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Effects of adding old shingles to granular material and hot mix asphalt : laboratory and field investigation

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EFFECTS OF ADDING OLD SHINGLES TO GRANULAR MATERIAL AND HOT MIX ASPHALT: LABORATORY AND FIELD INVESTIGATION

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A Thesis

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EFFECTS OF SHINGLES IN GRANULAR MATERIAL AND ASPHALT

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Master of Applied Science, Civil Engineering

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ABSTRACT

This thesis evaluates the potential use of processed tear-off shingles in road works. Six types of granular materials were investigated to determine the type of material that benefitted the most from using the shingles

The effects of shingles on the stability, as measured by California Bearing Ratio, were found to depend on properties such as gradation and fines content. In general shingles enhanced the stability of materials of relatively low CBR, but decreased the stability of angular well graded material of CBR larger than 100%. Optimum amount of shingles were found to enhance the resistance of stabilized granular materials to cycles of freezing and thawing; however, amounts higher than optimum decreased the resistance to freezing and thawing. In terms of permeability, the addition of shingles did not have a significant effect on the drainage characteristics of the tested materials.

A trial road was constructed and showed that after one week of construction dust generated by the control section was found to be twice the amount of dust generated by the shingle section.

ACKNOWLEDGEMENTS

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Dedication:

To My Parents

Contents

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Lists of Abbreviations:

AASHTO : American Association of State Highway and Transportation Officials

AC : Asphalt Cement, Asphalt content

ASMI : Athena Sustainable Materials Institute

ASTM : American Society for Testing and Materials

CA : California

CBR : California Bearing Ratio

CF : Consumer waste-fine

CMHB : Coarse-matrix, High-binder

CIWMB : California Integrated Waste Management Board

CMRA : Construction Materials Recycling Association

CSS : cationic slow-setting emulsion

DOT : Department of Transportation

ESALs : Equivalent Single Axle Load

HMA : Hot Mix Asphalt

IDOT : Iowa Department of Transportation

L : Litre

LA : Loss Angeles value

Lb : Pound

LS : Limestone

MDD : maximum dry density

MN : Minnesota

MPa : Mega Pascal

MTO	: Ontario Ministry of Transportation
MW	: Manufacture waste
NC	: North Carolina
NIOSH	: National Institute for Occupational Safety and Health
NJDOT	: New Jersey Department of Transportation
OMC	: optimum moisture content
PTWE	: Public Works Technical Bulletin
RAP	: Reclaimed Asphalt Pavement
RCA	: recycled concrete aggregate
S1	: Fine Sand from Construction Site
S2	: Fine Sand obtained by screening granular B (crushed natural gravel from Ontario) through the
TSR	: Tensile Strength Retained
WCA	: Waste Concrete Aggregate
U.S.	: United States of America
VMA	: Voids in Mineral Aggregate

Chapter 1

INTRODUCTION

1.1 Background

Use of recycled materials has become common practice as it is both economical and environmentally friendly. Both roof shingles and concrete are potential recycling materials. Bituminous shingles contain approximately 30% asphalt-cement binder (Marks and Petermeier, 1997). In addition to saving landfill space, the benefits of reusing recycled asphalt shingles as aggregate may include improved compactability, though this has so far not been tested or proved (CIWMB, 2009a). Processing shingles costs approximately US$30 per ton which is about US$10 less than the tipping fee at many local landfills (Grodinsky et al., 2002). Currently, the most common disposal method for asphalt shingles in the US is land filling (Mallick et al., 2000; Zickell, 2003). However, landfills are often located a great distance to the demolition sites, and hence transportation costs become an important cost consideration (PTWE, 2004).

Recycled concrete can be used for fill, bank stabilization, pavement for trails and other purposes. It is environmentally friendly as it replaces natural virgin aggregates. Where good aggregate is not available locally or is difficult to dispose of, recycled concrete aggregate (RCA) can often be used (PTWE, 2004).

The following estimates exist regarding the volume of shingle waste generated each year in the United States. Seventy-seven plants produce approximately 13,000,000 tons of shingles per year, of which some 65% are used for restoring roofs on houses. An equivalent amount of old shingles is thus removed and discarded (Brock, 2007). About 1.25 million scrap asphalt and saturated-felt shingles are generated from Canadian residential asphalt tear-off (re-roofing) shingles, new construction scrap, and related organic-felt scrap quantities (ASMI, 2007). Asphalt shingles are the most common type of roofing material used in both new homes and roof replacements, accounting for more than 60% of the residential roofing market in the United States (Foth et al., 2006). Approximately 11 million tons of asphalt-shingle waste is generated each year in the United States, of which most comes from either building renovations and demolitions or directly from the shingle manufacturers (Townsend et al., 2007), but, according to Dykes (2007), less than 5% of shingle waste is recycled. About 80% of the homes in the United States are covered with asphalt shingles due to their relatively light weight, comparatively low cost, ease of installation and low maintenance requirements (Enotes, 2008).

Shingles contain approximately 30% asphalt cement binder (Marks and Petermeier, 1997). The potential reuse of shingles includes use in Hot Mix Asphalt (HMA), as cold (asphalt) patching for roadways, as rural road base course to control dust, in temporary roads and driveways, in road/driveway aggregate base, in new shingle manufacturing, as fuel supplement in cement kilns, and as mulch (Townsend et al., 2007). As more than 4.5×10^{11}kg of HMA are produced annually in the U.S., adding only 2% shingles to HMA would be sufficient to consume all shingle waste (Button et al., 1995). If the roofing material generated by re-roofing projects were used in HMA rather than sent to the landfill, the load on North Carolina's landfills could be reduced by nearly 130,000 cubic yards each year (Hanson et al., 1997).

Shingles made before 1980 usually contain 50 to 55% asphalt with a felt or paper reinforcing mat, surface granules, filler, and backing materials. Shingles made after 1980 contains 20 to 30% asphalt with fiberglass reinforcing material, roofing surface granules, filler, and backing materials (Pavelek and Michael, 1996). Pavelek and Michael estimate that about 40% of manufactured roofing shingles are used in roof replacements. They estimate the annual production of new shingles to range within 2,100,000 to 3,360,000 tons. During the manufacturing process approximately 73,500 to 94,000 tons of waste material is produced annually, representing between 14,700 and 28,200 tons of asphalt.

Townsend et al. (2007) note that significant growth in the asphalt-shingle recycling industry has occurred in recent years. At least 17 states (Florida, Georgia, Maine, Massachusetts, Missouri, Minnesota, Nevada, New Jersey, New York, Pennsylvania, Maryland, North Carolina, Indiana, Michigan, Tennessee, Vermont and Texas) are using re-roof asphalt shingles in HMA applications for road projects (Foth et al., 2006).

The main sources of RCA are demolition works in road/highway rehabilitation projects (46% comes from demolition, 32% from road works, and the rest from construction, waste concrete and debris). In the United States, demolition of roads and buildings generates more than 200 million tons of recycled aggregates each year. RCA accounts for roughly 5% of the total aggregates needed (more than 2 billion tons per year) (PTWE, 2004).

Due to the lower unit weight of RCA, it is economically attractive to contractors for use in road construction and as railroad base material, fill, or as pavement constituents. On the basis of weight and volume, production of RCA is the biggest recycling industry in the United States. The Construction Materials Recycling Association (CMRA) estimates that more than 100 million tons of concrete are recycled every year in the U.S. (PWTE, 2004).

1.2 Research Objectives

The objective of this research project was to investigate the effects of adding shingles to granular materials and Hot Mix Asphalt (HMA). Within this main objective the research focused on investigating the effects of adding shingles on:

- stability and hydraulic conductivity of granular materials;
- stability of sand;
- indirect tensile strength of stabilized granular material;
- resistance of granular materials to freezing and thawing;
- dust control for exposed gravel roads; and
- moisture-induced damages in Hot Mix Asphalt containing shingles.

This research project consisted of both an experimental laboratory program and a field trial, which investigated the effects of shingles on a gravel road.

1.3 Outline of Thesis

This thesis is divided into five chapters. Chapter 2 presents a literature review on the effects of shingles in granular material, cold patches and Hot Mix Asphalt (HMA). Chapter 3 describes the materials used and the methodologies of the experimental testing program. Chapter 4 presents the test results and an analytical discussion. Finally, Chapter 5 summarizes and concludes this research work and provides recommendations for future research.

Chapter 2

LITERATURE REVIEW

The following review of the literature aims to provide an understanding of the use of shingles and RCA in both gravel roads and HMA. The limited number of papers reviewed here provides an indication that the recycling of shingles has yet to become a major research focus.

2.1 Shingles

Asphalt shingles are the most commonly used roofing material in both new homes and roof replacements (Townsend et al., 2007). Roll roofing made of asphalt-coated felt has been manufactured in the United States since 1893. Inorganic base materials have replaced traditional organic felt since the late 1950s, as they are more fire resistant and absorb less asphalt during the manufacturing process, thus reducing weight. Fiber-glass matting is the most popular asphalt-shingle base material since the late 1970s.

2.1.1 Composition of Shingles

Bituminous shingles contain approximately 30% asphalt cement binder (Marks and Petermeier, 1997). Tables 2.1 and 2.3 and Figure 2.1 provide details of the typical composition of asphalt shingles.

Figure 2.1: Typical Content of an Asphalt Shingle (Source: Powell, 2007)

Table 2.1: Roof Shingle Analysis

Description	Organic		Fiber glass		Old *	
	lbs. /100 sq. ft.	(%)	lbs. /100 sq. ft.	(%)	lbs. /100 sq. ft.	(%)
Asphalt	68	30	38	19	72.5	31
Filler	58	26	83	40	58	25
Granules	75	33	79	38	75	32
Mat	0	0	4	2	0	0
Felt	22	10	0	0	27.5	12
Cut-out	(2)	1	(2)	1	0	0
TOTAL	221		202		235	

(Source: Brock, 2007)
Note: The author did not provide details of what is meant by "old".

Mineral filler/stabilizer (limestone, silica, dolomite dust) used in shingles usually has a particle size (diameter) of less than 0.15mm, with at least 70% being smaller than 0.08mm. The content of sand-sized minerals in shingles ranges between 20-38% by mass (Powell, 2007). Granular material consists of sand-sized rock (Warner et al., 2007) and of basalt (Sengoz and Topal, 2004). The CBR of asphalt shingles lies within a range of 1% and 3% depending on shingle size (Warner and Edil, 2007). Table 2.2 provides an overview of the performance characteristics of new asphalt shingles.

Table 2.2: ASTM Specifications for Roofing Shingles

Property	Organic Felt Shingles (ASTM D225)	Glass Felt Shingles (ASTM D3462)
Asphalt penetration, 0.1 mm	N/A	15 minimum
Asphalt Softening Point, °F	N/A	235 maximum 190 minimum
Minimum Average Mass per Unit Area (lb/100 ft^2)	95.0	70.0
Minimum Mass per Unit Area of Mineral Matter passing No. 6 and retained on No. 70 (lb/100 ft^2)	18.5	25.0
Maximum Mass percent of Mineral Matter passing No. 70 and retained on No. 200, based on total asphalt and mineral matter passing No. 70	70.0	70.0

(Source: Newcomb et al., 1993)

The main types of shingles are glass-felt shingles and organic-backed shingles. Felt backing material and fibrous asphalt stabilizers are only permitted for glass-felt shingles (Newcomb et al., 1993). Asphalt used in shingles is considerably harder than that used in pavements (see section

2.1) with penetration values at 77°F ranging between 20dmm (decimillimeter) and 70dmm, as compared to between 50dmm and 300dmm for paving asphalts. Asphalt for shingles is stabilized with limestone powder (Newcomb et al., 1993).

Table 2.3: Granular Components of Shingles

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

(Source: Newcomb et al., 1993)
Note: Ceramic Granules are small crushed rock particles coated with ceramic metal oxides. Heap lap granules are coal slag ground to roughly the same size as the ceramic particles. Backsurfacer sand is washed natural sand which prevents the shingles from sticking to each other.

2.1.2 Sources and Generation

Shingles may contain materials, like wood, plastic wrap and other deleterious materials, which need to be separated prior to processing (Townsend et al., 2007). Waste shingles are of two types:

1. Post-manufacturing: Post-manufacturing asphalt-shingle waste is the scrap portion left over from the manufacturing process. Approximately 5 to 10% (550,000 to 1,100,000 tons) of total asphalt-waste generated in United States is scrap. This material is generally uniform and homogeneous.

2. Post-consumer: The main source of waste shingles is post-consumer asphalt shingles, which form part of the debris produced during construction, demolition and renovation of buildings (Townsend et al., 2007). Depending on the manufacturing technology the

service life of an asphalt-shingle roof is approximately 12 to 25 years. Approximately 7 to 9 million tons of post-consumer shingles are generated annually in the U.S., the asphalt and aggregate content of which may vary depending on the manufacturer, the degree of weathering and the degree of aging from exposure to ultraviolet sunlight.

2.1.3 Manufacturing Process

Asphalt is converted to oxidized asphalt by a process known as "blowing", i.e. the introduction of bubbles of oxygen into the liquid asphalt, which increases asphalt viscosity (NIOSH, 2001; Townsend et al., 2007). The base material (a layer of organic material (cellulose or wood fiber) or fiberglass) is coated by passing it through a saturator tank filled with hot asphalt (Townsend et al., 2007). Finely ground lime, silica, slate dust, dolomite and other mineral materials are used as stabilizers (NIOSH, 2001). One side of the shingles is surfaced with granules for protection against physical and sun damage (Townsend et al., 2007). In some plants, stabilized coating asphalt is applied to the top and bottom surfaces of the webbing sheet (NIOSH 2001). The granules remain exposed in the roofing application and are made of crushed rock coated with ceramic metal oxides (Townsend et al., 2007). A light coating of fine sand is applied on the bottom side to prevent shingles from sticking to each other during packaging and transport.

2.1.4 Asbestos Content in Shingles

A common concerns regarding reuse of roofing shingle is the potential presence of asbestos, which was used in shingles in the past, but few asbestos-containing tear-off shingles remain (Foth et al., 2006). The Iowa Department of Transportation (IDOT) tested 368 shingle samples between 1994 and 1997, but found asbestos in only 0.8% (3 samples). Similarly no samples containing asbestos were found when 2000 samples were tested by the Central Construction and

Demolition recycling facility in Des Moines (Iowa) in 2001. And only 1.67% of over 750 samples samples tested by the Waste Commission for Scott County in 2004 contained asbestos (Foth et al., 2006). Townsend et al. (2007) report that of 27,694 samples collected in Maine, Iowa, Florida, Missouri, Minnesota and Massachusetts asbestos was detected in 1.53% sample. Table 2.4 provides an overview of American manufacturers of asbestos-containing asphalt roofing products.

Table 2.4: Summary of Asbestos-containing Asphalt Roofing Products

Manufacturer	Years Manufactured	Products
Barber Asphalt Corporation	NA	Asphalt-asbestos roof felt
Carey Manufacturing Company	NA	Asphalt-asbestos shingles, asbestos finish felt, mastic
The Celotex Corporation	1906-1984	Asphalt roof coating and other miscellaneous materials
Fibreboard Corporation	1920-1968	Roof paint, roll roofing with asbestos-containing base sheets, caulking compounds, plastic cements, taping and finishing compounds
General Aniline and Film Corporation	NA	Roofing asphalt
Johns-Manville Corporation	1891-1983	Asphalt-asbestos shingles, rag-felt shingles, fibrous roof coating, shingle tab cement, roof putty
Kaylite Company	NA	Asbestos surface coating for shingles
National Gypsum Company	NA	Roofing and shingles
Monroe Company	NA	Asbestos surface coatings for shingles
Rhone-Poulenc Ag Company	Early 1930s-1976	Adhesives, coatings, sealants, and mastics
United States Gypsum Company	1930-1977	Paper and felt

(Source: Townsend et al., 2007)

2.1.5 Collection and Processing

Post-manufacturing shingle scrap is clean and consists of a combination of remnants and scraps from the manufacturing process and damaged or off-specification shingles. Since it is free of potential contaminants (e.g., nails), it is sought after for recycling. Contaminants such as packaging materials and strapping should be removed prior to recycling (Townsend et al., 2007).

Land Filling

Large amounts of asphalt-shingle waste end up in landfills (Zickell, 2003). Shingles are accepted at construction-and-demolition debris landfills. Some landfills charge a reduced tipping fee and use the shingles as road-base material or pads for trucks (Townsend et al., 2007).

Recycling

Both post-manufacturing and post-consumer waste shingles require processing before reuse (Townsend et al., 2007). Factory scrap shingles become plastic due to the heat and mechanical action of the shredding process, whereas tear-off roofing shingles have hardened with age. Factory shingles also tend to agglomerate making shredding of factory scrap more difficult than shredding of roofing shingles (Grodinsky et al., 2002). Recycling includes the following steps: (a) removal of all non-shingle waste; (b) reduction in size; (c) grinding and screening; (d) removal of nails, paper and other contaminants; and (e) screening to achieve the desired product size (Townsend et al., 2007).

2.2 Recycled Concrete Aggregates Used as Base Course

Recycled concrete aggregates (RCA) accounts for roughly 5% of the total aggregates market (more than 2 billion tons per year) in the U.S., with an estimated 85% being used as road base due to its availability, low transport cost, and good physical properties. The quality of RCA depends mainly on the properties of aggregates in the original concrete (PWTE, 2004).

In addition to laboratory tests, RCA and limestone test sections were constructed at the University of Central Florida Circular Accelerated Test Track (UCF-CATT) for a performance test of base courses, and a total of 362,198 load repetitions (representing a pavement life expectancy of over 36 years) were applied to the test sections. No rutting was found in any of the test sections (Kuo et al., 2002). Many transverse cracks and one longitudinal crack occurred in the limestone section, but no cracks were observed in RCA test section, indicating that the allowable number of load repetitions for RCA sections is likely to be very high for both fatigue and rutting.

Properties of Recycled Concrete Aggregate

The following discussion summarizes the literature with respect to basic properties of RCA. These properties may be taken as representative of many types of RCA. Topcu (2004) reports that the fineness modulus of Waste Concrete Aggregate (WCA) was 5.50, unit weight 2470 kg/m^3, loose unit weight 1160 kg/m^3, and water absorption 7% (after 30 min). The quality of RCA as building material depended to a great extent on the quality of the aggregates used in the demolished concrete (Chini et al., 1999).

Specific Gravity: The SSD specific gravities of recycled coarse aggregates with sizes 19.0-37.5mm, 12.5-19.0mm and 4.75-12.5mm were 2.455, 2.459 and 2.475, respectively (Won, 1999). The specific gravity of RCA was lower than that of the virgin aggregate, as the specific gravity of the mortar attached to the RCA was about 2.05. The lower specific gravity of RCA fines was due to their porous structure (Won, 1999).

Absorption value: The average water absorption rates of coarse aggregates with sizes 19.0-37.5mm, 12.5-19.0mm and 4.75-12.5mm were 3.9%, 4.0% and 4.1%, respectively. The high absorption rates were due to the highly porous old mortar attached to the RCA (Won, 1999; PWTE, 2004). Absorption of fine RCA was 7.9%, which was much higher than that of river sand (<1 %) (Won, 1999).

Soundness: Due to the presence of old mortar, sodium-sulfate soundness loss was greater than magnesium soundness loss in RCA, despite higher magnesium soundness loss for the virgin aggregate (Won, 1999). The author does not provide an explanation for these experimental results.

Loss Angeles (LA) value: LA of recycled aggregate was generally high. According to the Texas Department of Transportation the maximum LA for RCA was 40 (Won, 1999). Hansen and Narud found that, for aggregates produced from high strength concrete, the LA abrasion loss values were 22.4% and 41.4% for aggregate sizes 16-32mm and 4-8 mm, respectively (Topcu, 1997).

Angularity: The angularity of recycled fines and natural river sand were 38.55% and 34.50%, respectively (Won, 1999). Due to the higher angularity of the RCA fines, stability of asphalt and concrete produced with RCA was higher (PWTE, 2004).

Thermal coefficient: As about one-third of the volume of RCA was old mortar, the thermal coefficient of RCA was expected to be higher than that of the virgin aggregate (Won, 1999). The values of thermal coefficient of RCA for sizes 19.0-37.5mm, 12.5-19.0mm and for 4.75-12.5mm were $16\times10^{-6}/^{\circ}C$, $19\times10^{-6}/^{\circ}C$, and $26\times10^{-6}/^{\circ}C$, while that of virgin siliceous river gravel was about $8\times10^{-6}/^{\circ}C$.

Self-cementing properties: The strength of RCA, when used as sub-base material, increased over time due to self-cementing properties which were believed to be governed by the properties of the fines portion of the RCA (particle size less than 5mm) (Poon et al., 2006). The results indicated that the size fractions <0.15 and 0.3-0.6mm were most likely to be the principal cause of the self-cementing properties of the RCA fines.

Hydraulic conductivity: Hydraulic conductivity values ranged from 4.9×10^{-9} to 7.0×10^{-8}m/s for crushed limestone samples (specific surface area of the fines fraction was S_{sf} = 11.4 m²/g) and was 1.1×10^{-6}m/s for a sample of crushed limestone for which the specific surface area of the fines was unknown (Côté and Konrad, 2003). When comparing crushed granite, crushed shale and crushed limestone, the granite samples showed the highest values for porosity and hydraulic conductivity, while limestone had the lowest values (Côté and Konrad, 2003). Hydraulic conductivity of RCA depended on the duration and methods of curing as shown in Table 2.5.

When dissolution occurred, a possible consequence was an elevation of the groundwater pH due to the leaching of calcium hydroxide from the cement paste (Kelly, 1998). Dense road bases were less susceptible to leaching and may even become more tightly cemented by the chemical reaction as water passes through the material.

Table 2.5 Coefficients of Permeability of Samples

Fine aggregate	Immediately after compaction	7-days S-curing	7 days S-curing and 3 day air curing
NA (cm/s)	6.593×10^{-6}	4.950×10^{-6}	4.610×10^{-6}
RCA (cm/s)	3.828×10^{-4}	2.563×10^{-5}	7.195×10^{-6}

RCA is sub base material with max. size 40 mm (Source : Poon el. al. 2006)

2.3 Use of Shingles as Granular Material

This section provides a review of the literature regarding the use of shingles as granular materials in both laboratory and field tests. Generally, ground shingles are screened to produce appropriate particle sizes that can be mixed with gravel to cover rural unpaved roads (CIWMB, 2009a).

When vehicles move over stone, gravel and similar surfaces, dust is produced due to crushing and grinding of stones and/or stone particles. A portion of the dust may become airborne because of wind and passing vehicles (Pavelak and Michael, 1996). The use of shingle mixtures reduces dust generation, vehicle noise and road maintenance requirements (Marks and Petermeier, 1997).

Current Calfornia Department of Transportation (Caltrans) specifications do not allow asphalt shingles in aggregate base, and Caltrans Standard Specifications for Public Works Construction (Greenbook) provides no guidance with respect to use of shingles (CIWMB, 2009a). But according to Caltrans, adding 10% "crushed" asphalt roofing shingles to the road-base aggregate led to favourable results (CIWMB, 2009a). In October 1996, the California Integrated Waste Management Board, CIWMB, suggested to the Caltrans Pavement Design and Rehabilitation Committee (PDRC) to allow 10% ground tear-off shingles in aggregate bases. PDRC noted that it may be useful to allow shingles in asphalt, but stated that additional performance testing would be required prior to approval (CIWMB, 2009a).

