1026 | 691 | 438 | 286 | 188 | 126 | 74 | 39 |
| 9 | 1206 | 843 | 470 | 327 | 203 | 133 | 79 | 39 |
| Average | 1121 | 748 | 464 | 317 | 211 | 151 | 100 | 59 |

Table D26. **Indirect tensile creep modulus; test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Owens-Corning shingle addition.**

| Sample Number | Indirect Tensile Creep Modulus (MPa) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 736 | 513 | 314 | 210 | 139 | 98 | 68 | 43 |
| 5 | 800 | 570 | 349 | 243 | 157 | 107 | 71 | 45 |
| 9 | 664 | 416 | 265 | 172 | 113 | 77 | 48 | 24 |
| Average | 733 | 500 | 309 | 208 | 136 | 94 | 62 | 37 |

Table D27. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 0% shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.3473 | 0.2977 | 0.2852 | 0.2728 | 0.2728 | 0.2481 | 0.2356 | 0.2108 | 0.1985 |
| 5 | 0.4589 | 0.4093 | 0.3969 | 0.3845 | 0.3597 | 0.3349 | 0.3101 | 0.2852 | 0.2728 |
| 6 | 0.4217 | 0.3845 | 0.3597 | 0.3597 | 0.3473 | 0.3348 | 0.3225 | 0.3101 | 0.3101 |
| Average | 0.4093 | 0.3638 | 0.3475 | 0.3390 | 0.3266 | 0.3059 | 0.2896 | 0.2687 | 0.2605 |

Table D28. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 0% shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 1.1782 | 1.0914 | 1.0666 | 1.0418 | 0.9922 | 0.9426 | 0.9054 | 0.8310 | 0.8061 |
| 6 | 1.2030 | 1.1658 | 1.1410 | 1.1286 | 1.1038 | 1.0790 | 1.0418 | 1.0170 | 1.0046 |
| Average | 1.1906 | 1.1286 | 1.1038 | 1.0852 | 1.0480 | 1.01080 | 0.9736 | 0.9240 | 0.9054 |

Table D29. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Celotex shingles addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 0.4341 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2977 |
| 3 | 0.4217 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.2852 | 0.2728 |
| 4 | 0.4093 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3349 | 0.3225 | 0.2977 | 0.2852 |
| Average | 0.4217 | 0.3803 | 0.3679 | 0.3555 | 0.3431 | 0.3349 | 0.3225 | 0.2977 | 0.2853 |

Table D30. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 0.4837 | 0.4465 | 0.4465 | 0.4341 | 0.4217 | 0.4217 | 0.3969 | 0.3969 | 0.3721 |
| 3 | 0.5705 | 0.5333 | 0.5209 | 0.5085 | 0.4961 | 0.4713 | 0.4465 | 0.4217 | 0.3845 |
| 4 | 0.7069 | 0.6697 | 0.5953 | 0.5829 | 0.5705 | 0.5333 | 0.5085 | 0.4961 | 0.4589 |
| Average | 0.5870 | 0.5498 | 0.5209 | 0.5085 | 0.4961 | 0.4754 | 0.4506 | 0.4382 | 0.4051 |

Table D31. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.3473 | 0.3225 | 0.3101 | 0.3101 | 0.2977 | 0.2977 | 0.2605 | 0.2356 | 0.2232 |
| 6 | 0.2852 | 0.2605 | 0.2605 | 0.2481 | 0.2356 | 0.2356 | 0.2232 | 0.2108 | 0.2108 |
| Average | 0.3163 | 0.2915 | 0.2853 | 0.2791 | 0.2666 | 0.2666 | 0.2418 | 0.2232 | 0.2170 |

Table D32. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.3349 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2728 | 0.2481 | 0.2356 |
| 7 | 0.3969 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2852 | 0.2356 |
| 9 | 0.4341 | 0.3845 | 0.3721 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3101 | 0.2852 |
| Average | 0.3886 | 0.3597 | 0.3473 | 0.3390 | 0.3266 | 0.3142 | 0.3059 | 0.2811 | 0.2522 |

Table D33. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.3349 | 0.2852 | 0.2852 | 0.2728 | 0.2605 | 0.2481 | 0.2356 | 0.2232 | 0.2108 |
| 5 | 0.3597 | 0.3101 | 0.3101 | 0.2852 | 0.2977 | 0.2728 | 0.2605 | 0.2356 | 0.2356 |
| 8 | 0.2977 | 0.2605 | 0.2605 | 0.2481 | 0.2356 | 0.2232 | 0.2232 | 0.1985 | 0.1985 |
| Average | 0.3307 | 0.2853 | 0.2853 | 0.2687 | 0.2646 | 0.2480 | 0.2398 | 0.2191 | 0.2150 |