Warner and Edil (2007) found that the maximum dry density of asphalt shingles ranges between $8.8kN/m^3$ and $12.5kN/m^3$, depending on shingle size. Optimum moisture content was 8%, but compaction was not very sensitive to water content. CBR of asphalt shingles ranged between 1 and 3 depending on shingle size. The modulus of resilience of shingles depended on shingle size as shown in Figure 2.2. The moduli of resilience for asphalt shingles, gravel with 50% shingle, and gravel were 28-37, 62, and 75-100MPa, respectively. The resilient modulus versus bulk stress for shingles (passing 25.4mm) is shown in Figure 2.3. A mix of unstabilized asphalt shingles (50%) and gravel was weak, limiting its use to sub-base material, but fly-ash stabilization (20% Class C) of reroof shingle (passing 9.5mm) improved strength such that it became marginally feasible to use the mix as base material (M_r=50-55 MPa). (Table 2.6 provides an overview of suggested CBR values for soils used in pavement structures.)

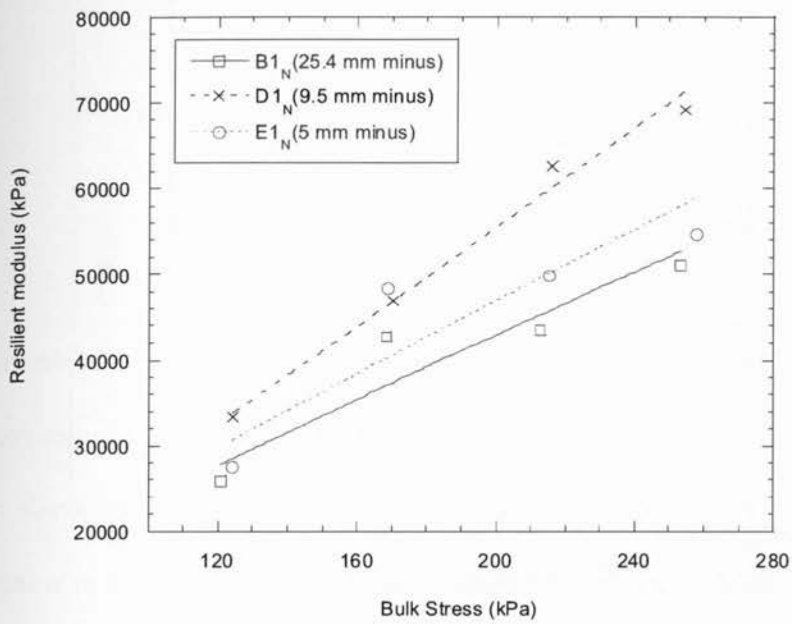

Figure 2.2: Resilient Modulus versus Bulk Stress for Shingles (Source: Warner and Edil, 2007)

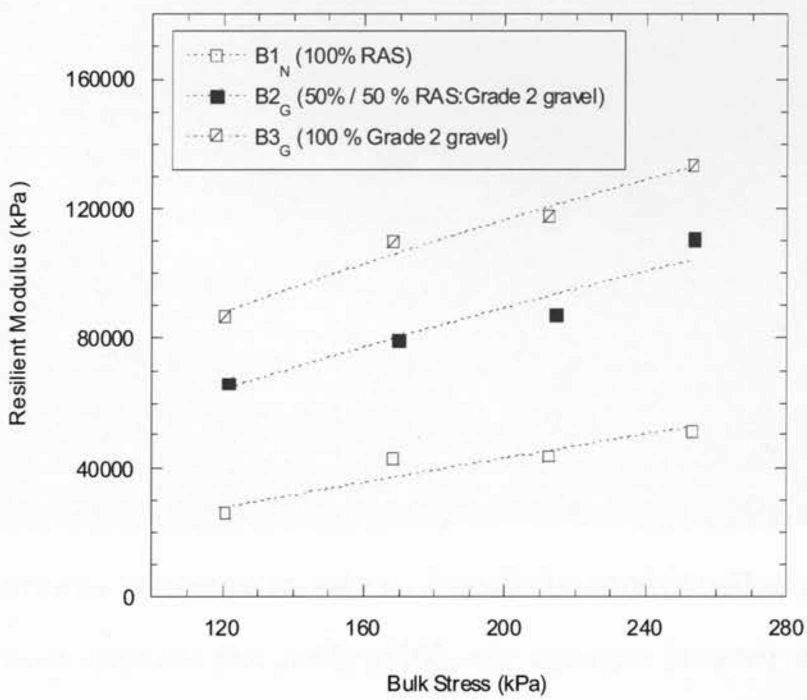

Figure 2.3: Resilient Modulus versus Bulk Stress for Shingles (25.4mm passing) (Source: Warner and Edil, 2007)

Table 2.6: Suggested CBR Values for Soils used in Pavement Structures

Pavement Course	Material	CBR (%)
Base Course	Good quality crushed rock	>80%
	Good quality gravel	50 to 80
Subbase Course	Good quality soil	30 to 50
	Very good	20 to 30
Subgrade Course	Good to fair	10 to 20
	Questionable to fair	5 to 10
	Poor	<5

(Source: Hooper and Marr, 2004)

Hooper and Marr (2004) found that the addition of 33% asphalt shingles (25.4mm passing) (replacing gravel) reduced CBR from 92% to 23%. Any further addition of shingles reduced the CBR even more, indicating that use of shingle blends should be limited to sub-grade materials. However gravel blended with shingles did not swell significantly when soaked in water. Adding 33% shingles (25mm passing) decreased CBR strength of silty sand from 33% to 19%, which is below the recommended CBR for sub-base use, but, again, the blend did not swell during the saturation procedure. The CBR reduction may have been caused by the reduction of inter-particle friction in highly angular particles in sands and gravels.

The performance of clays improved due to the addition of shingles. The performance of a clay (85% passing No.200 sieve) with a plasticity index of 13.4 and a CBR of 8%, which is considered “questionable to fair” as sub-grade material, improved after adding of 33% shingles (by volume) (25.4 mm passing). The CBR increased from 8% to 20% and swelling declined from 1.9% to 0.1%, indicating that the addition of shingles to clay results in “good” to “very good” sub-grade material. The addition of shingles to clay increased the proportion of sand-sized granular particles (retained on sieve No. 200), which may increase shear strength during undrained CBR loading. These results may also be due to the cohesiveness of the clay, which holds the shingle tabs in place and thus prevents slipping of the tabs during CBR loading (Figure 2.4) (Hooper and Marr, 2004).

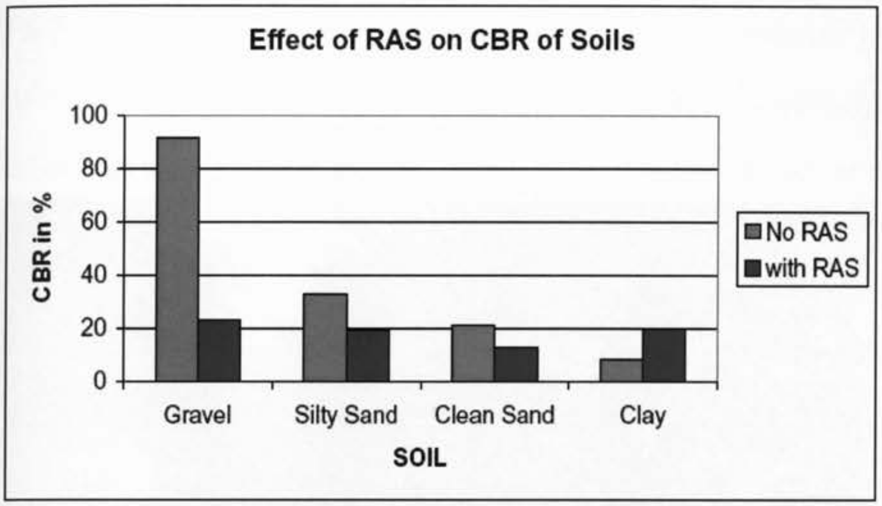

Figure 2.4: Effect of RAS (Roofing Asphalt Shingles) on CBR (Source: Hooper, 2004)

Figure 2.5: Private Road (Gravel with Shingles) (Source: McMullin, 2007)

Field studies have indicated that shingles help bond the aggregate particles together over time (Marks and Petermeier, 1997), and that the strength of certain soils may be increased by adding an asphalt emulsion to the shingle mixes (Hooper and Marr, 2004). They suggest that trial mixes of site-specific materials with the expected field density should always be made to quantify the effect of adding shingles on the strength of the mix. Figure 2.5 and Figure 2.6 show a private road and a sub-division road made with shingle mixtures.

Figure 2.6: Sub-division Road using Shingles (Source: McMullin, 2007)

Marks and Petermeier (1997) report on the use of ground shingles, which were used in a roadway in July 1995. A mix of 50% shingles with crushed limestone was used. Approximately 300 tons of ground shingles (passing 1 in.) and 600 tons (passing 2 in.) were blended. Five hundred tons of the shingle mixes were added to the crushed limestone. The ground shingles were placed on top of the crushed stone surface and blended with the help of a grader blade to achieve a uniform mixture. The thickness of the layer was approximately 65mm. Just after blade mixing, a sedan was driven over the roadway at approximately 80 km/h (50 mph), but no dust was generated at the trial section. After six month, the surface seemed to be somewhat "open", and a light spray (fog seal) of 2300L (500 gal.) of cationic slow-setting (CSS) emulsion diluted with 4500L (1000 gal.) of water (0.3 gal. per sq.yd) was applied at a coverage rate of 1.3 L/m^2 to seal the surface. The shingled roadway remained almost entirely dust-free one year after treatment (a sedan driven at 80 km/h generated almost no dust) and relatively dust-free two years after treatment. The bituminous shingles bound the crushed-stone aggregate and reduced loss of the granular material into the ditches. Benefits also included improved lateral control of cars as well as a smoother and quieter roadway.

Similarly, in Altus, Oklahoma, shingles were mixed with reclaimed asphalt pavement (RAP) and used for a parking lot surface (ASMI, 2007). The material was placed, compacted and sprayed with a calcium-chloride solution. The Vermont Agency of Natural Resources reported that the compactibility of the shingle mix was very good (Hooper and Marr, 2004). After the two-year evaluation period, the road resisted rutting and erosion, generated less dust, and maintenance requirements were less than for conventional gravel control sections. Hooper reports that a Massachusetts construction materials firm found that the addition of shingles (76.0mm passing) had positive effects on strength and deformability of an asphalt-amended silty sandy soil.

2.3.1 Light Duty Roadway with Shingle Layers

Pavelak and Machael (1996) discuss the use of shingle layers for light duty roadways. The shingles were cut into cyform strips, which generally retain their shape when used in road bases. The road may be made up with one layer or alternating layers of shingles and crushed aggregate, with the number and thickness of the layers depending on the traffic situation. Hydrocarbon distillates, such as asphalt, paraffin, bitumen and tar, may be used to rejuvenate the asphalt contained in the shredded roofing shingle and to improve adhesion of the binder to the aggregates. The addition of pre-consumer waste-shingle tabs into the layer of used asphalt roofing-shingle pieces enhanced kneadability and improved binding within the shingle layer as the asphalt in the tabs was more flexible and tackier.

Pavelak and Michael (1996) also note another important aspect of using layers of shingles and gravel, i.e. that the size of the shingle material may be reduced. They also note that it may be useful to cut the shingles into elongated strips of a size such that they can be graded into a layer with strips overlying one another. Ferrous material like nails should be removed from the shredded shingles prior to use. They suggest that the top-most layer be a layer of crushed aggregate to avoid shingle strips making contact with vehicle tires. Another manufacturing option is the addition of hydrocarbon distillate to the shredded roofing-shingle material at the construction site.

The roadway constructed by Pavelak and Michael was durable and resisted rutting because of the support provided by the shingle pieces which was due to the adhesion within the shingle layers. Traffic noise was reduced due to internal cushioning. The generation of dust was reduced as the shingle layer was impermeable and as crushing of aggregate was reduced because of the flexibility of the shingles. Due to shock absorption and internal adhesion, erosion of the road surface was reduced. This type of roadway was semi-permeable, tolerated freeze/thaw cycles and absorbed or held spilled fuels and oil (Pavelak and Michael, 1996). The cost of this type of road was similar to a conventional light-duty roadway but significantly less than blacktop or concrete surfaces. Maintenance cost was lower than that for a conventional surface (Pavelak and Michael, 1996).

2.3.2 Light Duty Roadway by Mixing Gravel with RAP and Shingles

During the 2000 and 2001 construction seasons about 4,000 tons of asphalt/RAP (reclaimed asphalt product)/gravel were laid as road surface in Hinesburg (Texas Hill Road, TH 17) (Figures 2.7 and Figure 2.8) on seven gravel town road sections (0.13-0.51 miles) in six municipalities in locations that were difficult to maintain (Surwilo, 2003). The mix was laid in the following steps:

1. Existing surfaces were graded, and drainage was corrected as needed;
2. The shingle/RAP/gravel mix was spread and graded to a 3" lift thickness;
3. The material was compacted with a vibratory roller;
4. A $CaCl_2$ solution was applied (600 gallons/mile); and
5. Steps 1-4 were repeated.

Figure 2.7: Shingles Mixed with Granular Material on TH17, Hinesburg (Source: Surwilo, 2003)

Reports by town officials were very positive: the road surface was hard and durable, and not as dusty as it would have been if only natural aggregate had been used. Potholes and wash boarding were less evident, and grading was less frequently required. It was estimated that the cost of the shingle/RAP/gravel mix was $5.50/ton less than the cost of virgin gravel (Surwilo, 2003).

Figure 2.8: Shingles Mixed with Granular Material, TH17, Hinesburg (Source: Surwilo, 2003)

2.4 Use of Shingles as Cold Patch

For cold patches, ground shingles are mixed with aggregate and an emulsion for patching mixes (Newcomb et al., 1993). If tear-off shingles are used, the mix is typically composed of approximately 25% dry roofing material, 3% solvents and 72% aggregate (CIWMB, 2009b). The use of cold patches containing recycled shingles may improve pavement performance due to the fiberglass and/or cellulose fibers contained in the shingles and reduce maintenance cost (CIWMB, 2009b; ASMI, 2007; Grodinsky et al., 2002).

Shingles have been employed in cold patches for several years in New Jersey, Washington State, California and the City of Chicago (ASMI, 2007). Presently, Gardner Asphalt Corporation of Tampa, FL, supplies a shingle-cold-patch product ("RePave"), which is a blend of ground roofing shingles, aggregate and an emulsifier, as a pothole- and driveway-repair material that behaves like a "high-performance" patch and has outlasted HMA and traditional cold mixes in field tests. Despite the higher initial cost compared to HMA and traditional cold patches, the overall cost of this patch is less due to the increased lifespan of the road and lower maintenance costs. Shingle cold patches are easier to use than traditional patches due to their lighter weight, slow hardening and ability to withstand traffic loads immediately after application. A few organizations are producing cold-patching materials or paving materials for bicycle paths and park trails containing up to 100% shredded shingles (typically passing 9.5mm), which are blended with aggregate and asphalt rejuvenators (diesel, kerosene or other asphalt rejuvenating agents) to produce patching mixes (Button et al., 1996).

The New Jersey Department of Transportation (NJDOT) paved a low-volume road with RePave. This product is considered to have performed successfully. Grodinsky et al. (2002) note that the performance of RePave may rival that of "high performance" cold patches. The California Integrated Waste Management Board (CIWMB) reports positive feedback on "RePave" from a number of New Jersey municipalities, the Washington DOT, and the Placer County Department of Public Works (CA) (Grodinsky et al., 2002).

2.5 Use of Shingles in Hot Mix Asphalt (HMA)

Manufacturing waste shingles are obtained directly from manufacturers and thus are a very uniform product with predictable properties, whereas tear-off shingles are variable in quality and contaminated with other building materials. However consumer waste can also be used successfully in HMA (Button et al., 1996). Use of shingles in HMA not only reduced cost but also improved resistance to pavement cracking and rutting as the fibers contained in shingles provided reinforcement (Townsend et al., 2007). One of the benefits of using shingles in HMA is that shingles already contain asphalt cement, granules and fiber. If shingles were not used, producers would have to purchase these materials separately to enhance the mixture (Forth et al., 2006).

Button et al. (1996) also note that the asphalt in shingles has a significantly higher viscosity and may contain proprietary antistripping agents and antioxidants. The fabric backing (usually fiberglass or cellulose) provides strength as well as fatigue resistance (Hanson et al., 1997). Shingle asphalt is, however, hard and therefore does little to coat the virgin aggregate (Button et al., 1996). According to Krivit (2007), the stiffness of the asphalt cement may also inhibit compaction. Griffiths and Krstulovich (2002) found that shingle tabs result in stiffer mixes with improved temperature susceptibility and rut resistance, but that the shingles may be susceptible to moisture-related damage. He suggests that an anti-strip or retained-stability test should be performed whenever shingles are used. The heating and mixing processes during sample preparation in the laboratory were sufficient to melt and disintegrate most of the roofing particles as well as larger pieces (Button et al., 1996).

A comparison of asphalt added to and extracted from the different mixtures is shown in Table 2.7.

Table 2.7: Comparison of Asphalt Added and Extracted from Different Mixture

Mixture	Binder added (%)	Asphalt extracted from mixture (%)
Control	5.2	5.3
3% shingle	4.6	5.2
5% shingle	4.2	5.3
7% shingle	3.8	5.0

(Source: Mallick et al., 2000)

The Florida DOT allows up to 10% of waste shingles with a maximum size of 25mm by mass of HMA, but due to the hardness of the asphalt in the shingles, Florida DOT uses AC-20 bitumen instead of the usual AC-30 bitumen. Draft specifications of the Minnesota DOT allow only 5%

19mm shingles (Button et al., 1996). Field tests with 5% and 7% shingle by-product were carried out in Minnesota in 1991. In some cases the test sections performed as well as the control sections more than a decade later ("Roofing shingles and roads", 2002).

According to reports of field trials in Nevada and Minnesota, addition of shredded shingles (25mm passing) reduced indirect tensile strength at 25°C, Hveem stability, Marshall stability and resilient modulus. Marshall flow and the failure strain of the mixtures were increased (Button et al., 1996).

According to Button et al. (1996) the Tennessee DOT replaced 5% sand and 5% screenings (dense-graded mixture) with 10% shingles. The virgin asphalt content was slightly reduced, and the mix temperature was increased by 6°C. The test results were described as very satisfactory. In 1994, the Georgia DOT performed field tests near Savannah by adding 5% shredded shingles to virgin aggregate. DOT representatives considered this test a success (Button et al., 1996). Test results of a trial project at Lynn Rd., Raleigh, NC, in 1995 showed that HMA with shingles performed as well as conventional HMA mixes, but that the mixture was stiffer due to sharp angular aggregate, polymers and the asphalt cement contained in the shingles (Hanson et al., 1997). Hanson does not provide a description of the types of polymers used.

Research conducted in Nevada showed that the cost of asphalt mixtures with shingles was lower than that of conventional HMA. Mixtures with shingle content of up to 20% have performed acceptably well in laboratory tests. The properties of the shingle-asphalt cement (e.g., softness) should be considered when selecting shingles for use in HMA (Newcomb et al., 1993).

Fiber-reinforced asphalt mixes were successful in resisting shoving and rutting in traffic lanes in the City of Columbus (Newcomb et al., 1993). An Indiana study found that a fiber (polypropylene) reinforced mixture retarded the growth of reflective cracks and improved the maintainability of the overlaid sections. Research at Clemson University, South Carolina, showed that polyester fibers increased tensile strength and toughness of mixes. A Finnish elongation-test study showed that the addition of fibers increased the strain capacity of asphalt. Fibers increased the softening point temperature of the mixes. The surface area of the fibers influenced the absorption of asphalt cement. Cellulose fibers, for instance, are porous and have a flat cross-section, resulting in a larger specific surface area than for glass or other fibers. A qualitative comparison of binding effects of cellulose, fiberglass, polyester and mineral fibers found that cellulose fibers had the greatest stabilizing effect on liquid asphalt cement, which in turn affected the optimum asphalt content of asphalt mixtures with fibers. Hanson et al. (1997) reported that the PG grade of the asphalt binder increased due to the addition of shingles as shown in Table 2.8.

Table 2.8: PG Grades in HMA Mixtures

Mix	No Shingle	5% Shingle	10% Shingle
A	PG 64-22	PG 70-16	PG 76-10
B	PG 64-22	PG 70-16	>PG 76-10*

*- The grade of the recycled binder was greater than PG 76-10 (Source: Hanson et al., 1997)

Disposal cost for shingles ranges from $18 per ton to $60 per ton in United States, and the cost of hot mix asphalt may be reduced by $2.79 per ton by using 5% organic shingles (Hanson et al., 1997). Kandhal (1992) estimates that HMA cost can be reduced by $3.08 per megagram (Mg) by adding 5% organic shingles.

2.5.1 Use of Shingles in Dense-graded Mixtures

Effect of Shingles on Marshall Stability

Marshall-stability values were higher for samples with 4% and 4.5% binder content after 1% shingles had been added than for control samples with an optimum binder content of 5%. Addition of roofing shingles to HMA thus reduced the optimum asphalt content by approximately 0.5% (Table 2.11). Mixtures containing shingles have fewer air voids because they are easier to compact than conventional mixtures and because the shingles contain a higher amount of fillers (30% filler) (Sengoz and Topal, 2004).

According to Brock (2007), Marshall stability at optimum asphalt content decreased if 5% shingles were added (Table 2.9). And Senzog (2004) reported that stability values of mixtures containing 3% and 4% shingles were lower than those of control samples, although they remained above the minimum specification value of 900 kg (Table 2.10). Stability increased when binder content was reduced and 1% shingles were added (Table 2.11).

Table 2.9 Marshall Properties at Optimum Asphalt Content

Aggregate Proportion (Cold feed)	54% stones, 46% screening	55% stones, 40% sand, 5% glass shingles	53% Stone, 42% sand, 5% organic shingles
Stability at 140ºF (lbs)	2380	1950	1550
Flow at 140ºF, 0.01”	12.3	13.5	13.8
Air voids (%)	4.4	4.5	4.5

(Source: Brock, 2007)

Table 2.10: Marshall Stability Test Results Based on Shingle-waste Addition

Shingle %	0%	1%	2%	3%	4%	5%
Binder added%	5%	5%	5%	5%	5%	5%
Stability	1053	1196	1138	1025	968	874
Flow (mm)	2.70	3.27	2.37	2.97	3.27	3.10

(Source: Sengoz and Topal, 2004)

Table 2.11: Marshall Stability Test Results Based on Optimum Binder Content

Shingle %	0%	1%	1%
Binder %	5%	4.5%	4%
Stability	1053	1328	1260
Flow (mm)	2.70	2.90	1.73

(Source: Sengoz and Topal, 2004)

Table 2.12 shows that, even though less virgin asphalt was added, total binder content increased if shingles were added.

Table 2.12: Effect of Felt-Backed Roofing Waste on Binder Content

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

(Source: Newcomb et al., 1993)

Newcomb et al. (1993) report that the addition of pre-consumer fiberglass shingles or of post-consumer shingles (where it was not known whether the shingles contained felt or fiberglass) reduced the optimum binder content, but no reduction of neat asphalt content was required when pre-consumer felt-backed shingles were added. Compared to the control sample, optimum asphalt-cement content was reduced by 12%, if 5% fiberglass shingles were added, and by 25%, if 7.5% fiberglass shingles were added. Marshall stability generally improved due to the addition of shingles, with the exception of adding 5% felt-backed shingles to for 85/100 pen asphalt or 7.5% felt-backed shingles to 120/150 pen asphalt. These results are shown in Table 2.13. (No explanations for these exceptions were provided by Newcomb.) The Florida DOT found increasing Marshall stability, tensile strength and resistance to rutting (from wheel tracking test) when factory shingle waste was added to HMA (Button et al., 1996).

Table 2.13: Summary of Marshall Mix Design Parameters for Dense Graded Mixtures

AC grade	Shingle type	Shingle content	Marshall mix design test results at optimum asphalt cement content					
			OPT. AC %	Air Voids %	VMA %	Marshall Stability (lb)	Marshal l Flow (0.1 in)	Unit Wt. (pcf)
120/150	Control	0%	4.1	4.0	14.5	3115	10.0	150.2
	Felt	2.5%	4.2	4.0	15.1	3456	8.0	149.5
		5.0%	3.9	3.6	13.9	3407	9.0	148.1
		7.5%	3.9	3.9	15.0	2466	12.0	147.7
	Fiber Glass	2.5%	4.2	4.0	13.5	3200	7.0	149.0
		5.0%	3.4	3.9	12.8	4264	9.0	149.3
		7.5%	2.9	4.3	12.2	4142	7.0	149.3
	Re-Roof	5.0%	3.6	3.7	13.1	4754	10.0	149.1
		7.5%	3.1	4.8	14.1	4461	13.0	146.6
85/100	Control	0%	4.3	4.9	14.2	2800	10.0	148.5
	Felt	5.0%	3.6	5.4	14.7	2697	13.0	146.3
		7.5%	3.6	4.8	15.1	3754	11.0	145.6
	Fiber Glass	5.0%	3.4	3.8	12.7	3746	8.0	149.8
		7.5%	2.9	3.0	11.6	4119	10.0	150.6
	Re-Roof	5.0%	3.4	4.0	13.2	4567	12.0	148.6
		7.5%	2.9	3.5	13.3	5192	10.0	147.9

Note: 75 Blow Marshall Mix design (Source: Newcomb et al., 1993)

Effect of Shingles on Indirect Tension

Mallick et al. (2000) found that indirect tensile strength depended on the shingle content. At 4°C the tensile strengths of a control mixture and of mixtures with 3% shingles, 5% shingles and 7% shingles were 380.5, 430.05, 415.07 and 448.9, respectively. (Note that the author did not provide units for these values.) The addition of manufacturing waste or consumer fines reduced the tensile strength in dense-graded mixtures (Button et al., 1996) as shown in Figure 2.9. The indirect tensile test (ASTM D 4123) indicated the susceptibility of the mixture to fatigue cracking (higher strength indicates better performance with respect to fatigue cracking) (Hanson et al., 1997). Indirect tensile strength was not significantly different (Mallick et al., 2000). But according to Newcomb et al. (1993), indirect tensile strength depended on the grade of the asphalt and the type of shingles.

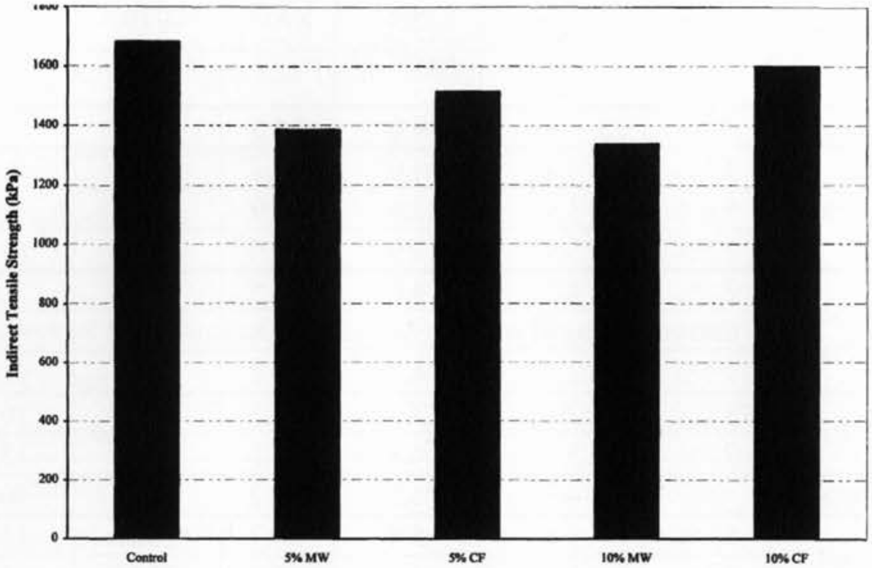

Figure 2.9: Indirect Tensile Strength at 25° C for Dense-graded Specimens Containing Shingles (Button et al., 1995)
Note: MW: Manufacture waste, CF: Consumer waste-fine.

Effect of Shingles on Hveem Stability

Hveem stability decreased for HMA consistently when roofing waste was added (manufacture waste or consumer-waste fines). The stability reduction was independent of the type or quantity of the roofing waste added, but the average Hveem stability remained at an acceptable level (more than 35%) for all mixtures (Button et al., 1996). Button also showed that fibrous shingle flakes did not completely disintegrate during mixing. The reduction of Hveem stability of the mixtures was due to these flakes and individual fibers reducing stone-to-stone contact, thereby reducing the angle of internal friction of the mixture. The effect of shingles on stability of coarse-matrix, high-binder (CMHB) mixtures was less than on dense-graded mixtures due to relatively thicker asphalt films and the higher VMA of the CMHB mixtures. The CMHB mixtures were therefore better able to accommodate roofing waste than the dense graded mixtures (Button et al., 1996).

Effect of shingles on Rutting

Mallick et al. (2000) found that rut depths for mixes with post-manufacture shingles were significantly smaller than the rut depths of the control mix. Rut depths of 4.91mm, 1.91mm and 1.4mm, respectively, obtained for the control mix and for mixtures with 5% and 7% shingles. Shingle tabs resulted in a stiffer mix with improved temperature susceptibility and rut resistance (Griffiths et al., 2002).

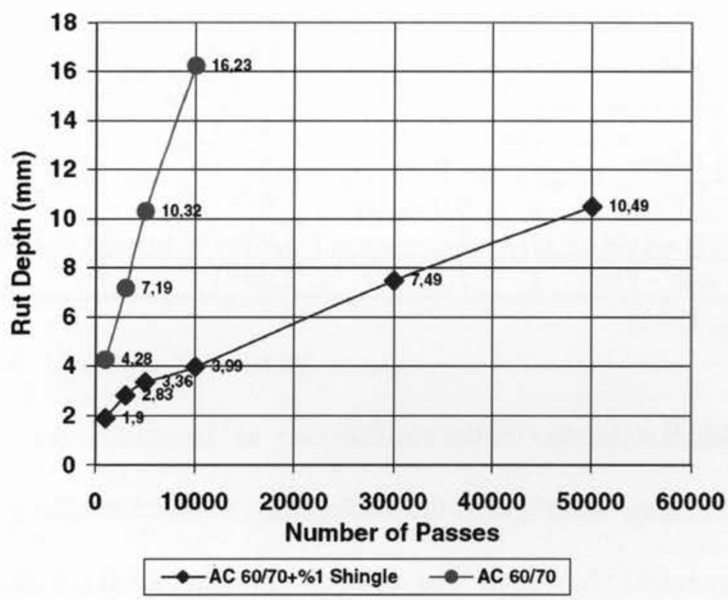

Fig. 2.10: Rutting due to the Addition of Shingles (Sengoz and Topal, 2004)

Figure 2.10 visualizes the extent to which the addition of roofing shingles improved rutting resistance of the mixture. Mallick et al. (2000) also found that the addition of shingles reduced rutting potential significantly and that rut depths at room temperature for the mixes with shingles were significantly smaller than those of control mixes.

Effect of Shingles on Texas DoT Static Creep Test

Button et al. (1996) found that, although the addition of shingles in dense graded mixtures had negative effects on static creep, all mixtures passed the TxDOT's permanent-strain criterion (Table 2.14). But none passed the slope criterion (slope of the steady state portion of the creep curve), and only mixtures with 5% manufacturing waste satisfied the stiffness criterion as shown in Table 2.14. Generally, creep stiffness of dense-graded mixtures decreased significantly when roofing shingles were added.

Table 2.14: Summary of TxDOT Creep Test Results for Dense-Graded Mixtures

Description	Air Voids %	Permanent Strain mm/mm	Slope mm/sec	Creep stiffness
Specification	4.0	$<5.00\times10^{-4}$	$<8.89\times10^{-7}$	>41370
Control	3.5	3.31×10^{-6}	1.03×10^{-6}	67513
5% Manufacturing Waste	3.6	3.82×10^{-6}	9.91×10^{-7}	57507
10% Manufacturing Waste	4.0	1.47×10^{-6}	5.37×10^{-6}	29790
5% Consumer Waste - Fine	5.3	1.03×10^{-6}	3.85×10^{-6}	34044
10% Consumer Waste - Fine	5.7	1.93×10^{-6}	7.7×10^{-6}	23194

Source: (Button et al., 1996)

Effect of Shingles on Temperature Susceptibility

Newcomb et al. (1993) also investigated the resilient modulus of mixtures containing shingles. His results are inconclusive, however. The resilient modulus of the control mixtures (dense-graded mixtures prepared with 120/150 pen grade binder) at 1°C was 1.5 to 2 times greater than that of a felt-shingle mixture, but similar to mixtures with re-roof waste. At 25°C, the resilient modulus of the control mixture was consistent with that of a mix with 5% shingles, but at 40°C the control mixture was slightly stiffer, except for a mixture with 5% felt roofing waste. Mixture stiffness decreased at all temperatures when roofing-shingle content was increased from 5% to 7.5%. This effect was less pronounced for harder types of binder (Newcomb et al., 1993). A mixture with 7.5% fiberglass manufacturing shingles was softest, followed by felt-backed shingles. Mixtures with re-roofing shingles were stiffest. The softer behavior of the shingle mixtures was due to the increased binder content of the asphalt in the roofing waste. Figure 2.11 shows that the temperature dependence of the resilient modulus was only marginally affected by the shingle content of the dense-graded mixtures (Button et al., 1996).

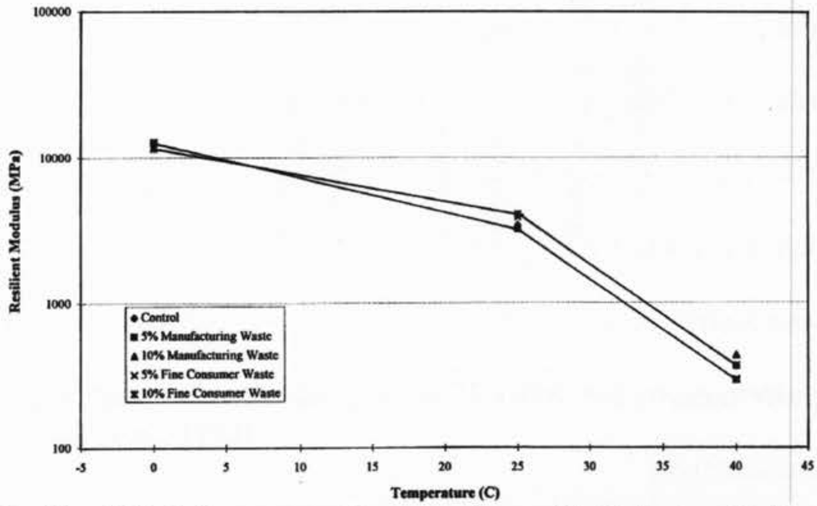

Figure 2.11: Resilient Modulus versus Temperature with Shingles (Button et al., 1995)

Effect of Shingles on Moisture Sensitivity

Moisture sensitivity was measured as the difference in tensile strength between dry and conditioned samples and as the ratio of the wet and dry tensile strengths. This ratio is known as the tensile strength retained (TSR) (Janisch and Turgeon, 1996).

Moisture resulted in similar loss of strength, as measured by resilient modulus and tensile strength, for the control sample and samples containing felt-backed shingles. In consequence felt-backed shingles had no effect on moisture sensitivity (Newcomb et al., 1993). However the test results for mixtures with the fiberglass-backed shingles showed that moisture sensitivity depended on the grade of the asphalt cement used: For the softer 120/150 pen asphalt cement the change of the resilient modulus due to variation of the moisture content was very similar for both the control and the fiberglass-shingle mixes as shown in Figure 2.12. But for the harder 85/100 pen asphalt cement, moduli decreased for both unconditioned and conditioned asphalt, as shown in Figure 2.13. Although the unconditioned tensile strengths of both softer and harder asphalt cement decreased, loss of strength was higher for the harder asphalt as shown in Figures 2.14 and 2.15. But conditioned tensile strength was similar to the control, except when 7.5% shingles were added to the harder asphalt cement. When the samples were conditioned, strength increased about 20% for softer asphalt cement as shown in Figure 2.14. But addition of fiberglass shingles increased conditioned strength by 50% while addition of 7.5% led to an additional increase of only 10% for harder asphalt cement as shown in Figure 2.15 (Newcomb et al., 1993). Due to the inconsistent increase in strength it was difficult to conclude whether or not fiberglass shingles decreased moisture sensitivity.

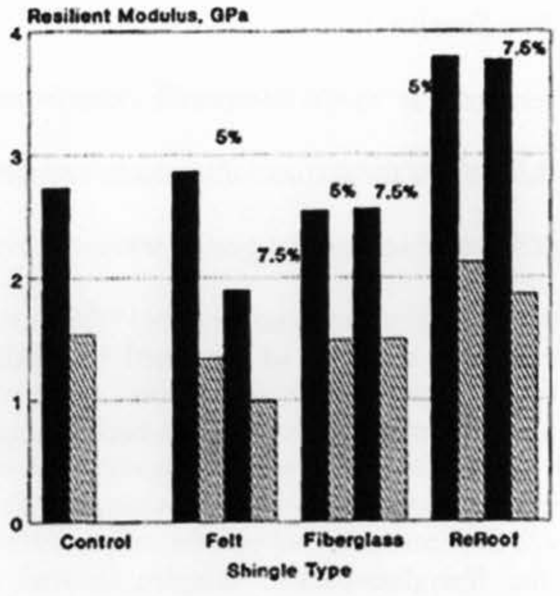

Figure 2.12: Moisture Sensitivity (Resilient Modulus) of Dense Graded Mixtures, 120/150 AC

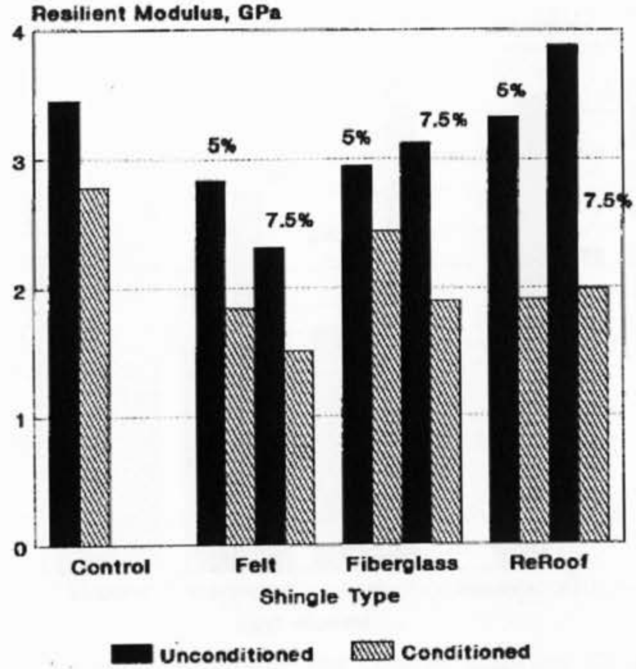

Figure 2.13: Moisture Sensitivity (Resilient Modulus) of Dense Graded Mixtures, 85/100 AC (Source: Newcomb et al., 1993)

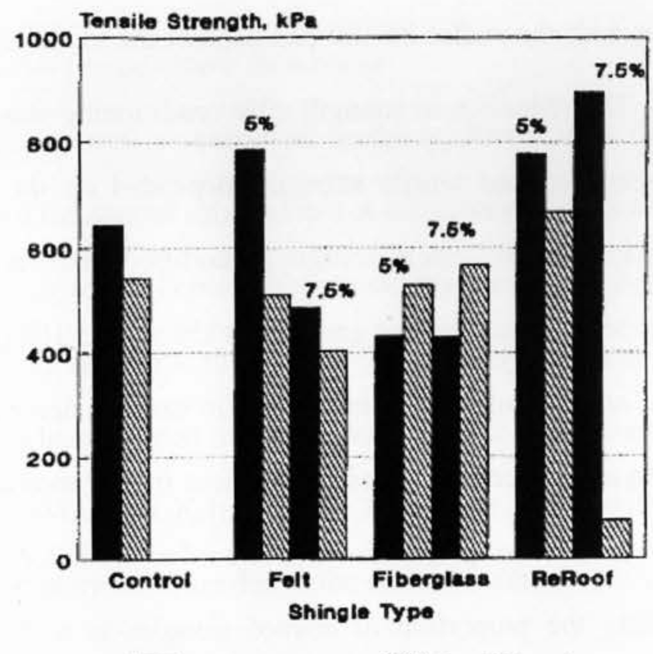

Figure 2.14: Moisture Sensitivity of Dense Graded Mixtures, 120/150 AC (Source: Newcomb et al., 1993)

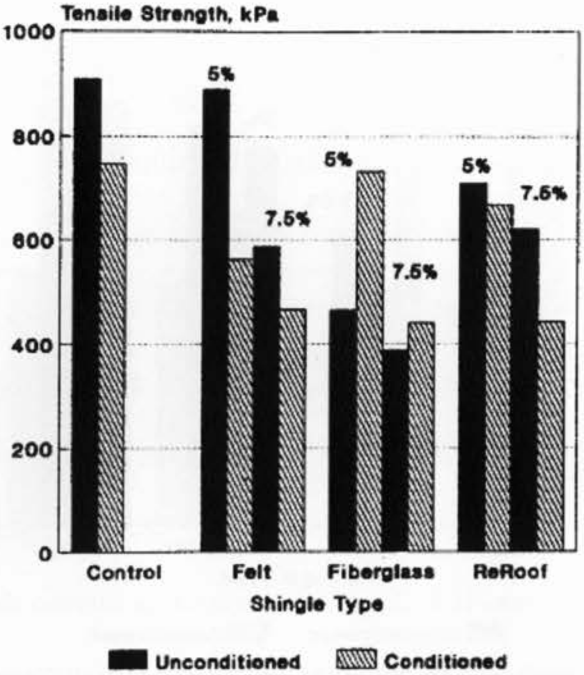

Figure 2.15: Moisture Sensitivity of Dense Graded Mixtures, 85/100 AC (Source: Newcomb et al., 1993)

The addition of re-roof shingles resulted in unconditioned moduli increasing about 40% for softer 120/150 pen asphalt, but with the stiffer 85/100 pen asphalt the modulus hardly changed at all (Newcomb et al., 1993). The reduction in strength after conditioning was similar to that of felt-backed shingles. The unconditioned tensile strengths depended on the percentage of re-roof shingles and the grade of the binder. Tensile strength of modified mixtures were slightly different than control mixtures for both asphalt cement grade (120/150 and 85/100 pen) when 5% shingles were added, but with the addition of 7.5% shingles tensile strength decreased 30% for a sample made with the 85/100 pen asphalt cement. These differences further increased after conditioning. The 120/150 pen asphalt-cement samples with 7.5% re-roof waste failed after conditioning, and it appeared that increasing the proportion of re-roof shingles in a given mixture adversely affected moisture sensitivity.

Table 2.15: Tensile Strength Ratio Values for Dense-Graded and CMHB Specimens.

Mixture Composition	Tensile Strength Ratio (TSR)	
	Dense Graded	CHMB
Control	0.58	0.86
5% Consumer Waste (fine)	0.71	0.78
10% Consumer Waste (fine)	0.72	0.78
5% Manufacturing Waste	0.56	0.96
10% Manufacturing Waste	0.72	0.80
5% Consumer Waste (coarse)	N/A	0.71

Source: Button et al., 1996

For the dense-graded mixtures, the TSR results showed that roofing shingles (except for 5% manufacturing waste) provided higher resistance to freeze-thaw or moisture damage as shown in Table 2.15 (Button et al., 1996). Mixing and compaction temperatures for mixtures containing roofing shingles were 14°C higher than for the control in order to improve the adhesion of asphalt to the aggregate. Laboratory results showed improved resistance to moisture due to the higher temperature.

Effect of Shingle on Low-Temperature Behaviour

Low-temperature results as well as statistical analyses showed that the volumetric and low-temperature properties of the control mix and mixes with shingles were not significantly different (Mallick et al., 2000). Sengoz and Topal (2004) found that fiberglass-shingle waste did not affect the low-temperature properties of the mixtures and that it may improve the resistance to fatigue cracking of pavements. He suggested that more tests need to be performed to evaluate fatigue-cracking properties of HMA. But Krivit (2007) found that HMA with shingles can be more susceptible to low-temperature cracking due to the stiffer binder.

According to Newcomb et al. (1993), for the softer 120/150 pen asphalt, tensile strengths at cold temperatures (-18°C) decreased about 10% and 55% for additions of 5% felt-backed shingles and 7.5% felt-back shingles, respectively. Strain also decreased as shingle content increased, with the exception of felt shingles. In the case of harder 85/100 pen asphalt cement, strength decreased 45% (5% shingles) and 55% (7.5% shingles), but failure strain increased by about 25% (5% shingles) and more than 40% (7.5% shingles). The strain ability of the 85/100 pen mixtures with felt-backed shingles was equal to unmodified 120/150 pen mixtures at cold temperatures, indicating that low-temperature behavior can be improved by adding felt-backed shingles. The magnitude of the decline in tensile strain was independent of the percentage of shingles added. Strain decreased 35% with 120/150 pen asphalt, but hardly any change occurred with 85/100 mixtures, which indicates that fiberglass shingles were not advantageous for low temperature behavior.

For mixtures with 120/150 pen asphalt cement the strain reductions were 30% and 50% for re-roof shingle content of 5% and 7.5%, respectively, whereas for the 85/100 pen asphalt cement the reductions were 15% and 45% for shingle content of 5% and 7.5%, respectively. This difference in behaviour of felt-back shingles and fiber-back shingles was due to higher neat binder content of the mixtures with felt-backed shingles (Newcomb et al. 1993).