Table D34. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.3101 | 0.2728 | 0.2728 | 0.2605 | 0.2605 | 0.2605 | 0.2356 | 0.2232 | 0.2108 |
| 5 | 0.3845 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2977 | 0.2605 | 0.2481 |
| 7 | 0.4341 | 0.3969 | 0.3845 | 0.3721 | 0.3597 | 0.3597 | 0.3349 | 0.3101 | 0.2852 |
| Average | 0.3762 | 0.3431 | 0.3349 | 0.3225 | 0.3142 | 0.3101 | 0.2894 | 0.2646 | 0.2480 |

Table D35. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 5% granulated Owens-Corning addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.3721 | 0.3349 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2232 |
| 7 | 0.3845 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2481 |
| 9 | 0.2852 | 0.2481 | 0.2356 | 0.2356 | 0.2232 | 0.2108 | 0.2108 | 0.1860 | 0.1736 |
| Average | 0.3473 | 0.3101 | 0.2977 | 0.2894 | 0.2770 | 0.2646 | 0.2563 | 0.2398 | 0.2150 |

Table D36. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 5% shredded Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.4093 | 0.3845 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3101 | 0.2977 |
| 6 | 0.4837 | 0.4465 | 0.4217 | 0.4217 | 0.4093 | 0.3845 | 0.3721 | 0.3473 | 0.2977 |
| 7 | 0.5953 | 0.5581 | 0.5457 | 0.5457 | 0.5333 | 0.5209 | 0.5085 | 0.4961 | 0.4713 |
| Average | 0.4961 | 0.4630 | 0.4506 | 0.4465 | 0.4341 | 0.4176 | 0.4051 | 0.3845 | 0.3555 |

Table D37. **Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 10% granulated Owens-Corning shingle addition.**

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.4465 | 0.3969 | 0.3845 | 0.3721 | 0.3721 | 0.3597 | 0.3473 | 0.3473 | 0.3349 |
| 3 | 0.3969 | 0.3597 | 0.3473 | 0.3473 | 0.3349 | 0.3225 | 0.3225 | 0.2977 | 0.3977 |
| 4 | 0.3101 | 0.2728 | 0.2728 | 0.2605 | 0.2728 | 0.2605 | 0.2481 | 0.2356 | 0.2232 |
| Average | 0.3845 | 0.3431 | 0.3349 | 0.3266 | 0.3266 | 0.3142 | 0.3059 | 0.2935 | 0.2853 |

Table D38. **Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Owens-Corning shingle addition.**

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.3721 | 0.3349 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2356 |
| 2 | 0.3721 | 0.3225 | 0.3225 | 0.3101 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 |
| 9 | 0.3721 | 0.3225 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2481 |
| Average | 0.3721 | 0.3266 | 0.3225 | 0.3101 | 0.3018 | 0.2894 | 0.2770 | 0.2646 | 0.2480 |

Table D39. **Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 15% granulated Owens-Corning shingle addition.**

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 0.3721 | 0.3473 | 0.3349 | 0.3225 | 0.3225 | 0.3101 | 0.2977 | 0.2852 | 0.2728 |
| 6 | 0.3597 | 0.3225 | 0.3101 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2728 | 0.2605 |
| 7 | 0.2977 | 0.2605 | 0.2481 | 0.2356 | 0.2232 | 0.2232 | 0.2108 | 0.1985 | 0.1860 |
| Average | 0.3431 | 0.3101 | 0.2977 | 0.2894 | 0.2811 | 0.2728 | 0.2605 | 0.2522 | 0.2398 |

Table D40. **Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 15% shredded Owens-Corning shingle addition.**

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.2852 | 0.2481 | 0.2481 | 0.2356 | 0.2232 | 0.2232 | 0.2108 | 0.1860 | 0.1736 |
| 2 | 0.3473 | 0.2852 | 0.2852 | 0.2728 | 0.2728 | 0.2481 | 0.2356 | 0.2232 | 0.2108 |
| 9 | 0.2977 | 0.2481 | 0.2605 | 0.2356 | 0.2356 | 0.2232 | 0.2108 | 0.1985 | 0.1860 |
| Average | 0.3101 | 0.2605 | 0.2556 | 0.2480 | 0.2439 | 0.2315 | 0.2191 | 0.2026 | 0.1902 |