Effect of Shingles on Permanent Deformation Characteristics

Creep compliance is the axial strain at a point in time over the center third of the sample divided by the applied stress, Higher creep compliance implies a greater tendency for deformation (Newcomb et al., 1993). The 30-minute-creep compliance at 25ºC for 7.5% shingle content was higher than for 5% shingles, which indicates greater strain, but the relationship was reversed at 40°C. Creep compliance was lower for the 85/100 control samples than for mixtures containing shingles, but the opposite occurred for samples made with 120/150 asphalt cement. Thus the addition of shingles to the softer 120/150 pen asphalt improved resistance to permanent deformation but reduced resistance of the harder 85/100 pen asphalt. At 40°C, the results indicate the onset of failure of the control sample. Creep compliances at 40°C of the other samples were higher than those tested at 25°C, except for the samples with 7.5% re-roof shingles.

2.5.2 Field Observations

The MN/DOT tested overlay projects on Trunk Highway 25 south of Mayer in 1991 and on the Willard Munger recreational trail in 1990. Mixtures with shingle scraps performed as well as the control sections (Janisch and Turgeon, 1996). Scott County prepared HMA incorporating manufacturing shingles in 1991. When the project was reviewed in 1995, the test sections were found to be in excellent condition with minimal transverse cracking. Shingle scrap added to the HMA contributed between 0.27% and 0.30% asphalt cement to the wearing course as shown in Table 2.16. Shingle-scrap sections were harder than the control sections but the amount of cracking of the test sections was the same, indicating that a small increase in stiffness did not cause problems.

Table 2.16: Asphalt Cement Contribution of Scrap Shingles

Type of Mix	Extracted A.C. Content	Target A.C. Content from job mix formula	Total A.C. Contribution of shingle scrap	A.C. contribution of each percent of shingle scrap
Wearing course mixture (MN/DOT 2331 Type 42)				
5% shingle scrap (MN T. H. 25)	6.8 %	5.4%	1.4%	0.28%
7% shingle scrap (MN T. H. 25)	7.0%	5.1%	1.9%	0.27%
9% shingle scrap (Willard Munger Trail)	5.7%	3.0%	2.7%	0.30%

(Source: Janisch and Turgeon, 1996)

Effect of Shingles on Temperature Susceptibility

The temperature dependence of the resilient modulus of field mixes (mixture of felt-back shingle and fiberglass shingle but predominately felt shingles) was similar to that of laboratory-prepared samples containing 5% felt-backed shingles (Newcomb et al., 1993). The resilient modulus of field mixtures with 6% shingles is tabulated in Table 2.17.

Table 2.17: Temperature Susceptibility of Field Mixes

Mixture	Sample No.	Resilient Modulus, ksi		
		1°C	25°C	40°C
Field	1	359	364	201
6% Mixed Shingles	2	386	NA	228
120/150 Pen	3	365	401	207
	Average	370	383	212

(Source: Newcomb et al. 1993)

Effect of Shingles on Moisture Sensitivity

Newcomb et al. (1993) found that the unconditioned and conditioned moduli of field mixtures were 1758MPa and 848MPa, respectively. Unconditioned and conditioned tensile strengths of field samples were substantially greater than those of laboratory-prepared mixtures, which may have been be due to the differences in neat binder content resulting from differences in field and laboratory mixing procedures, and due to different aggregate sources. Conditioned tensile strength was less than unconditioned strength. The shingle field mixes showed performance trends similar to felt-backed laboratory-prepared samples.

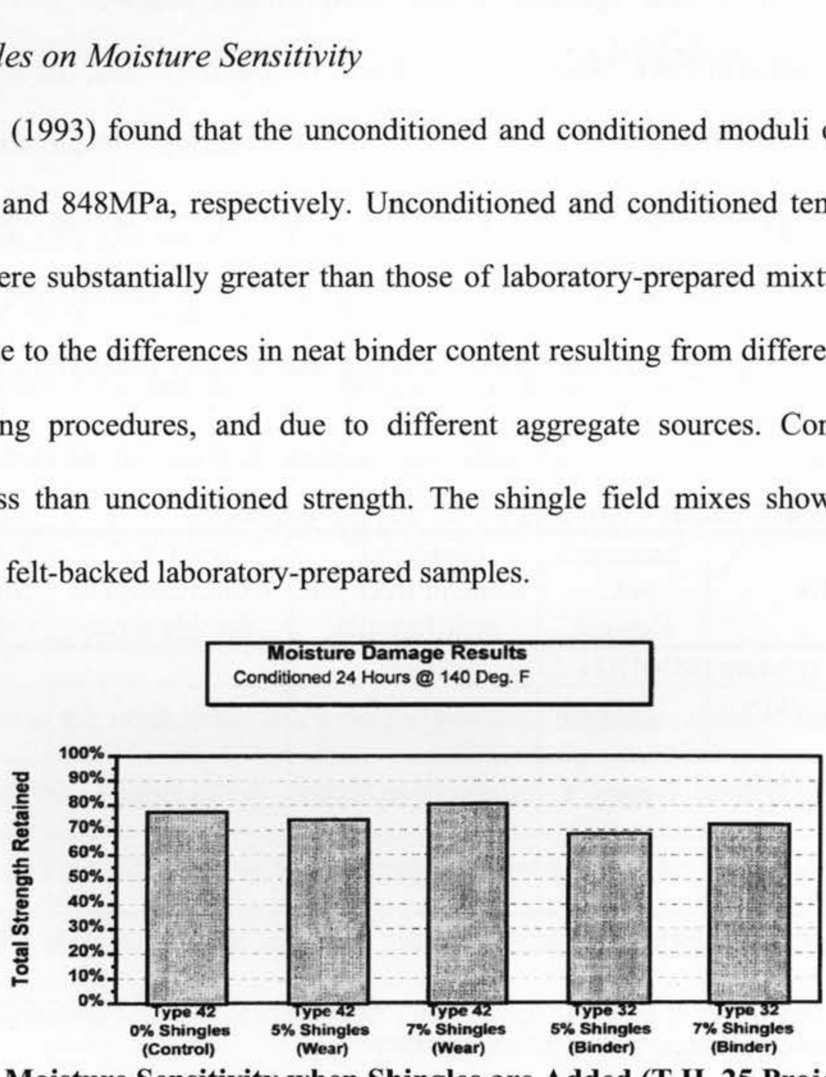

Figure 2.16: Moisture Sensitivity when Shingles are Added (T.H. 25 Project) (Source: Janisch and Turgeon, 1996)

No appreciable difference existed in the retained strengths of the control mixture (no shingles) and the mixtures containing shingles in test section T.H. 25 in Mayer, Minnesota, which indicates that the moisture damage of the shingle mixtures was not more severe than for the conventional mixture (Figure 2.16).

Effect of Shingles on Low Temperature Behaviour

The cold tensile strength of the field mixtures was greater than that of laboratory-prepared mixtures and field strain was roughly 50% to 75% lower than that of laboratory specimens (Newcomb et al., 1993).

Chapter 3

EXPERIMENTAL PROGRAM

3.1 Materials Used

3.1.1 Granular Material

Three types of recycled concrete aggregates (RCA1, RCA2 and RCA3), two types of crushed limestone (LS1 and LS2) and one type of natural granular aggregate (riverbed material) were used in this research. The gradations of the granular aggregates are shown in Figure 3.1. RCA also contained pieces of brick and reclaimed asphalt product (RAP), and was thus a non-homogeneous material.

Based on California Bearing Ratio (CBR) tests, RCA1 was the weakest of the recycled aggregates while RCA3 was the strongest. Grain size distributions were also different. RCA2, for instance, contained more sand-sized particles (passing 4.75mm). Percentage passing sieve #4 (4.75mm) of RCA1, RCA2 and RCA3 were 44.65%, 49.07% and 45.23%, respectively. Percentage passing sieve #200 (75μm) for RCA1, RCA2 and RCA3 were 7.85%, 5.12% and 3.97%, respectively.

One of the two types of crushed limestone was sourced directly from the quarry (LS1), while the other was sourced from a pulverized road section (LS2). LS2 contained more fines than LS1 because of maintenance and addition of fines to the road. Percentage passing sieve #200 of LS1 and LS2 were 8.56% and 15.5%, respectively. Percentage passing sieve #4 of LS1 and LS2 were 44.6% and 64.3%, respectively. The natural granular material contained 54.3% sand (sieve #4) and 7.75% fines (sieve #200).

The effect of adding shingles to the road bases prepared with RCA, crushed limestone or natural gravel was measured using the CBR test and the indirect-tensile-strength test.

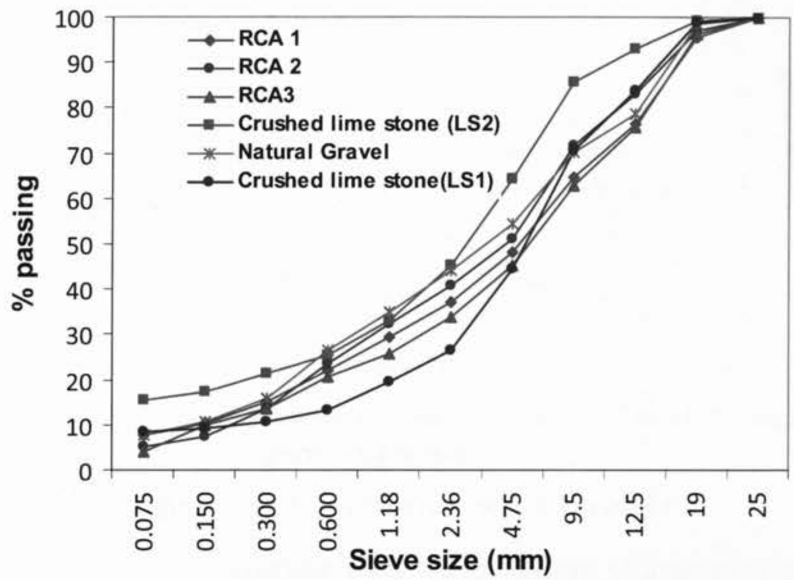

Figure 3.1: Sieve Analysis of RCA, Crushed Limestone and Natural Gravel

3.1.2 Fine Sand

Two types of fine sand were used to determine the effects of shingles in fine sand. One of them (S1) was sourced from a construction site (excavation for a foundation). One-hundred percent of this material passed the 1.18mm sieve. The second type of sand (S2) was obtained by screening granular B (crushed natural gravel from Ontario) through the 2.36mm sieve. Percentage passing sieve #200 of S1 and S2 were 8.29% and 11.61%, respectively. The sieve analysis of fine sand is shown in Figure 3.2.

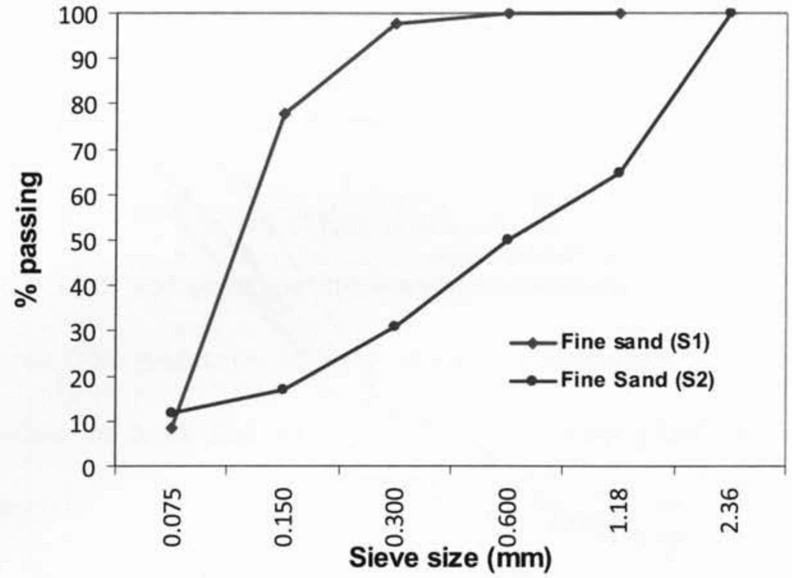

Figure 3.2: Sieve Analysis of Fine Sand

3.1.3 Shingles

Two types of shingles were used. Type 1 (referred to as processed shingles) consisted of post-consumer shingles which were processed to remove nails and other undesirable material (Figure 3.3). The second type (ground shingles) was produced by further grinding the processed shingles (Figure 3.3). The processed shingles that passed through the 12.5 mm sieve seemed more stable and stronger than the larger shingle fractions. It was difficult to analyse the effect of the particle size of the processed shingles on the strength of granular materials due to the larger particles easily breaking under applied loads. Hence the processed shingles were screened to remove larger particles. Ground shingles, on the other hand, dispersed more easily within the granular material, making the final product more homogenous.

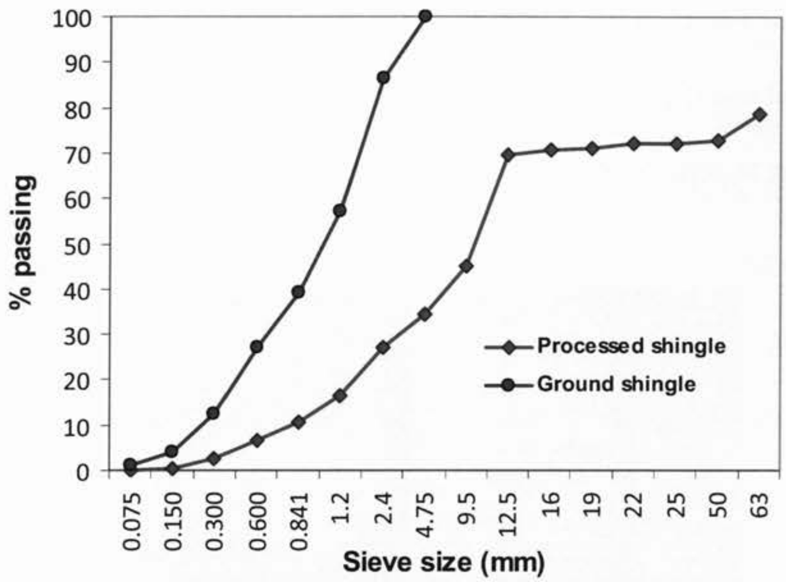

Figure 3.3: Sieve analysis of Processed and Ground Shingle

3.1.4 Bag House Dust

Bag house dust, i.e. fine particles generated from the movement of limestone aggregates during crushing and asphalt mixing, was used as fines for the asphalt mixture.

3.2 Equipment and Experimental Details

3.2.1 CBR Load Frame

A CBR Load Frame with a loading capacity of 10,000 lb was used to determine the CBR of the granular material as per ASTM D1883-05. The CBR Load Frame, shown in Figure 3.4, was equipped with a movable head and base that traveled at a uniform rate of 1.27mm/min (piston penetration rate). The machine was equipped with a digital load-indicating device which could measure a minimum load of 10 lb. The California Bearing Ratio (CBR) is a measure of the bearing capacity of a given soil, but it may also be used to measure the strength of the granular material in pavement design. The Standard Test Method for the CBR of Laboratory-compacted Soils was followed (ASTM D 1883-05). All CBR test samples were prepared at the optimum moisture content (ASTM Standard Test Method for Laboratory Compaction Characteristics of

Soils using Modified Effort (ASTM D 1557-02)). The absorption rate of RCA was higher than that of natural gravel and depended on the duration of soaking. RCA was therefore soaked for 24 hours prior to testing to achieve the desired moisture content.

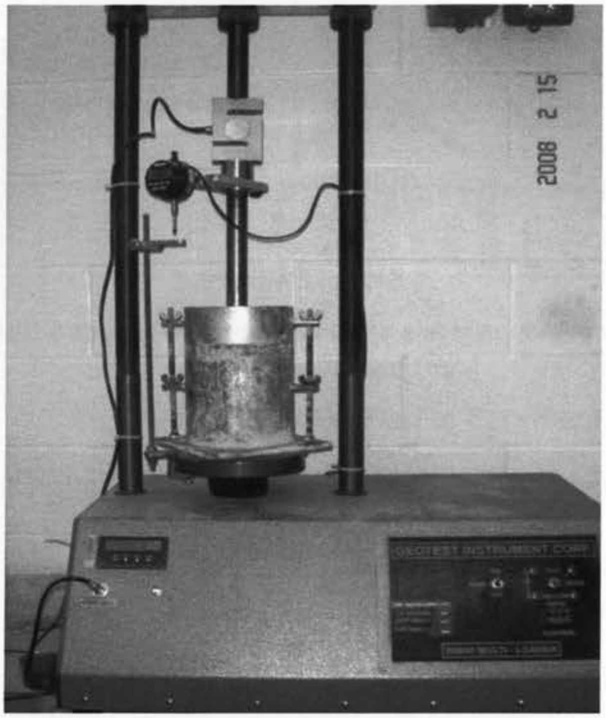

Figure 3.4: Motorised CRB Load Frame

3.2.2 Constant Head Permeameter

The permeameter (Figure 3.5) consisted of a proctor mould, a collar and rubber sealing in-between, as well as rubber sealing between top plate and collar and between bottom plate and mould. The bottom plate includes an inlet valve that is connected to a constant-head water-storage tank. The top plate contains an outlet and air-release valves. The storage tank was an overhead tank with an inlet connected to the water tap and overflow pipes which enabled maintaining a constant head. A spring exerted a force against the top stone to prevent soil density changes during the test (Figure 3.6).

The Ontario Ministry of Transportation's (MTO) Method of Test for Determination of Permeability of Granular Soil (MTO LS-709) was followed to determine permeability. The samples were prepared inside the permeameter mould in five layers with 56 blows (each) of a 4.54kg hammer at optimum moisture content by following ASTM D 1557-02. The specimens were placed between two porous stones, which were covered with filter paper to restrict the migration of fines from the samples. The specimens were soaked inside the mould for 24 hours to achieve saturation.

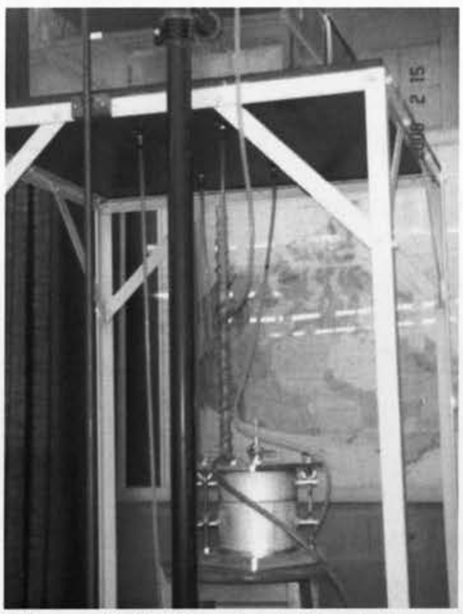

Figure 3.5: Constant Head Permeameter

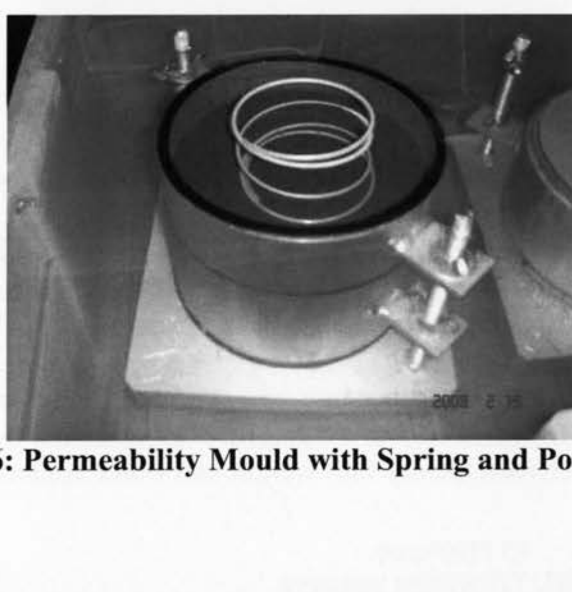

Figure 3.6: Permeability Mould with Spring and Porous Stone

3.2.3 Micro-Deval Abrasion Machine

The Micro-Deval Abrasion Machine consisted of a rolling mill capable of rotating at 100±5 rpm. The mill jar consisted of a 5-litre stainless-steel cylindrical container. The inside and outside surfaces of the jar were smooth. For the test, 5000±5g of steel balls of diameter 9.5±0.5mm were added. The MTO's LS-618, Method of Test for the Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus, was followed.

3.2.4 Indirect Tensile Strength of Stabilized Granular Material

For the determination of the indirect tensile strength, the granular material was also prepared according to ASTM D 1557-02. To facilitate the sample extraction from the CBR mould the following procedure was followed: 2% cement was added to the granular material. The samples were cured at 100% relative humidity for seven days and then dried at room temperature for 7 days. Following extraction they were left to dry for another 15 days at room temperature in the laboratory.

3.2.5 Determining Maximum Dry Density and Optimum Moisture Content

Two different Standard Test Methods were used to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for CBR tests and freeze-and-thaw tests.

3.2.5.1 Determining MDD and OMC for CBR

In preparation of the CBR tests, the maximum dry density (MDD) and optimum moisture content (OMC) of the granular material and fine sand were measured according to ASTM D 1557-02. The samples were prepared inside the mould in five layers with 56 blows (each) of a 4.54kg hammer dropped from 457 mm. The procedure was repeated for several levels of water content to establish a relationship between the dry unit weight and water content.

3.2.5.2 Determining MDD and OMC of Fine Sand for Freeze-and-Thaw Test

Sample preparation for freeze-thaw tests was somewhat different. To determine MDD and OMC of fine sand the samples were prepared inside a 10.1cm mould (five layers with 25 blows (each) with a 2.49kg hammer) as per the Standard Test Method for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures (ASTM D 558-04). Two percent cement was added to every specimen as well.

3.2.6 Preparation of and Freeze-Thaw Methodology for Fine-Sand Specimens

The specimens were prepared at OMC in moulds with a diameter of 50mm and a height of 179.4mm. For calculating the exact volume of the mould the volumes of the top and bottom compaction plates were also considered. After adding water and 2% cement, the soil-cement mixtures were placed into the moulds and static compaction pressure was applied. After extraction the specimens were cured for 7 days at 100% relative humidity (23ºC). After that the specimens were placed onto a 6mm-thick water-saturated pad for 7 days. The freeze-thaw cycles consisted of 24 hours in a freezer at -23ºC, followed by storage in a humidity room (100% relative humidity) for another 23 hours. In total each specimen was exposed to 12 freeze-thaw cycles. The CBR test was conducted as per Standard Test Method for CBR (California Bearing Ratio) of Laboratory-compacted Soils (ASTM D 1883-05). During the freeze and thaw cycles, ice lenses formed inside the specimens thereby reducing their stability. The CBR test is a testing procedure to measure stability based on shear failure of specimen.

3.2.7 Preparation of and Freeze-Thaw Methodology for Granular Materials

Granular materials were compacted according to ASTM D 1557-02. The samples were soaked in water for two days at room temperature. Freeze-thaw cycles consisted of 24 hours in the freezer followed by soaking of the samples in water at room temperature for 23 hours. Each specimen was exposed to 12 cycles. The CBR test was conducted as per ASTM D 1883-05.

3.2.8 Field Measurement of Dust Generation and Road Performance

A trial road was constructed on Miller Road near Brechin as shown in Figure 3.7 (co-ordinates: 44.60397N, 79.10455W) on July 24, 2008. The road was mainly used by heavy gravel trucks. The road consisted of three sections:

1. a control section without shingles (600 m length);
2. a section with 8% processed shingles (300m length); and
3. a section with 8% ground shingles (150m length).

The construction of the control section began with pulverizing the existing gravel road (10cm thickness). Then water was sprinkled, and the pulverized gravel was mixed by a road grader and compacted with a roller. Density testing was performed with a nuclear gauge.

The construction of the sections with shingles was similar to that of the control section. After the pulverization of the gravel (Figure 3.9), a pre-determined amount of shingles was sprayed from a dump truck as shown in Figure 3.8 and 3.10 and spread uniformly using the road grader (Figure 3.11). Then water was sprinkled (Figure 3.12). The shingles were mixed with the gravel with the help of the pulverizing machine (Figure 3.13). The mixture was further mixed by the grader (Figure 3.14) and then compacted with the roller (Figure 3.15). The percentage of shingles was determined based on the laboratory stability tests for the crushed limestone. After completion of the road it was found that the crushed limestone at the site contained more fines and was less angular than the limestone used in the laboratory. This trial (i.e. the first trial) was therefore not effective, but the experience from this trial was used in preparing for the second trial. The 2nd trial therefore omitted a section with ground shingles. Also, the shingle percentage was increased.

Figure 3.7: Location of Construction Site

Figure 3.8: Spreading of Ground Shingles

The second trial was conducted on October 6, 2008. The trial consisted of a 200m control section and a 300m section with 12% processed shingles. Twelve percent was found to be the optimum shingle content for the material collected from the job site. The procedure was the same as for the first trial.

After 8 days, dust generation on the road was measured by two air suction tools as shown in Figure 3.16. The setup of the machines (distance from centre of roadway and suction rate (30 cft/minute)) was identical for both sections. The air was filtered through filter paper. The mass of the filter was measured before and after the test. The mass difference was the dust collected.

Figure 3.9: Pulverization of Existing Gravel Road

Figure 3.10: Placing Processed Shingles

Figure 3.11: Spreading of Processed Shingles by Grader

Figure 3.12: Sprinkling of Water

Figure 3.13: Mixing of Shingles and Gravel with Pulverization Machine

Figure 3.14: Mixing of Shingles and Gravel with Grader

Figure 3.15: Compaction of Gravel

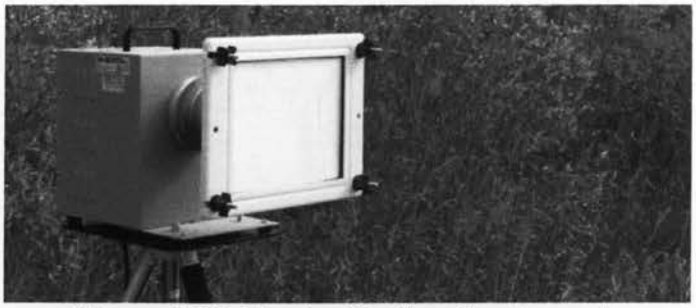

Figure 3.16: Dust-collection Equipment

3.2.9 Equipment Requirements for HMA

The potential use of shingles in HMA was investigated. This study focused on the effects of shingles on optimum binder content and tensile strength.

3.2.9.1 Oven

All samples were short-term aged prior to compaction in a convection oven chamber as shown in Figure 3.17.

Figure 3.17: Oven

3.2.9.2 Gyratory Compactor

The specimens were prepared in a gyratory compactor (Brovold Gyratory Compactor (Figure 3.18), Pine Instrument Company), which followed SCSC according to AASHTO PP35. The compactor limited the maximum height of the specimens to 160mm. In a gyratory compactor, two types of compaction efforts are applied to the specimen, i.e. a constant compressive force of 600kPa and a shear (or kneading) force.

Figure 3.18: Gyratory Compactor

3.2.9.3 Freezer

For the TSR tests the samples were frozen at 0±5°F using a commercial freezer as shown in Figure 3.19.

Figure 3.19: Freezer

3.2.9.4 Water bath

The temperature of the water bath (Figure 3.20) used for this project was adjusted as per ASTM test requirements.

Figure 3.20: Water Bath

3.2.9.5 Sample Preparation for Determining Optimum Binder Content

SuperPave mix design procedures were followed to prepare the specimens (Atkins, 2003). The samples were designed for traffic loads of less than 30 million ESALs (Equivalent Single Axle Load). Initial gyrations (N_{in}), designed gyrations (N_{des}), and maximum gyrations (N_{max}) were 8, 109 and 174, respectively. Aggregate, bitumen, dust and the mould were heated to a temperature of 150°C for 4 hours before mixing and compaction. The compaction was performed in the Gyratory Compactor. Bitumen content was chosen for air voids of 4.0±0.5% for all specimens. Only control specimens and specimens with 3% shingles were investigated.

3.2.9.6 Sample Preparation for Tensile Strength Ratio

Aggregate, binder and fines were mixed at 150°C. After mixing the mixture was placed in a pan with an approximate depth of 25 mm, where it was allowed to cool to room temperature for

2±0.5 hours. After that the mixture was heated in the oven at 60°C for 16 hours. Then the mixture was heated in the oven for 2 hours at a temperature 150°C. Six specimens each with a diameter of 150mm and thickness of 95mm were made for the control and the shingle mixture. All specimens were cooled at room temperature. Air voids of all specimens were within the required range of 7.0±0.5%. Three specimens each of the control and the shingle mixture were kept inside a water-tight plastic bag and were placed in a water bath at 25°C for 2 hours. The remaining control and shingle-mixture specimens were placed in water and 70-80% of the air voids were saturated using a vacuum pump. After that they were wrapped with plastic wrap and placed into plastic bags with 10g water. The specimens were placed in the freezer for 16 hours, followed by 24 hours and 2 hours in a 60°C and 25°C water baths, respectively. Following these sample preparations the indirect tensile strength tests were conducted. The thickness of the specimens was measured with a Vernier calliper as per ASTM D 3549. The tensile strength ratio was calculated as the ratio of average indirect tensile strengths for the conditioned and dry specimens. The test procedures followed the Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-induced Damage (AASHTO T 283-07).

Chapter 4

RESULTS AND ANALYSIS

The experimental results are organized as follows. Section 4.1 describes the Micro-Deval test results for the coarse aggregate. The laboratory results regarding the shingle modifications of the granular materials and fine sand are then discussed (sections 4.2-4.4). After that the field results of the trial road are reviewed (section 4.5). Finally, section 4.6 presents the results of adding shingles to dense graded Hot Mix Asphalt.

Sections 4.2-4.4 are presented in the following order. First, the effects of shingles on optimum moisture content (OMC) and maximum dry density (MDD) of the granular materials and the fine sand (section 4.2) are shown. These results were used to determine the effects on stability of shingle content and particle size of the granular materials (section 4.2.1). Then the effects of curing methods (section 4.3.2) and freeze-and-thaw exposure (section 4.3.3) on shingle-modified granular materials are discussed. Section 4.3.4 investigates the effect of shingle content on indirect tensile strength of granular materials. The effects of shingle content on the stability of fine sand are discussed in section 4.3.5, which is followed by a discussion of the effects of freeze-and-thaw exposure on the stability of shingle-modified fine sand (section 4.3.6). Section 4.4 discusses the effects of shingles on permeability.

4.1 Micro-Deval Abrasion Test

Micro-Deval abrasion loss of the RCA1 was highest at 20.3%, whereas that of RCA2 and RCA3 were 17.9% and 18.5%, respectively. These differences were considered marginal. The test results are summarized in Table 4.1.

Table 4.1: Micro-Deval Values and Fractions of Sand and Fines

Material	Micro-Deval Loss (%)	Sand (%)	% fines (passing 75µm)
RCA1	20.3	44.64	7.85
RCA2	17.9	49.07	5.12
RCA3	18.5	45.23	2.62
LS1	7.3	37.94	8.58
Crushed Natural Gravel	5.4	55.50	7.50

4.2 Effect of Adding Shingles on OMC and MDD

Optimum moisture content (OMC) and maximum dry density (MDD) of the different types of granular materials and fine sand with and without shingles were determined to investigate the effects of shingles on OMC and MDD. The results are summarized in Tables 4.2 and 4.3. For both granular materials and fine sand, MDD declined as the percentage of shingles was increased. For the granular materials this effect was likely attributable to the lower density of the shingles. A correlation between shingle content and OMC was not found, however.

Table 4.2: OMC (%) and MDD (kg/m^3) of Granular Materials

Shingle %	RCA1		RCA2		RCA3		LS1		LS2		Natural gravel	
	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD	OMC	MDD
0	9.0	2054	8.9	2106	8.7	2106	5.9	2260	4.65	2350	5.1	2293
3	9.2	2025			8.6	2038	6.0	2262				
5			8.5	2071	8.9	2027	6.2	2229			5.2	2198
8	9.1	1967			8.7	2003	6.4	2187				
10	9.3	1964	8.3	1992	8.4	1997	5.9	2176			5.2	2182
15	8.6	1953					5.8	2144	5.25	2140		

Similarly addition of shingles decreased the MDD of fine sand due to the lower density of shingles. The addition of shingles resulted in a reduction of OMC, which may be due to improved compactability of shingle mixtures.

Table 4.3: OMC (%) and MDD (kg/m^3) of Fine Sand

Shingle %	OMC	MDD
0	9.4	1974.8
5	8.9	1935.1
10	8.6	1899.6

4.3 Effect of Shingles on the Stability of Granular Materials and Fine Sand

The effect of shingles on the stability of the granular materials and the fine sand were determined on the basis of the California Bearing Ratio (CBR), as discussed in chapter 3.

4.3.1 Effect of Shingles Content and Size on Stability of the Granular Materials

At OMC, RCA1 was found to be the weakest and RCA3 the strongest of the 3 recycled aggregates. The CBR values increased for both ground and processed shingle in the case of RCA1 when 5% shingles were added (Figure 4.1). It is noteworthy that strength increased with the addition of up to 5% shingles in the case of low strength RCA. But a negative effect obtained with RCA3 (Figure 4.2). RCA3 itself was a stronger material, indicating that the shingles acted as lubricant under crushing load. RCA2 was stronger than RCA1 as well, but contained more sand and finer particle than RCA3. CBR values for RCA2 increased slightly due to the addition of 5% ground shingles (Figure 4.2). Further addition of shingles reduced stability.

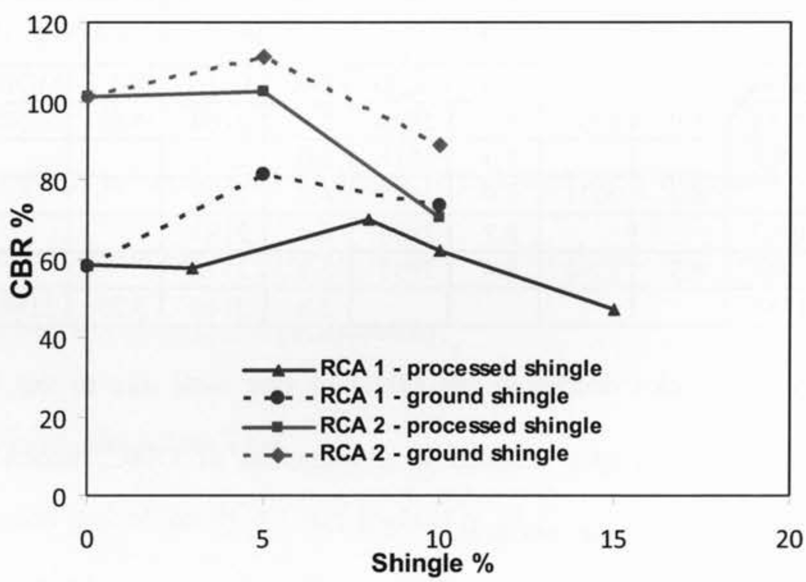

Figure 4.1: Effect of Adding Shingles to RCA1 and RCA2

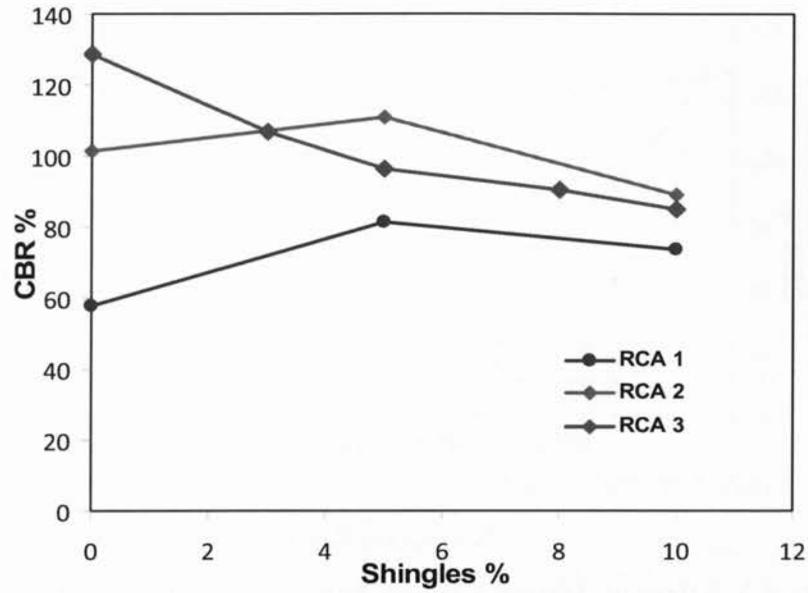

Figure 4.2: Effect of Adding Ground Shingles to RCA

The results of the CBR tests for the limestone were as follows. The coarse crushed limestone (LS1) (8.5% passing #200, and 44.6% passing #4) became less stable when either processed or ground shingles were added (Figure 4.3 and Figure 4.4). The limestone particles had an angular shape with high initial stability; the addition of shingles seemingly had the same lubricating, and hence stability-reducing, effect as with the higher-strength RCA. The other type of limestone (LS2), which was sourced from the site and contained 15.5% fines (passing #200) and 64.3% sand (passing #4), experienced a small increase in stability due to the addition of a relatively large amount of shingles (15%). Visual inspection indicated that LS2 was less angular than LS1. LS2 had a higher initial stability despite containing more fines. The addition of 5% shingles to LS2 led to a minor decline of the CBR. However, the CBR of LS2 increased slightly when more shingles were added. It would appear that the addition of shingles was beneficial for granular materials with higher fines content.

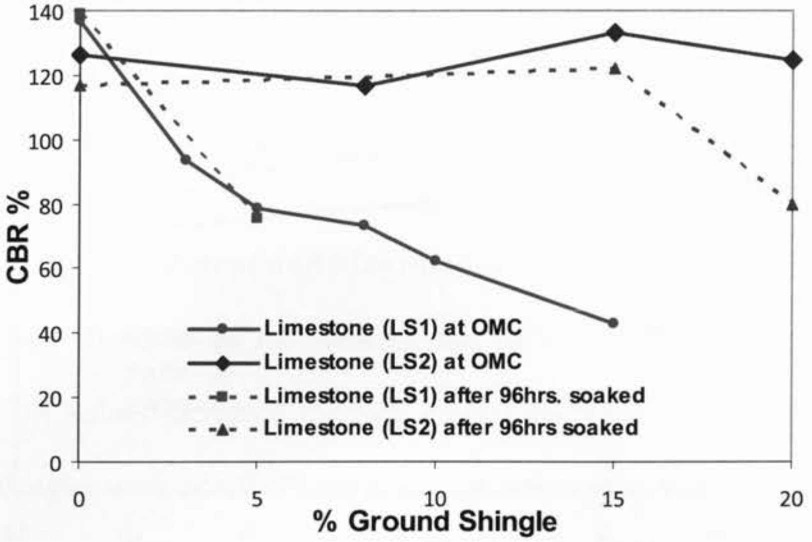

Figure 4.3: Effect of Adding Ground Shingles to Crushed Limestone

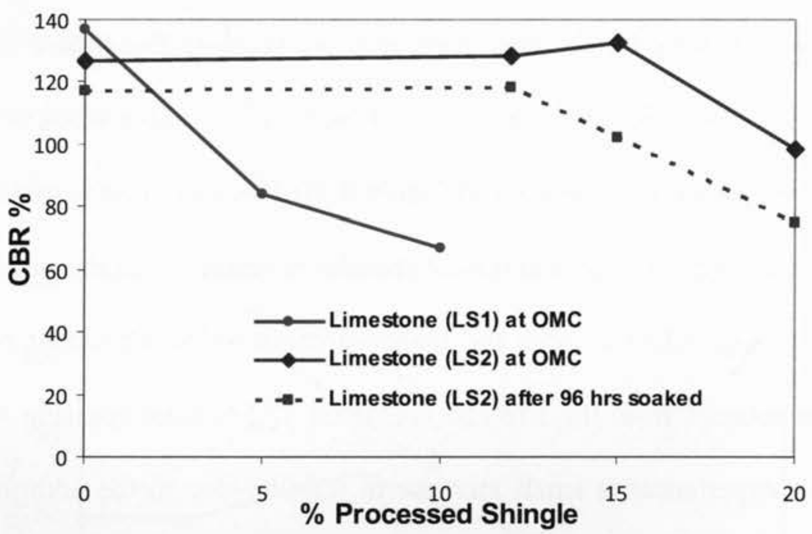

Figure 4.4: Effect of Adding Processed Shingles to Crushed Limestone

With respect to the natural gravel, the CBR tests showed that CBR values slightly increased for shingle additions of up to 5% (Figure 4.5). Further shingle additions decreased CBR values. Although the riverbed material contained round and sub angular aggregate, the initial stability of the riverbed material was high, so that the addition did not increase the CBR value significantly.

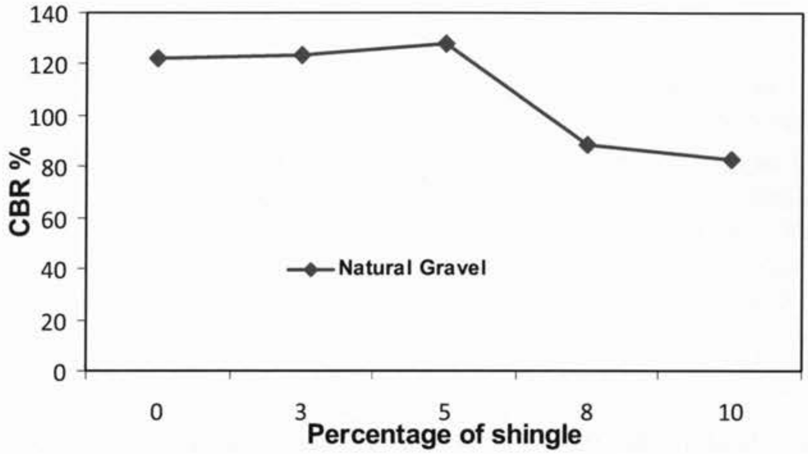

Figure 4.5: Effect of Adding Shingles to Natural Gravel

Although the CBR results showed that some granular materials did not benefit from the addition of shingles, it should be noted that the reduction in CBR for these materials was not large enough to render them unsuitable for road works. In fact the minimum CBR obtained for the 5 tested granular materials at 5% shingles was 80%.

4.3.2 Effect of Curing on Stability of Shingle-Modified Granular Materials

Since road construction in Canada usually takes place during spring and summer, it is imperative to investigate the role of the ambient temperature during construction on the shingle-modified granular materials. RCA2 and RCA3 were selected for this investigation. RCA2 was mixed at the optimum moisture content with ground shingles, placed in plastic bag, and stored at 38°C for 24 hours. After that the mixture was compacted, left in air for 7 days and then tested. The results are shown in Figure 4.6, which shows that the curing regime resulted in higher CBR values. The CBR curve after curing versus shingle content was more or less parallel to that of the materials when tested just after compaction. This indicates that the shingles were not a major source (if at all) of the strength gain. The increase in stability therefore was probably a result of drying and/or any self-cementing properties of the RCA.

Figure 4.7 visualizes the effect of curing on shingle-modified RCA3. Three different curing regimes were investigated. The first regime involved compacting the specimens and leaving the compacted samples in air for 3 days. The other regimes involved packing loose mixtures of RCA3 and shingles at optimum moisture content in thick plastic bags. For the second regime the bags were kept in a heat room at 38°C for 4 hours, while regime 3 did not include exposure to heat. The mixtures were compacted and left in air for 3 days. Figure 4.7 shows that both regimes 2 and 3 resulted in similar CBR values, again indicating that the improvement in strength was due to drying and not due to the presence of shingles.