Table D41. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.7689 | 0.6821 | 0.6573 | 0.6325 | 0.6201 | 0.5953 | 0.5705 | 0.5333 | 0.5209 |
| 2 | 0.8186 | 0.7565 | 0.7193 | 0.6945 | 0.6697 | 0.6449 | 0.5953 | 0.5457 | 0.5209 |
| 8 | 0.7938 | 0.7069 | 0.6695 | 0.6449 | 0.6077 | 0.5829 | 0.5581 | 0.5333 | 0.5085 |
| Average | 0.7398 | 0.7152 | 0.6820 | 0.6573 | 0.6325 | 0.6077 | 0.5746 | 0.5374 | 0.5168 |

Table D42. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 5% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.7069 | 0.6573 | 0.6449 | 0.6325 | 0.6201 | 0.5953 | 0.5829 | 0.5581 | 0.5457 |
| 5 | 0.6077 | 0.5454 | 0.5457 | 0.5457 | 0.5333 | 0.5209 | 0.4961 | 0.4713 | 0.4589 |
| 6 | 0.7069 | 0.6573 | 0.6449 | 0.6325 | 0.6201 | 0.5953 | 0.5829 | 0.5581 | 0.5333 |
| Average | 0.6739 | 0.6200 | 0.6119 | 0.6036 | 0.5912 | 0.5705 | 0.5540 | 0.5292 | 0.5126 |

Table D43. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.5457 | 0.4961 | 0.4837 | 0.4713 | 0.4589 | 0.4465 | 0.4341 | 0.4093 | 0.3845 |
| 2 | 0.5581 | 0.5085 | 0.4977 | 0.4837 | 0.4589 | 0.4465 | 0.4217 | 0.3969 | 0.3597 |
| 4 | 0.7069 | 0.6697 | 0.6449 | 0.6325 | 0.6201 | 0.6077 | 0.5953 | 0.5705 | 0.5325 |
| Average | 0.6036 | 0.5581 | 0.5421 | 0.5292 | 0.5126 | 0.5002 | 0.4837 | 0.4589 | 0.4256 |

Table D44. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with limestone aggregate and 10% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 0.6573 | 0.6201 | 0.5953 | 0.5829 | 0.5705 | 0.5457 | 0.5333 | 0.5085 | 0.4837 |
| 3 | 0.6201 | 0.5705 | 0.5581 | 0.5457 | 0.5333 | 0.5209 | 0.4961 | 0.4837 | 0.4713 |
| 8 | 0.5457 | 0.5085 | 0.4961 | 0.4837 | 0.4713 | 0.4589 | 0.4341 | 0.3969 | 0.3845 |
| Average | 0.6077 | 0.5664 | 0.5498 | 0.5374 | 0.5250 | 0.5085 | 0.4878 | 0.4630 | 0.4465 |

Table D45. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 15% granulated Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 3 | 0.3969 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2852 | 0.2728 |
| 4 | 0.4217 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2852 |
| 5 | 0.4341 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3101 | 0.2977 | 0.2728 |
| Average | 0.4176 | 0.3803 | 0.3679 | 0.3555 | 0.3431 | 0.3307 | 0.3142 | 0.2977 | 0.2770 |

Table D46. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Celotex shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.4341 | 0.3845 | 0.3845 | 0.3719 | 0.3719 | 0.3589 | 0.3349 | 0.3101 | 0.2977 |
| 2 | 0.5457 | 0.4837 | 0.4589 | 0.4465 | 0.4341 | 0.4093 | 0.3845 | 0.3721 | 0.3349 |
| 6 | 0.4217 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3349 | 0.3225 | 0.3101 | 0.2852 |
| 7 | 0.5209 | 0.4713 | 0.4713 | 0.4589 | 0.4465 | 0.4341 | 0.4093 | 0.3721 | 0.3473 |
| 9 | 0.4961 | 0.4713 | 0.4589 | 0.4465 | 0.4341 | 0.4237 | 0.4093 | 0.3845 | 0.2852 |
| Average | 0.4920 | 0.4465 | 0.4341 | 0.4216 | 0.4133 | 0.3973 | 0.3762 | 0.3555 | 0.3059 |