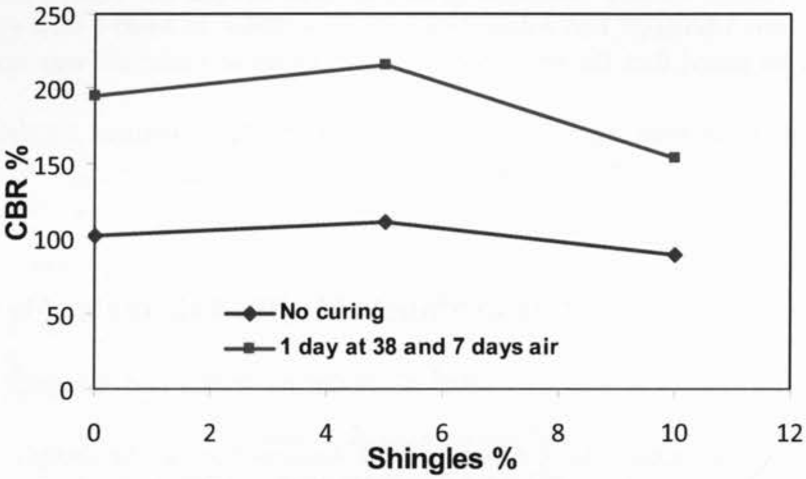

Figure 4.6: Effect of Curing on shingle-stabilized RCA2

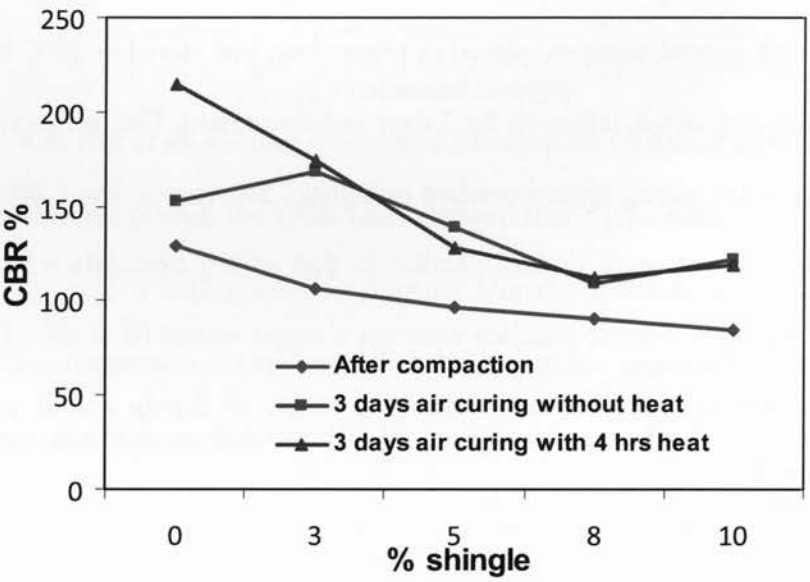

Figure 4.7: Effect of Curing on shingle-stabilized RCA3

4.3.3 Effect of Freezing and Thawing on the Stability of Shingle-modified Granular Material

The effect of freezing and thawing on shingle-modified limestone (LS1) was investigated by exposing the mixtures to 12 freeze-and-thaw cycles after 96 hours of soaking in water. The stability of the following specimens was tested with and without shingle: (a) LS1 and LS 2 at OMC (no freeze-thaw exposure), (b) LS1 and LS2 after soaking for 96 hours (no freeze-thaw exposure), and (c) LS1 and LS2 after 12 freeze-and-thaw cycles. The specimens were prepared as described in sections 3.2.5 and 3.27. Figure 4.8 shows that for all materials the stability decreased as the shingle content increased. It also shows that soaking did not significantly affect stability. The changes of the CBR values due to the increase of the shingle content were almost identical for the specimens at OMC and the specimens after 96 hours of soaking. The figure also shows that the loss of stability due to freeze-and-thaw exposure was significantly higher for the samples without shingles. Addition of shingles therefore had a positive effect on durability. Figure 4.11 and Figure 4.12 show that there were fewer cracks due to freeze and thaw in the shingle-modified specimens. The surface of shingle-modified limestone exhibited fewer cracks than the limestone without shingles. But addition of processed shingles to LS2, slightly reduced the stability (Figure 4.9) after it had been soaked for 96 hours. After 12 cycles freeze-and-thaw cycles, loss of stability was significant. The reduction of stability showed that addition of larger amounts of shingle can make the material vulnerable to freeze-and-thaw exposure. The CBR of site-collected samples was found to be less for all types of sample preparations investigated, which indicates that the shingle content mixed at the site was perhaps higher than 12%.

In the case of RCA2, the decline of stability, when shingles were added, was approximately the same for all exposure types investigated (Figure 4.10). Generally, freeze-and-thaw exposure thus had little effect on the RCA (Figure 4.13 and Figure 4.14). Tables 4.4, 4.5 and 4.6 report the heave measurements for the samples. Heave height for shingle-modified limestone and RCA was marginally less than heave for specimens without shingles. Heave height and surface disintegration of limestone and RCA was significantly different, because of the differences in the fines content of the granular materials. Limestone (LS1) contained about 8.5% fines and RCA2 five percent.

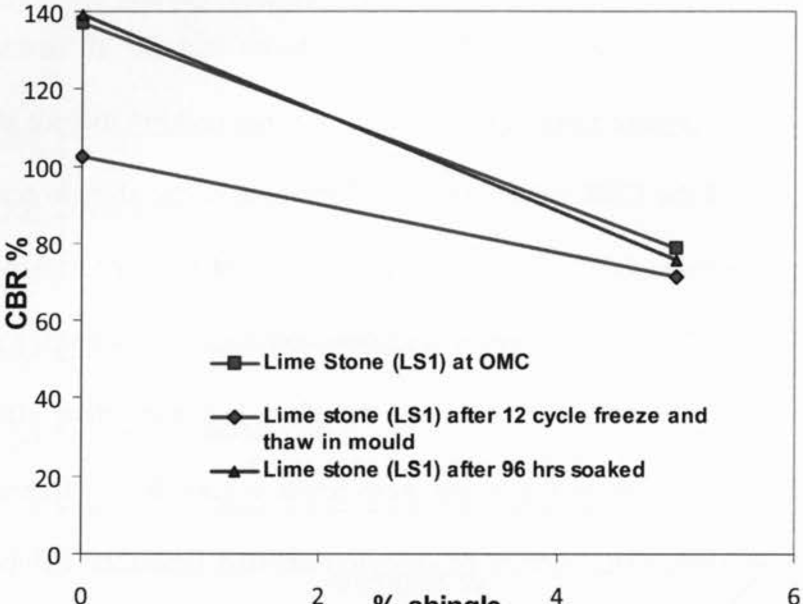

Figure 4.8: Effect of Freeze and Thaw for Shingle-modified Limestone (LS1)

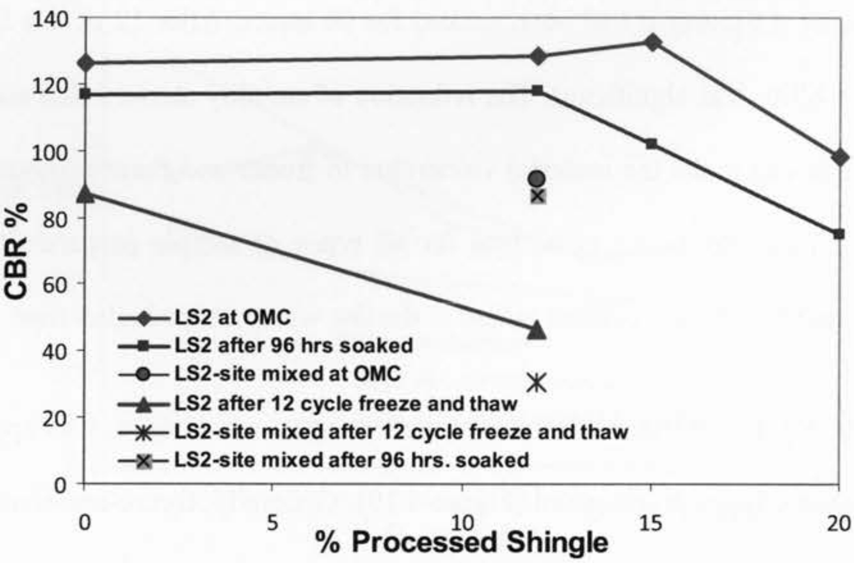

Figure 4.9: Effect of Freeze and Thaw for Shingle-modified Limestone (LS2)

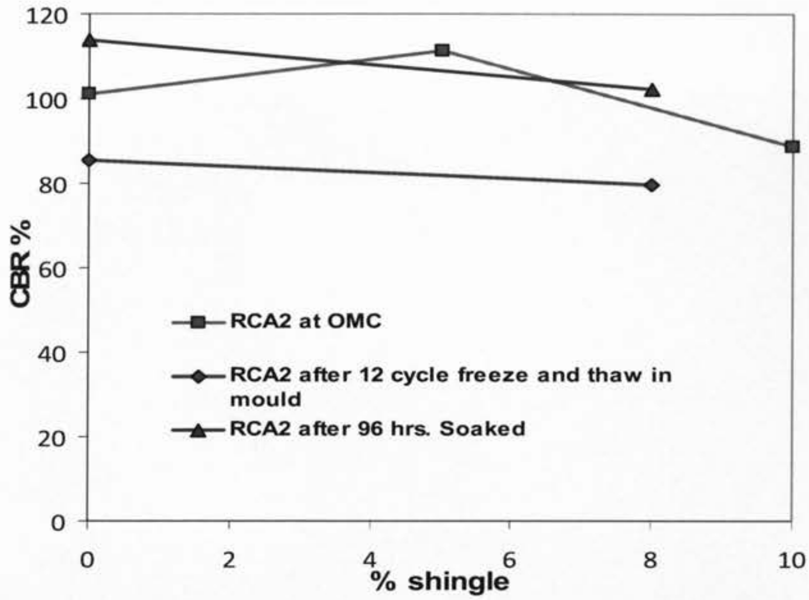

Figure 4.10: Effect of Freeze and Thaw for Shingle-modified RCA2

Table 4.4: Heave in Limestone (LS1) after Freeze and Thaw

Specimen No.	% shingle	Heave height (mm) in center during:		Remarks
		Freezing	Thawing	
1	0 %	11.33	7.62	Cracks in centre
2	0 %	11.86	8.32	Cracks in centre
3	8 %	10.96	6.98	Fewer cracks
4	8 %	11.19	8.56	Fewer cracks

Table 4.5: Heave in Limestone (LS2) after Freeze and Thaw

Specimen No.	% shingle	Heave height (mm) in center during:		Remarks
		Freezing	Thawing	
1	0 %	8.14	7.48	No Cracks
2	0 %	8.39	7.98	No Cracks
3	12 %	9.23	8.63	No Cracks
4	12 %	9.82	7.91	No Cracks
5	Site mixed	8.09	7.81	No Cracks
6	Site mixed	8.86	8.36	No Cracks
7	Site mixed	8.64	7.37	No Cracks
8	Site mixed	9.77	8.53	No Cracks

Table 4.6: Heave in RCA2 after Freeze and Thaw

Specimen No.	% shingle	Heave height (mm) in center during:		Remarks
		Freezing	Thawing	
1	0 %	6.28	4.52	No cracks
2	0 %	6.31	4.93	No cracks
3	8 %	5.19	4.27	No cracks
4	8 %	5.73	4.52	No cracks

Figure 4.11: Limestone without Shingles

Figure 4.12: Limestone with 5% Shingles

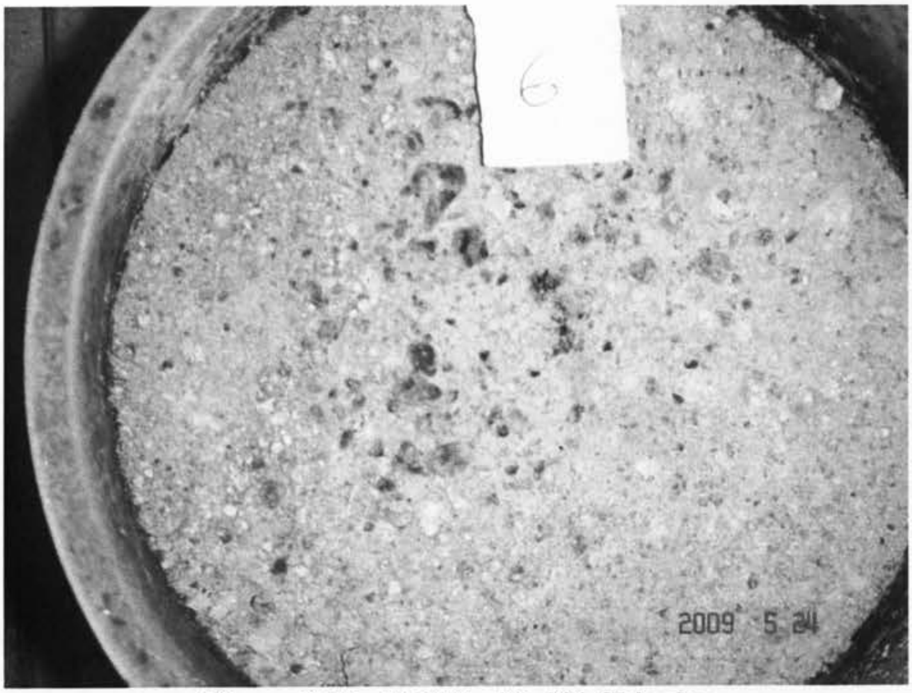

Figure 4.13: RCA2 with 0% Shingles

Figure 4.14: RCA2 with 8% Shingles

4.3.4 Effect of Shingles on Indirect Tensile Strength of Granular Material

Indirect-tensile-strength tests were conducted for crushed limestone and RCA2. Two percent cement was added to all samples to facilitate specimen extrusion from the moulds. It should be noted that this amount of cement was less than what is commonly used to stabilize granular materials (a cement content of 5% is usually used) to reduce the effect of the cement addition on the strength of the material. Two specimens were made with 0% and 8% shingles for both RCA2 and limestone (LS1), i.e. a total of 8 specimens. For both shingle-modified crushed-limestone specimens indirect tensile strength was higher than for the crushed-limestone specimens without shingles (Table 4.7). The crushed-limestone specimens are shown in Figure 4.18 and Figure 4.19. Figure 4.14 shows that the strain energy of shingle-modified limestone was greater than that of limestone without shingle. Hence it can be concluded that shingle-modified limestone has a higher resistance to fatigue cracking.

In the case of RCA2, all samples exhibited very similar strength values (Table 4.8), but visual inspections of Figures 4.16 and 4.17 indicates that RCA2 specimens with 8% shingles were denser and had fewer cracks. These specimens can thus be considered to have performed better than RCA2 specimens without shingles. Due to equipment error measurements of the strain energy of shingle-modified RCA2 are not shown here.

Table 4.7: Indirect Tensile Strength of Crushed Limestone

Shingle content	Indirect tensile strength (N/cm^2)	Average indirect tensile strength (N/cm^2)
0%	40.03	37.92
	35.80	
8%	43.28	43.04
	42.79	

Table 4.8: Indirect Tensile Strength of RCA2

Shingle content	Indirect tensile strength (N/cm^2)	Average indirect tensile strength (N/cm^2)
0%	44.6	46.65
	48.7	
8%	44.6	44.6
	*	

*Note: The tensile strength for this sample could not be determined due to equipment malfunction.

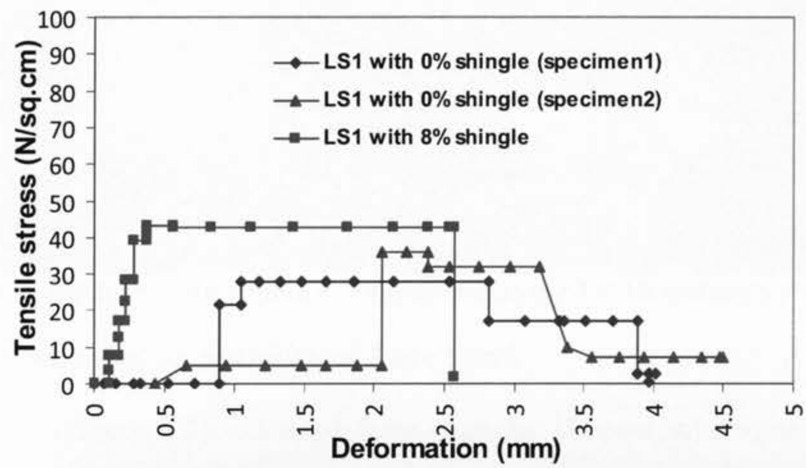

Figure 4.15: Comparison of Indirect Tensile Stress and Strain of Limestone (LS1)

Figure 4.16: Crushed RCA2 Specimen without Shingles after Indirect Tensile Test

Figure 4.17: Crushed RCA2 Specimen with 8% Shingles after Indirect Tensile Test

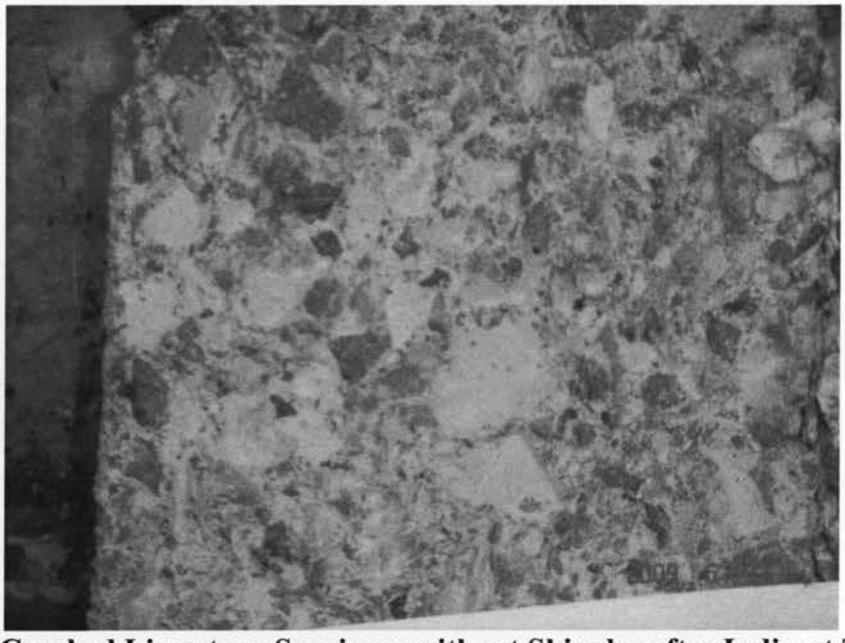

Photo 4.18: Crushed Limestone Specimen without Shingles after Indirect Tensile Test

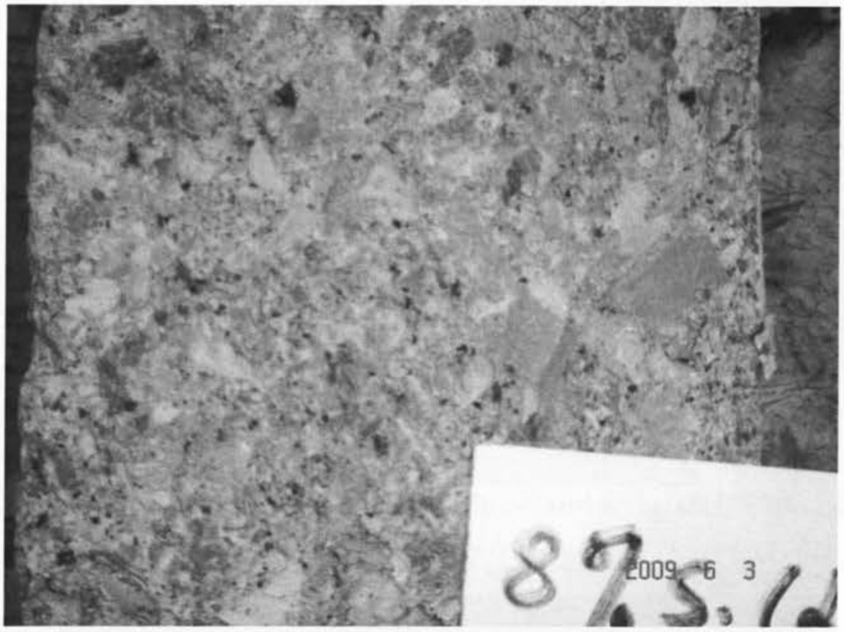

Photo 4.19: Crushed Limestone Specimen with 8% Shingles after Indirect Tensile Test

4.3.5 Effect of Shingles on Stability of Fine Sand

Two types of sand (Figure 3.2) extracted from granular B were investigated, i.e. S2 (100% passing 2.36mm sieve and 31% passing 0.3mm sieve) and S1 (100% passing 1.18mm sieve and 97.9% passing 0.3mm sieve). The addition of ground shingles resulted in declining CBR values for both types of sand. Figure 4.20 shows that the CBR values of both LS1 and LS2 were nearly identical irrespective of shingle content. The decrease of stability was due to the lubricating effect of shingles on sand particles which were found to be angular (visual inspection). Figure 4.20 also shows that the stability of fine sand did not significantly depend on gradation (recall that the gradations of S1 and S2 were substantially different). The increase of the CBR value as the shingle content was increased from 16% to 20% was unexpected and cannot be explained.

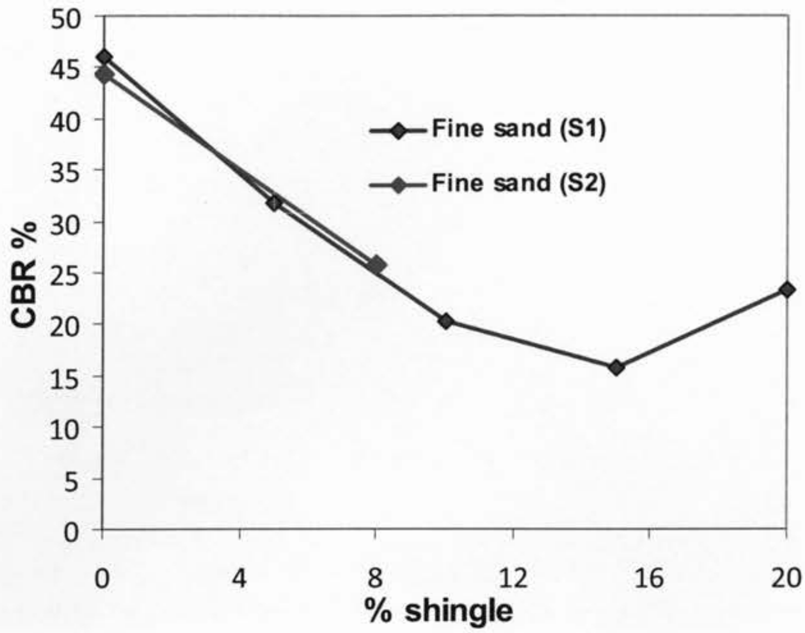

Figure 4.20: Effect of Adding Shingles to Fine Sand

4.3.6 Effect of Freeze-and-Thaw Exposure on Stability of Shingle-modified Fine Sand

Fine sand was prepared from granular B (passing 2.36mm sieve). Two specimens each were made without shingles, with 5% shingles and with 10% shingles. To all the specimens 2% cement was added. As the strength of the specimens was very low, comparison of the specimens was made only by visual inspection. After 9 freeze-and-thaw cycles the specimens without shingles started disintegrating. After 12 cycles the specimens without shingles had much more disintegrated than the others. The specimens with 10% shingles were found to be in the best condition: they exhibited no cracks. The specimens with 5% shingles had some cracks but, but fewer than the specimens without shingles (Figure 4.21 to Figure 4.23).


Figure 4.21: Effect of Freeze and Thaw of Fine-Sand Specimen without Shingles

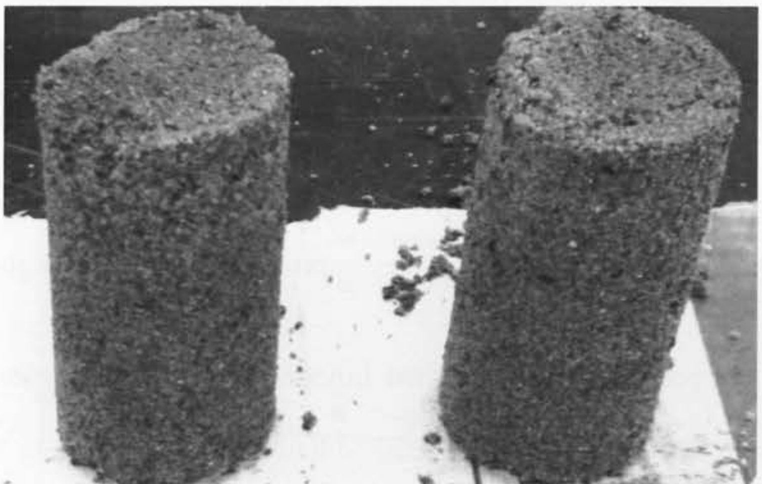
Figure 4.22: Effect of Freeze and Thaw of Fine-Sand Specimen with 5% Shingles

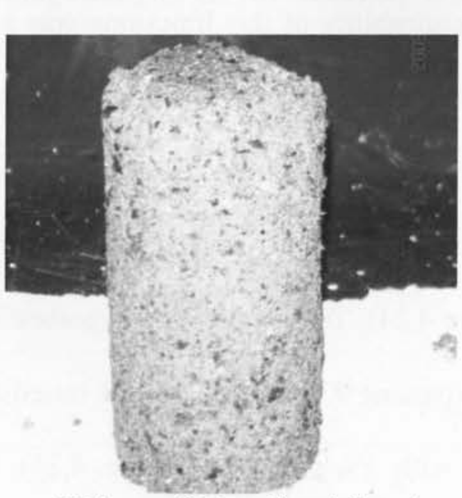
Figure 4.23: Effect of Freeze and Thaw of Fine-Sand Specimen with 10% Shingles

4.4 Effect of Shingles on Permeability

The effect of shingles on permeability of granular materials was investigated using RCA2, the two types of crushed limestone and the riverbed material. The permeability was evaluated using the constant head test described in MTO LS-709. The coefficient of permeability of RCA2 was found to slightly decrease with increasing shingle content. The permeability of LS1 declined significantly with the addition of 5% shingles. Increasing the shingle content to 10% led to only a marginal further decline in permeability (Figure 4.24). However, all the obtained permeability coefficients were within the range recommended by the Ministry of Transportation of Ontario for granular materials (10^{-4} to 10^{-8} m/sec). Thus the addition of shingles to granular materials does not jeopardize drainage requirements of the RCA and LS1. For crushed limestone LS2, which contained 15.5% fines (passing #200) and 64% sand (passing #4), hydraulic conductivity was very low but addition of 12% processed shingles improved permeability slightly.

The reduction in the permeability of crushed limestone with 5% shingles was an interesting finding. By examining the gradation of the crushed limestone (LS1) (Figure 3.1 and Table 4.1), it can be seen that this material contained a relatively small amount of sand, especially particles finer than 2.36mm. The high permeability of this limestone was a result of the relatively open gradation of this material. It was thought that the addition of 5% ground shingles, which had a maximum size of 4.75mm (Figure 3.3), would result in a modification of the gradation and make it similar to RCA2. This should reduce the permeability of the limestone to a value within the range obtained for RCA2 (Figure 4.24). To examine this hypothesis, the permeability of crushed limestone mixed with 5% sand (passing 4.75mm sieve) was tested and found to be very close to that of the crushed limestone with 5% shingles (Figure 4.24). Hence the reduction in the permeability of limestone with 5% shingles was a result of increasing the sand-size fraction in the material rather than being due to some specific property of the ground shingles.

For riverbed material permeability decreased with increasing shingle content as shown in Figure 4.25. The limestone brought from site (LS2), which contained 64.33% sand and 15.48% fines, exhibited significantly lower permeability than all other materials tested, but permeability improved with the addition of processed shingles (Figure 4.26). Processed shingles contained only 34.47% sand-sized particles whereas ground shingles consisted almost entirely (99.93%) of sand-sized particles. Similarly, the fractions passing the 0.6mm sieve of processed and ground shingles were 6.61% and 27.3%, respectively. The experimental results show that the effect of adding shingles to granular material depended mainly on the size of shingle particles.

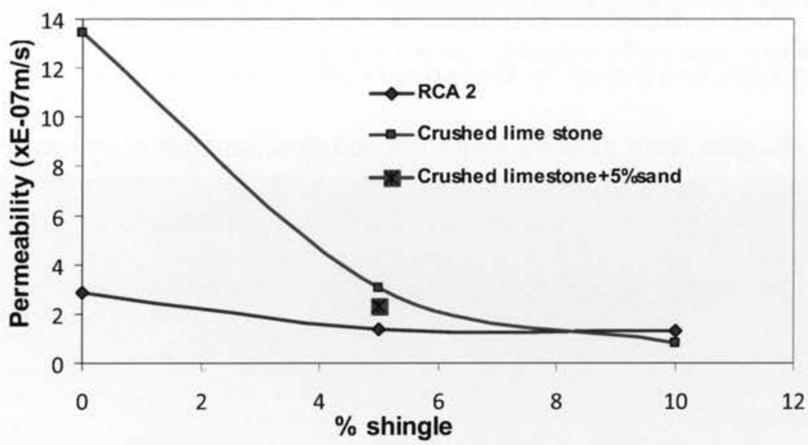

Figure 4.24: Effect of Adding Shingles on Permeability of RCA2 and Limestone (LS1)

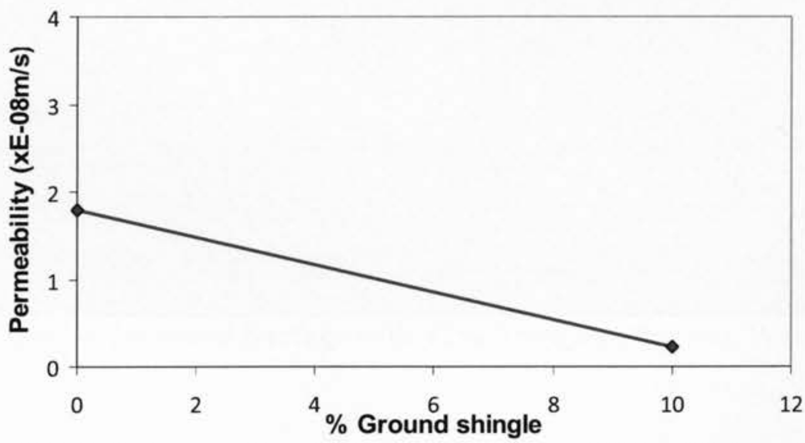

Figure 4.25: Effect of Adding Shingles on Permeability of Natural Gravel

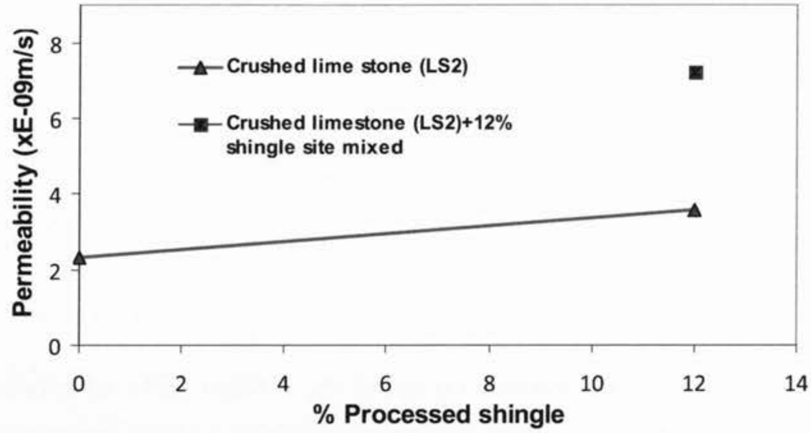

Figure 4.26: Effect of Adding Shingles on Permeability of Limestone (LS2)

4.5 Road Construction and Performance

After the 8-days construction period for the second trial sections, both the control section and the section with 12% shingles were visually inspected and dust generation was measured. The riding surface of the section containing shingles was found to be in better condition compared to the control (Figures 4.27 and Figure 4.28). The shingle section also appeared to be smoother. Figure 4.29 shows that very little dust was generated by trucks in section containing shingles. Dust generated at the two sections was simultaneously collected by the dust suction equipment described in section 3.2.8. Dust was collected for two hours with an air-suction rate of 30 cubic feet per minute. At the control section 40mg of dust was collected, whereas only 20mg was collected at the shingle section.

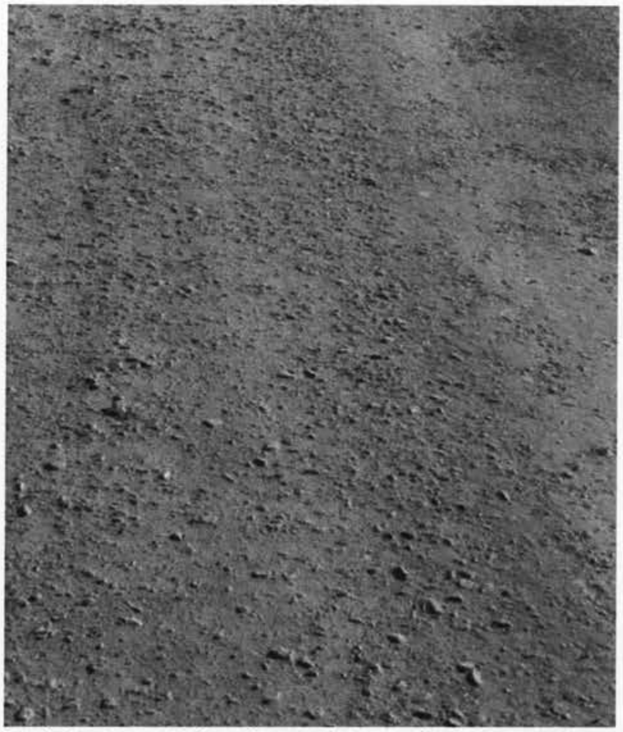
Figure 4.27: Road Surface without Shingles after one Week


Figure 4.28: Road Surface with 12% Shingles after one Week

Figure 4.29: No Generation of Dust under Moving Truck (12% Shingles) after one Week

Figure 4.30: Road Surface without Shingles after six months

Figure 4.31: Road Surface with 12% Shingles after six months

After six months, on 19 April, 2009, both sections were inspected. Hardly any differences were visible between the two sections (figures 4.30 and 4.31), but the control section had experienced more erosion due to water (figure 4.30 and 4.31). After six months, both sections were in need of maintenance.

4.6 Shingles in Dense Graded Hot Mix Asphalt

4.6.1 Mix Properties

Table 4.6 shows the specific mix characteristics of the samples tested in terms of MRD, BRD and air voids. Optimum binder content of the control mix and mix with shingles (3%) were 4.55% and 3.68% respectively. When 3% shingles were added, the optimum binder content was decreased by 0.87%. The mineral filler contained and asphalt contents of the shingles may have reduced the voids, thereby saving binder content. The values listed in Table 4.9 are the averages of two specimens each.

Table 4.9: Mix Properties

	Asphalt Added	BRD (N_{des})	MRD (N_{des})	Air Voids (N_{des})	Compaction (N_{in})	Compaction (N_{fin})
Control	4.55 %	2.512	2.6163	3.97%	88.09%	97.00%
With shingles	3.68 %	2.494	2.6015	4.13%	88.00%	97.06%

4.6.2 Resistance of Compacted HMA to Moisture-Induced Damage

The indirect tensile strengths of the control mixture were 604.08 and 573.30kPa for the dry and conditioned specimens, respectively. For the shingle mixture the indirect tensile strength of the dry and conditioned specimens was 764.9 and 702.8kPa, respectively, as shown in Figure 4.31. The tensile-strength ratio of the control mixture and the mixture with shingles were 94.9% and 91.9%, respectively So the tensile-strength ratio of both mixtures were similar but there is an increase in the tensile strength when shingles were used (Figure 4.32).

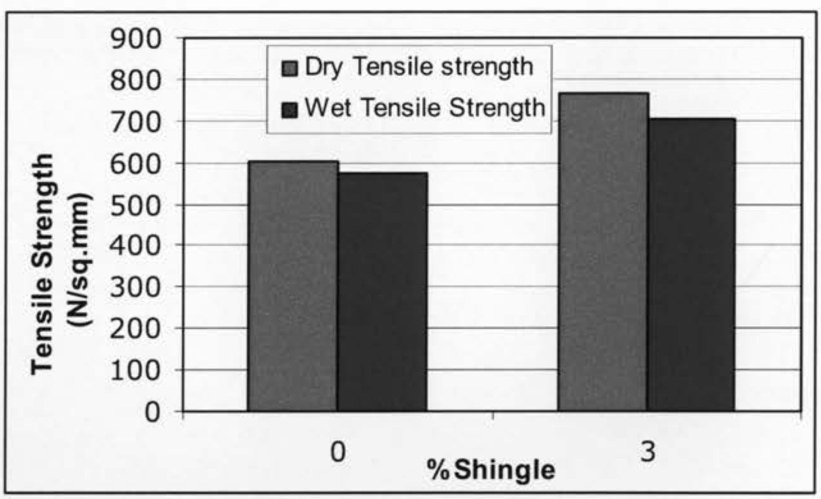

Figure 4.32: Tensile Strength of Control Mixture and Mixture with Shingles

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

The results presented here confirms the feasibility of using tear-off shingles to enhance the performance of granular materials used as road base/subbase or as surface course for unpaved roads. Within the range of materials investigated, the following specific conclusions are drawn:

(1) The effects of shingles on the stability of granular materials depend on material properties, including angularity and fines contents, and the amount of shingles added. In general, shingles were effective in enhancing the stability of granular materials with relatively low CBR (< 80%). Also, the optimum amount of shingles depended on the fines content of the granular material: the higher the fines content, the higher the optimum shingle percentage.

(2) For granular materials with high CBR (above 100%), the addition of shingles was found to have no positive effects, and in some cases negative effects, on the stability as determined by CBR.

(3) Stability of the sand tested in this study decreased with the addition of shingles. Although, the gradations of the two types of sands were significantly different, the effects of shingle addition were similar. This may be attributable to the angular nature of the tested sand, as the shingles reduce the friction between sand particles and hence stability.

(4) The drainage characteristics of the tested granular materials were not significantly affected by the addition of shingles. The drainage effects of shingles in granular material depend on grain size of the shingle particles. It was found that addition of processed shingles was beneficial for granular material with high portions of sand and fines.

(5) The indirect tensile strength of granular material containing shingles was greater than that of the control. This indicates that the addition of shingles to crushed limestone was beneficial regarding any distress mode that created tensile stresses, i.e. freezing or repetitive truck loading.

(6) The test results showed that the addition of shingles to granular material or fine sand enhanced freeze-and-thaw durability.

(7) The short-term beneficial effects of adding shingles to gravel roads were obvious. However no noticeable longer-term effects of shingle additions were found.

(8) The use of shingles in HMA mixtures was found to enhance their tensile strength. The tensile strength ratios of the control mix and the mix with shingles were nearly identical, indicating that the addition of shingles reduced moisture-induced damage. The addition of 3% shingles reduced the binder contents by 0.87%, which provides economic advantages.

Both the literature review and the research presented here indicate that our knowledge of shingle use in road bases or in HMA is still incomplete. The following list of suggestions for further research regarding gravel roads aims at improving this body of knowledge.

1. The road selected for this research was very busy with most of the traffic consisting of heavy trucks. This may be a major reason why the benefits of adding shingles were perhaps overwhelmed by the excessive traffic. It would be useful to conduct field trials with roads of different traffic loads.

2. An alternative mix procedure may prove beneficial. Gravel mixed with shingles should be compacted on the road surface. Then a mixture of emulsion and water should be applied over the

shingle mixture. As the shingles are already coated with asphalt, less emulsion would probably be required than with the mix procedure used here.

3. A base course of adequate strength should be made. Then a thin layer of shingles should be spread on the gravel surface and compacted. This approach may reduce dust generation thereby reducing maintenance of road.

4. Hydrocarbon distillates, such as asphalt, bitumen and tar, may be used to rejuvenate the asphalt contained in the shredded roofing shingle (similar to Pavelak and Michael (1996)). This would help with the extraction of the binder from the shingles.

5. Supplementary cementing materials, e.g., high-calcium fly ash, may be used to increase the stability of shingle mixes.

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APPENDIX

CBR values at OMC of the Granular Materials with Processed Shingles

Granular material	Shingle							
	0%	3%	5%	8%	10%	12%	15%	20%
RCA1	58.3	57.4		69.7	61.8		46.9	
RCA2	101.2		102.2		70.2			
Limestone1	136.8		83.8		66.7		133	124.8
Limestone2	126.5					128.5	132.7	98.1

CBR values at OMC of the Granular Materials with Ground Shingles

Granular material	Shingle							
	0%	3%	5%	8%	10%	12%	15%	20%
RCA1	57.9		81.2		73.6			
RCA2	101.2		111.1		88.9			
RCA3	128.8	106.6	96.6	90.4	85.1			
Limestone1	136.8	93.5	78.7	73.4	62.4		42.6	
Limestone2	126.5			116.8				
Natural Gravel	122.2	123.5	127.6	88.7	82.5			
Finesand(S1)	46.1		31.8		20.4		15.8	23.3
Finesand(S2)	44.4			25.8				

CBR values at OMC of RCA1 with Processed Shingles

Shingle (%)	CBR at OMC (%)	CBR %
0	55.6	58.3
0	61.1	
3	59.2	57.4
3	55.5	
8	70.4	69.7
8	69.1	
10	61.5	61.8
10	62.0	
15	47.6	46.9
15	46.2	

CBR values at OMC of RCA1 with Ground Shingle

Shingle (%)	CBR at OMC (%)	Average CBR%
0	58.3	57.9
0	57.4	
5	76.7	81.2
5	85.7	
10	77.8	73.6
10	69.4	

CBR value at OMC of RCA2 with Processed Shingles

Shingle (%)	CBR %
0	101.2
5	102.2
10	70.2

CBR values at OMC of RCA2 with Ground Shingles

Shingle (%)	CBR at OMC (%)	CBR % with 24 hr. heat and curing 15 days	CBR after 12 cycle Freeze and Thaw	CBR after 12 cycle Freeze and Thaw	CBR after 12 cycle Freeze and Thaw	Soaked CBR % after 96 hrs.
0	101.2	194.4		88.9	85.4	114.0
0				81.9		
5	111.1	215.7				
8				81.5	79.6	
8				77.8		102.3
10	88.9	153.8				

CBR values following 15 days curing in air of RCA2 with Ground Shingles

Shingle (%)	CBR %	Average CBR%
0	222.2	194.4
0	166.7	
5	198.1	215.7
5	233.3	
10	166.7	153.8
10	140.9	

CBR value at OMC of RCA3 with Ground Shingles

Shingle (%)	CBR % at OMC	Average CBR % at OMC	CBR % 3 days air curing without heat	Average CBR %	CBR % 3 days air curing with 4 hrs. heat	Average CBR%
0	140.4	128.8	140.0	152.6	198.1	214.9
0	117.2		165.2		231.7	
3	97.5	106.6	145.0	168.3	164.2	174.6
3	115.8		191.7		185.0	
5	98.9	96.6	133.3	139.0	122.2	127.6
5	94.3		144.7		133.0	
8	87.0	90.4	109.6	109.0	112.0	111.8
8	93.8		108.3		111.7	
10	84.9	85.1	125.4	121.9	106.7	118.7
10	85.3		118.5		130.8	

CBR values at OMC of LS1 with Ground Shingles

Shingle (%)	CBR % at OMC	Average CBR % at OMC	Soaked CBR (96 hrs.)	Average Soaked CBR % (96 hrs.)	CBR % after 12 cycle Freeze and Thaw	CBR % after 12 cycle Freeze and Thaw
0	142.2	136.8	139.4	139.3	111.1	102.4
0	131.4		139.2		93.7	
3	93.5	93.5				
3	93.5					
5	83.0	78.7	83.0	75.9	71.8	71.5
5	74.3		68.8		71.1	
8	75.1	73.4				
8	71.7					
10	68.2	62.3				
10	58.5					
10	60.3					
15	5.8	42.6				

CBR values at OMC of LS1 with Processed Shingles

Shingle (%)	Optimum Moisture Content	Max dry density (Kg/cum)	CBR %
0	5.9	2260.3	136.8
5	5.6	2169.4	83.8
10	5.9	2126.6	66.7

CBR values at OMC of Natural Gravel with Ground Shingles

Shingle (%)	CBR % at OMC	Average CBR%
0	127.7	122.2
0	116.7	
3	111.1	123.5
3	135.9	
5	121.9	127.6
5	133.3	
8	77.4	88.7
8	100.0	
10	81.7	82.5
10	83.3	

CBR value at OMC of LS2 with Ground Shingles

Shingle (%)	CBR % at OMC	Average CBR % at OMC	Soaked CBR %	Average Soaked CBR %
0	129.9	126.5	120.0	117.0
0	123.1		115.5	
8	114.5	116.8		
8	119.0			
15	122.2	133.0	99.0	122.0
15	143.7		125.0	
20	125.0	124.8	77.0	
20	124.6		83.0	80.0

CBR values at OMC of LS2 with Processed Shingles

Shingle (%)	CBR % at OMC	Average CBR % at OMC	Soaked CBR %	Average Soaked CBR %	CBR % after 12 cycle Freeze and Thaw	CBR % after 12 cycle Freeze and Thaw
0	129.9	126.5	120	117.8	77.7	87.3
0	123.1		115.5		96.9	
12	128.5	128.5	118	118.0	40.7	46.3
12	128.5				51.8	
15	130.6	132.7	94	102.0		
15	134.9		107			
20	96.3	98.2				
20	100.0		75	75.0		
12% site mix	91.5	91.5	86.8	86.8	30.6	30.8
12% site mix					34.3	
12% site mix					27.4	

CBR values at OMC of Fine Sand with Ground Shingles

Shingle (%)	CBR % Fine Sand (S2)	CBR % Fine Sand (S1)	Average CBR % of Fine Sand (S1)
0	44.4	47.5	46.1
0		44.6	
5		28.8	31.8
5		34.8	
8	25.8		
8			
10		21.7	20.4
10		19.0	
15		19.7	15.8
15		13.7	
20		23.8	23.3
20		22.9	

Sieve Analysis of Granular Materials

Sieve Designation		Cumulative percent passing					
Traditional	Metric	RCA1	RCA2	RCA3	Limestone (LS1)	Limestone (LS2)	Natural Gravel
3 in	75 mm						
2.5 in	63 mm						
2 in	50 mm						
1 in	25 mm	0.0	100.0	100.0	100.0	100.0	100.0
7/8 in	22.4 mm		100.0		100.0		99.3
3/4 in	19 mm	95.8	97.2	96.3	99.1	99.3	95.7
5/8 in	16 mm		91.9		94.4	97.8	87.7
1/2 in	12.5 mm	76.5	83.2	75.7	83.9	93.1	78.7
3/8 in	9.5 mm	64.6	71.6	62.9	70.6	85.7	70.2
No. 4	4.75 mm	48.1	51.0	45.2	44.6	64.3	54.3
No. 8	2.36 mm	37.3	40.7	34.0	26.6	45.0	44.2
No. 16	1.18 mm	29.4	32.2	25.9	19.4	33.0	35.1
No. 20	841 micron		28.8	21.9	15.8		31.1
No. 30	600 micron	22.0	23.6	20.7	13.3	25.3	26.5
No. 40	420 micron		17.3		11.8		19.9
No. 50	300 micron	14.9	13.5	13.7	10.7	21.5	15.9
No. 60	250 micron		13.5				15.1
No. 100	150 micron	10.1	7.5	9.8	9.3	17.2	10.5
No. 200	75 micron	7.8	5.1	4.0	8.6	15.5	7.8

Sieve Analysis of Fine Sand

Sieve Designation		Cumulative percent passing	
Trdditional	Metric	Fine sand (S2)	Fine sand (S1)
No. 4	4.75 mm		
No. 8	2.36 mm	99.3	
No. 16	1.18 mm	64.9	100.0
No. 20	841 micron		
No. 30	600 micron	50.0	99.9
No. 40	420 micron		
No. 50	300 micron	31.1	97.9
No. 60	250 micron		
No. 100	150 micron	17.0	78.0
No. 200	75 micron	11.6	8.3