Table D47. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 5% granulated Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.6573 | 0.6325 | 0.6201 | 0.6077 | 0.6077 | 0.5953 | 0.5829 | 0.5705 | 0.5581 |
| 7 | 0.4961 | 0.4217 | 0.4093 | 0.3969 | 0.3845 | 0.3721 | 0.3473 | 0.3225 | 0.2852 |
| 9 | 0.4689 | 0.7193 | 0.7193 | 0.7069 | 0.6821 | 0.6697 | 0.6449 | 0.6201 | 0.6077 |
| Average | 0.6408 | 0.5912 | 0.5829 | 0.5705 | 0.5581 | 0.5457 | 0.5250 | 0.5044 | 0.4837 |

Table D48. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.5953 | 0.5320 | 0.5085 | 0.4961 | 0.4713 | 0.4589 | 0.4465 | 0.3845 | 0.3473 |
| 5 | 0.5457 | 0.4961 | 0.4837 | 0.4713 | 0.4465 | 0.4341 | 0.4217 | 0.4093 | 0.3721 |
| 6 | 0.6077 | 0.5581 | 0.5203 | 0.5333 | 0.5085 | 0.4961 | 0.4961 | 0.4837 | 0.4589 |
| Average | 0.5829 | 0.5287 | 0.5042 | 0.5002 | 0.4754 | 0.4630 | 0.4548 | 0.4258 | 0.3927 |

Table D49. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 10% granulated Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 2 | 0.4217 | 0.3721 | 0.3721 | 0.3597 | 0.3597 | 0.3473 | 0.3349 | 0.3101 | 0.2977 |
| 5 | 0.4093 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3473 | 0.3225 | 0.3101 | 0.2977 |
| 8 | 0.4341 | 0.3969 | 0.3845 | 0.3721 | 0.3597 | 0.3597 | 0.3473 | 0.3349 | 0.3225 |
| Average | 0.4217 | 0.3845 | 0.3762 | 0.3638 | 0.3555 | 0.3514 | 0.3349 | 0.3183 | 0.3059 |

Table D50. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 10% shredded Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 3 | 0.4961 | 0.4713 | 0.4589 | 0.4465 | 0.4217 | 0.4093 | 0.3969 | 0.3597 | 0.3473 |
| 6 | 0.5209 | 0.4713 | 0.4589 | 0.4465 | 0.4341 | 0.4217 | 0.3969 | 0.3845 | 0.3597 |
| 8 | 0.5333 | 0.4713 | 0.4465 | 0.4217 | 0.3639 | 0.3845 | 0.3721 | 0.3349 | 0.2977 |
| Average | 0.5168 | 0.4713 | 0.4547 | 0.4382 | 0.4176 | 0.4051 | 0.3886 | 0.3597 | 0.3349 |

Table D51. **Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens** produced with gravel aggregate and 15% granulated Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 1 | 0.3597 | 0.3225 | 0.3101 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2356 |
| 2 | 0.2852 | 0.2605 | 0.3481 | 0.2356 | 0.2232 | 0.2108 | 0.1860 | 0.1612 | 0.1736 |
| 6 | 0.3721 | 0.3101 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2356 | 0.2232 |
| 7 | 0.4713 | 0.4093 | 0.3845 | 0.3721 | 0.3597 | 0.3473 | 0.3225 | 0.2977 | 0.2852 |
| 9 | 0.3473 | 0.3101 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2481 | 0.2852 |
| Average | 0.3307 | 0.2977 | 0.2894 | 0.2811 | 0.2687 | 0.2563 | 0.2398 | 0.2232 | 0.2315 |

Table D52. Indirect tensile creep - vertical deformation after load removal; test results for asphalt concrete specimens produced with gravel aggregate and 15% shredded Owens-Corning shingle addition.

| Sample Number | Vertical Deformation (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 3 | 10 | 30 | 100 | 300 | 1000 | 3600 |
| 4 | 0.4713 | 0.4217 | 0.4093 | 0.3969 | 0.3845 | 0.3721 | 0.3473 | 0.3225 | 0.3101 |
| 5 | 0.3721 | 0.3349 | 0.3202 | 0.3101 | 0.2977 | 0.2852 | 0.2728 | 0.2605 | 0.2481 |
| 9 | 0.3845 | 0.3349 | 0.3225 | 0.2977 | 0.2868 | 0.2728 | 0.2605 | 0.2481 | 0.2356 |
| Average | 0.4093 | 0.3638 | 0.3506 | 0.3346 | 0.3230 | 0.3100 | 0.2935 | 0.2770 | 0.2646 |