Sieve Analysis of Shingles

Sieve designation		Cumulative percent passing	
Traditional	Metric	Processed Shingle	Ground Shingle
3 in	75 mm	78.6	
2.5 in	63 mm	78.6	
2 in	50 mm	72.7	
1 in	25 mm	72.1	
7/8 in	22.4 mm	72.0	
3/4 in	19 mm	71.1	
5/8 in	16 mm	70.8	
1/2 in	12.5 mm	69.6	
3/8 in	9.5 mm	45.1	
No. 4	4.75 mm	34.5	99.9
No. 8	2.36 mm	27.2	86.4
No. 16	1.18 mm	16.6	57.2
No. 20	841 micron	10.8	39.0
No. 30	600 micron	6.6	27.3
No. 40	420 micron	4.2	
No. 50	300 micron	2.5	12.4
No. 60	250 micron		
No. 100	150 micron	0.2	4.0
No. 200	75 micron	0.2	1.0

Permeability of Different Materials at 23°C

With:	RCA2 (10^{-07}m/s)	LS1 (10^{-07}m/s)	LS2 (10^{-09}m/s)	LS1 with 5% Sand (10^{-07}m/s)	Natural Gravel (10^{-08}m/s)
0 % shingles	2.89	13.45	2.299	13.45	1.79
5% shingles	1.36	3.07		2.29	
10% shingles	1.28	0.839			0.225
12% shingles			3.558		
5% sand					
12% shingles mixed at site			7.2169		

CBR data at OMC of RCA1 with Ground Shingles

Deformation (in.)	Load (lb)			
	5% shingles	5% shingles	10% shingles	10% shingles
0.015	70	80	100	50
0.025	140	150	220	130
0.035	250		350	240
0.05	470	520	600	440
0.065	720	800	850	680
0.075	880	1000	1060	
0.08				900
0.085	1080	1230	1240	
0.1	1340	1590	1550	1180
0.125	1840	2170	2030	1590
0.15	2290	2690	2430	1970
0.175	2720	3200	2850	2350
0.2	3150	3690	3250	2740
0.225	3530	4140	3660	3120
0.25	3920	4540	3990	3440
0.275	4320	4900	4300	3760
0.3	4660	5310	4470	4080
0.35	5320	6140	5010	
0.375				4940

CBR data at OMC of RCA1 with Processed Shingles

Deformation (in.)	Load (lb)									
	0% shingles		3% shingles		8% shingles		10% shingles		15% shingles	
0.025	0	20	0	10	50	20	60	160	60	70
0.05	30	70	20	30	160	80	230	380	200	230
0.075	100	140	40	70	420	250	500	660	420	440
0.1	180	240	90	150	770	550	880	1010	670	650
0.125	330	380	180	290	1170	940	1230	1350	940	890
0.15	540	580	310	470	1560	1330	1570	1700	1210	1160
0.175	740	790	470	700	1990	1720	1920	2080	1470	1420
0.2	1020	1040	690	980	2380	2140	2230	2420	1710	1670
0.25		1740	1240	1630	3120	2870	2810	3130	2210	2170
0.3	2320	2360	1890	2320	3750	3560	3320	3720	2650	2610
0.4	3650	3920	3290	3670	4860	4710	4210	4720	3480	3360
0.44										
0.5	5020	5590	4570	4870	5870	5670	5060	5490	4190	4210

CBR data at OMC of RCA2 with Processed Shingles

Deformation (in.)	Load (lb)	
	5% shingles	10% shingles
0.025	140	200
0.05	490	560
0.075	960	1000
0.1	1580	1440
0.125	2310	1860
0.15	2980	
0.155		2360
0.175	3610	
0.18		2760
0.2	4280	3030
0.22		
0.225	4860	3370
0.25	5410	3700
0.275	6000	3990
0.3	6550	4250
0.36		4880
0.4		5250
0.425		5500

CBR data following 15 days curing in air of RCA2 with Ground Shingle

Deformation (in.)	Load (lb)					
	0% shingles		5% shingles		10% shingles	
0.015		680	470	200	440	
0.025	790	1090	930	340	770	320
0.035		1470			1210	700
0.05	2340	2130	2390	1280	2000	1270
0.065		2910		2480	2880	1900
0.075	4150	3530	4040	3610	3370	2360
0.09				4970	4140	3040
0.1	6000	4980	5570	5790	4600	3450
0.115	7040	5840		7110	5230	
0.125		6450	6900		5670	4480
0.14		7540				
0.15					6620	5380
0.175						6260
0.2						7050

CBR data at OMC of RCA2 with Ground Shingles

Deformation (in.)	Load (lb)		
	0% shingles	5% shingles	10% shingles
0.025	50	340	390
0.05		850	880
0.055	170		
0.075	350	1530	1450
0.1	630	2260	2020
0.125	1020	2960	2550
0.15	1490	3540	3040
0.175			3530
0.18	2150	4250	
0.2	2600	4720	3930
0.225	3180	5330	4340
0.25	3800	5780	4730
0.275	4510	6190	5070
0.3	5180	6540	5370
0.31			
0.32		6800	
0.35	6550		5950
0.4			6450

CBR data at OMC of RCA3 with Ground Shingle

Deformation (in.)	Load (lb)									
	0% shingles		3% shingles		5% shingles		8% shingles		10% shingles	
0.015	180	100	120	200	200	170	140	200	240	230
0.025	350	210	250	370	350	330	300	380	450	420
0.035	560	340	430	620	560	500	470	580	650	630
0.05	960	640	700	1030	880	820	700	910	950	930
0.065	1380	980	1020	1450	1160	1120	980	1270	1260	1250
0.075	1760	1260	1250	1760	1440	1350	1160	1530	1460	1480
0.09	2320	1720	1630	2200	1840	1720	1490	1930	1840	1800
0.1	2710	2030	1890	2510	2090	1970	1720	2200	2030	2030
0.115	3280	2480	2240	2940	2450	2310	2050	2550	2370	2350
0.125	3660	2760	2470	3160	2690	2530	2270	2770	2530	2550
0.135	4050	3080	2740	3460	2950	2770	2460	3000	2700	2750
0.15	4600	3600	3100	3890	3350	3120	2820	3270	2970	3060
0.175	5400	4400	3750	4490	3930	3660	3370	3780	3430	3500
0.2	6150	5130	4250	5210	4450	4190	3830	4190	3820	3840
0.212		5500			4960	4750				4080
0.225	7060		4800		5370		4320	4550	4140	
0.23						4850				
0.25			5280		5770		4740		4500	
0.275			5780		6230		5080		4810	
0.3			6210				5470		5070	
0.325			6710						5390	

CBR data of RCA3 with Ground Shingles following exposure to air for 15 days without heat treatment

Deformation (in.)	Load (lb)									
	0% shingles		3% shingles		5% shingles		8% shingles		10% shingles	
0.015	380	370	540	660	1010	410	180	100	490	90
0.025	620	600	970	1310	1310	850	250	190	950	220
0.035	920	930	1430	2000	1700	1340	420	320	1410	470
0.05	1480	1570	2120	2970	2240	1990	800	550	2030	910
0.065	2080	2280	2760	4000	2810	2660	1360	990	2650	1480
0.075	2570	2790	3200	4540	3190	3130	1740	1320	2950	1900
0.09	3340	3600	3820	5250	3690	3810	2320	1860	3410	2510
0.1	3810	4260	4250	5650		4210	2640	2220	3670	2880
0.105					4180					
0.115	4520	5080	4730	6260	4460	4820	3110	2780	4080	3430
0.125	5000	5610	5040	6590	4750	5200	3420	3100	4320	3720
0.135	5480	6120	5370	6970	5080	5560	3710	3440	4620	4050
0.15	6270	7060	5780		5520	6050	4190	3860	4980	4480
0.16			6070		5900		4610	4110	5180	4790
0.175	7250		6460		6150		4850	4520	5480	5140
0.2							5470	5190	5960	5780
0.225							6090	5750	6360	6390

CBR data of RCA3 with Ground Shingles following exposure to air for 7 days with 4 hours of heat treatment

Deformation (in.)	Load (lb)									
	0% shingles		3% shingles		5% shingles		8% shingles		10% shingles	
0.015	160	260	110	330	310	360	370	490	420	290
0.025	380	620	230	730	490	660	620	780	760	640
0.035	710	1200	420	1470	790	1060	940	1140	1090	1120
0.05	1420	2330	990	2190	1410	1680	1450	1670	1560	1760
0.065	2290	3710	1740	3060	2020	2450	2080	2170	2060	2360
0.075	2930	4560	2280	3690	2480	2900	2490	2490	2430	2740
0.09	4020	5710	3170	4720	3220	3580	3050	3000	2870	3380
0.1	4710	6510	3750	5290	3660	3990	3360	3350	3200	3770
0.105		6950								
0.115	5560		4520	6090	4310	4530	3960	3820	3660	4260
0.125	6280		4960	6660	4740	4890	4280	4090	3930	4610
0.13				7070						
0.135	6950		5370		5130	5320	4620	4340	4220	4960
0.143					5330					
0.15			5730				5040	4710	4640	5440
0.165										6010
0.175							5660	5250	5210	
0.19							6010	5760		

CBR data at OMC of LS1 with Processed Shingles

Deformation (in)	Load (lb)	
	5% shingles	10% shingles
0.025	350	230
0.05	820	590
0.075	1400	1010
0.1	1870	1410
0.125	2350	1780
0.15	2770	2210
0.175	3230	2560
0.2	3680	2910
0.225	4180	3220
0.25	4590	3580
0.275	5020	3890
0.3	5430	4230
0.35	6270	4820
0.4	6840	5350

CBR data at OMC of LS1 with Ground Shingles

Deformation (in)	Load (lb)											
	0% shingles		3% shingles		5% shingles		8% shingles		10% shingles			15% shingles
0.025	80	50	20	10	20	20	20	20	10	20	20	10
0.05	340	300	60	30	60	80	70	100	40	50	60	40
0.075	830	800	180	100	140	170	190	260	100	140	120	70
0.1	1490	1500	380	190	300	320	360	530	190	290	260	150
0.125	2190	2180	650	360	550	550	660	870	340	520	520	270
0.15	3050	2970	1040	640	860	820	1010	1240	540	780	650	390
0.175	3880	3800	1480	940	1230	1140	1400	1700	810	1080	920	590
0.2	4820	4460	1900	1350	1650	1520	1840	2150	1090	1400	1240	800
0.225									1430	1710	1570	1040
0.25	6500	6110	2980	2360	2590	2380	2730	3050	1810	2040	1900	1280
0.275									2220	2410	2280	1520
0.28	7670										2640	1780
0.3		7600	3970	3450	3540	3360	3580	3840	2620	2760	3380	2830
0.35									3410	3510	4060	
0.4			6060	5810	5570	5540	5080	5440	4170	4290		
0.42											4310	
0.425				6390								
0.43			6690							4640		
0.44					6430							
0.445									4870			
0.46						6900						
0.49							6420					
0.5												3820

CBR data at OMC of Natural Gravel with Ground Shingles

Deformation (in)	Load (lb)									
	0% shingles		3% shingles		5% shingles		8% shingles		10% shingles	
0.015	30	10	30	120	310	360	80	120	140	150
0.025	80	40		270	490	660	180	260	270	320
0.035	130	130	240	530	790	1060	320	500	440	500
0.05	270	230	510	1030	1410	1680	540	900	750	910
0.065	470	430	870	1640	2020	2450	810	1400	1070	1320
0.075	650	600	1180	2090	2480	2900	1040	1780	1320	1650
0.09	1040	970	1720	2880	3220	3580	1400	2390	1740	2150
0.1	1410	1340	2120	3330	3660	3990	1650	2780	1940	2450
0.115	2040	1940	2690	3980	4310	4530	2040	3370	2320	2910
0.125	2460	2400	3030	4370	4740	4890	2290	3730	2520	3210
0.135			3530	4790	5130	5320				
0.143					5330					
0.15	3970	3570	4000	5360			2880	4620	3070	3970
0.175	5330	5020	5110	6620			3540	5500	3680	4660
0.195	6900	6310								
0.2			5970	7530			4120	6190	4220	5230
0.215		7210								
0.225			6830				4680		4770	5790
0.24										6040
0.25			7730				5270		5310	
0.3							6210		6380	
0.321							6350			

CBR data at OMC of LS2 with Ground Shingles

Deformation (in)	Load (lb)							
	0% shingles		8% shingles		15% shingles		20% shingles	
0.015	10	10	30	20	300	310	290	260
0.025	20	20	60	50	610	590	610	550
0.035	40	40	100	70	960	960	1000	870
0.05	60	60	210	120	1510	1560	1550	1410
0.065	110	110	340	200	2120	2240	2190	1930
0.075	170	150	460	290	2480	2750	2580	2340
0.09	270	230	700	580	2970	3400	3110	2890
0.1	360	300	900	830	3260	3770	3400	3220
0.115	520	420	1210	1070	3670	4290	3810	3640
0.125	670	540	1410	1270	3930	4600	4060	3910
0.135	860		1660	1660	4200	4890	4310	4180
0.14		740						
0.15	1150	890	2060	2360	4500	5340	4630	4550
0.175	1780	1360	2790	3160	4990	5930	5100	5090
0.2	2560	1980	3550	3940	5440	6400	5520	5490
0.225	3470	2730	4340	4780	5820	6870	5880	5920
0.24						7120		
0.25	4400	3530	5100	5630	6200	7280	6180	6310
0.275	5480	4590	5770	6400	6640		6520	6680
0.3	6470	5680	6500		6900		6880	
0.31	6850							
0.32		6750	7010	7010				

CBR data of Limestone LS2 in addition of Processed Shingle at OMC

Deformation (in.)	Load (lb)									
	8% shingles		12% shingles		15% shingles		20% shingles		Shingles mixed at site	
0.015	40	40	50	50	120	110	100	90	170	120
0.025	100	90	140	150	170	250	220	210	330	200
0.035	160	160	260	270	340	430	400	370	530	360
0.05	330	360	490	510	690	810	730	670	860	650
0.065	580	660	830	850	1110	1260	1120	1040	1210	980
0.075	780	880	1060	1120	1420	1610	1390		1450	1200
0.08								1480		
0.09	1250	1370	1550	1590	1980	2270	1790	1800	1830	1580
0.1	1580	1780	1880	1960	2380	2620	2070	2110	2070	1830
0.115	2100	2540	2360	2450	2970	3220	2460	2540	2450	2210
0.125	2480	3040	2700	2770	3320	3570	2680	2770	2680	2450
0.135	2860	3490	3030	3110	3630	3940	2920	3010	2890	2720
0.15	3500	4230	3520	3590	4120	4410	3220	3340	3180	3050
0.165									3450	3360
0.175	4480	5530	4350	4370	4880	5150	3690	3880	3620	3560
0.19									3910	3800
0.2	5410	6640	5020	5030	5480	5660	4130	4290	4080	3990
0.225	6430	7500	5640	5620	6010	6210	4490	4670	4450	4410
0.25	7290		6210	6290	6540	6720	4810	4980	4770	4790
0.265					6840					
0.27			6630							
0.275			6740	6800			5100	5220	5110	5120
0.3							5350	5490	5420	5450
0.32							5580	5760	5700	5730
0.35							5820	6040	6000	6010
0.375							6040	6330	6270	6250
0.4									6520	6520

CBR data of Soaked LS2 with Processed Shingles

Deformation (in.)	Load (lb)					
	0% shingles		12% shingles	15% shingles		20% shingles
0.015	10	0	100	80	50	40
0.025	20	10	240	160	130	110
0.035	30	20	430	310	220	180
0.05	60	40	760	650	430	380
0.065	100	80	1270	1070	700	630
0.075	140	110	1640	1370	950	850
0.09	210	170	2230	1790	1370	1160
0.1				2040	1700	1350
0.105	310	220	2610			
0.115	410	320	3080	2410	2140	1630
0.125	540	420		2650	2440	1840
0.13			3530			
0.135	670		3720	2850	2680	2010
0.15	890	720	4110	3130	3080	2270
0.175	1370	1120	4680	3500	3670	2660
0.2	1990	1700	5170	3800	4130	2990
0.225	2640	2330	5650	4080	4550	3300
0.25	3360	3050	6000	4300	4910	3580
0.275	4160	3940	6320	4510	5190	3820
0.3	4910	4750	6640	4700	5460	4060
0.325	5770	5550		4890	5750	4280
0.35	6700	6530		5040	6020	4500
0.36		6850				
0.375				5210	6280	4700
0.4					6510	4880
0.405				5370		
0.45				5650		5250
0.475				5810		5410
0.5				5940		5570

CBR data of Soaked LS2 with Ground Shingles

Deformation (in.)	Load (lb)			
	15% shingles		20% shingles	
0.015	50	20	60	130
0.025	130	50	190	310
0.035	220	80	360	560
0.05	500	170	700	940
0.065	840	290	1080	1340
0.075	1150	430	1330	1570
0.09	1660	670	1710	1940
0.1	1960	880	1950	2130
0.115	2450	1190	2290	2380
0.125	2800	1450	2470	2540
0.135	3150	1720	2630	2680
0.15	3630	2090	2890	2880
0.175	4300	2670	3230	3170
0.2	4930	3300	3510	3400
0.225	5460	3820	3760	3620
0.25	5910	4270	3990	3830
0.275	6320	4700	4190	4010
0.3	6730	5120	4360	4230
0.325		5490	4570	4420
0.35		5850	4730	4600
0.375		6200	4890	4760
0.4		6530	5080	4940
0.425			5230	5100
0.45			5400	5260
0.475			5620	5410

CBR data following 12 freeze-and-thaw cycles of LS1 with Ground Shingles

Deformation (in.)	Load (lb)			
	0% shingles	0% shingles	5% shingles	5% shingles
0.015	20	0	0	0
0.025	50	10	10	10
0.035	80	30	20	20
0.05	150	50	30	30
0.065	300	110	60	40
0.075	400	140	70	60
0.09	570	220	120	90
0.1	730	290	150	110
0.115	1050	410	230	160
0.125	1260	520	270	190
0.135	1560	640	350	240
0.15	1930	850	470	350
0.175	2500	1270	730	560
0.2	3020	1770	1080	810
0.225	3790	2370	1460	1140
0.25	4550	3000	1910	1520
0.275	5220	3650	2340	1960
0.3	5900	4260	2810	2380
0.325	6750	4890	3290	2850
0.35		5440	3710	3470
0.375		6020	4150	3850
0.395		6660		
0.4			4580	4420
0.425			5000	4910
0.45			5420	5530
0.475			5760	5990
0.5			6120	6400
0.525			6460	

CBR data following 12 freeze-and-thaw cycles of RCA2 with Ground Shingles

Deformation (in.)	Load (lb)			
	0% shingles		8% shingles	
0.015	10	10	30	0
0.025	10	20	50	20
0.035	20	30	80	30
0.05	40	50	110	50
0.065	60	70	140	80
0.075	80	90	190	110
0.09	120	130	270	170
0.1	150	170	350	220
0.115	220	220	470	300
0.125	260	270	610	400
0.135	310	310	730	500
0.15	430	400	1050	650
0.175	620	600	1460	990
0.2	920	890	1890	1420
0.225	1340	1210	2390	1890
0.25	1790	1610	2880	2390
0.275	2350	2060	3300	2910
0.3	2920	2560	3750	3400
0.325	3500	3120	4170	3820
0.35	4080	3670	4580	4260
0.375	4770	4280	4980	4700
0.4	5380	4880	5380	5110
0.425	6020	5390	5750	5460
0.45	6670	5980	6060	5840
0.475		6450	6400	6190
0.5				6500

CBR data following 12 freeze-and-thaw cycles of LS2 with Processed Shingles

Deformation (in.)	Load (lb)							
	0% shingles		12% shingles mixed at site				12% shingles (lab mixed)	
0.015	0	0	0	10	0	0	0	10
0.025	0	0	10	10	10	0	0	30
0.035	10	10	10	10	10	10	0	40
0.05	10	10	20	20	10	10	0	40
0.065	10	20	20	30	20	20	10	70
0.075	20	20	30	30	30	20	20	70
0.09	30	30	40	40	40	30	30	100
0.1	40	50	40	60	40	40	40	120
0.115	50	80	50	90	60	50	50	170
0.125	50	130	70		70	60	50	200
0.135	70	220	70		70	70	70	
0.15	80	370	100	140	110	90	90	290
0.165					130	100	110	370
0.175	120	590	160	200	150	110	130	430
0.19					190	150	160	520
0.2	170	940	220	300	210	170	190	600
0.225	260	1380	320	440	290	230	260	790
0.25	370	1900	460	600	390	320	360	1030
0.275	520	2520	620	800	500	420	480	1330
0.3	740	3170	780	990	610	540	650	1610
0.325	990	3800	970	1200	750	680	810	1930
0.35	1320	4520	1150	1420	870	830	1020	2260
0.375	1710	5180	1350	1610	980	1020	1250	2600
0.4	2100	5830	1500	1780	1080	1180	1500	2910
0.425	2590	6390	1640	1950	1190	1370	1880	3260
0.45	3100	6660	1800	2090	1280	1550	2050	3560
0.475	3590		1950	2230	1370	1700	2260	3810
0.5	4340		2060	2360	1450	1850	2500	4090
0.53	4740		2180	2470	1520	2010	2750	4320
0.55	5150		2290	2650	1610	2160	3030	4530
0.575	5640		2450	2690	1690	2280	3270	4780
0.6	6110		2490	2790	1750	2410	3490	5020
0.625	6590		2590	2890	1830	2550	3740	5250
0.65			2690	2980	1900	2670	3990	5460
0.675					1960	2790	4330	5700
0.685			2830	3080				
0.7			2900	3160	2030	2900	4460	5960
0.725			3000	3250	2100	3010	4680	6200
0.75			3100	3320	2170	3150	4890	6390
0.775			3190	3390	2220	3260	5080	
0.8			3290	3490	2300	3360	5290	
0.825			3380	3580	2390	3470	5500	
0.85			3450	3670	2450	3570		
0.875			3550	3770	2520	3670		
0.9				3880	2600	3770		
0.925				3980	2660	3880		
0.95				4080				

CBR data at OMC of Fine Sand S1 with Ground Shingles

Deformation (in.)	Load (lb)									
	0% shingles	0% shingles	5% shingles	5% shingles	10% shingles	10% shingles	15% shingles	15% shingles	20% shingles	20% shingles
0.015	80	80	30	90	30	30	20	10	30	30
0.025	130	130	50	160	50	50	20	20	60	60
0.035	240	220	80	260	80	70	40	30	120	90
0.05	420	360	140	410	110	90	60	50	190	180
0.065	640	550	220	560	170	150	100	80	280	260
0.075	800	700	270	680	210	190	130	100	360	320
0.09	1060	970	370	870	310	260	190	120	460	410
0.1	1220	1130	470	990	360	330	220	150	520	490
0.115	1470	1360	600	1170	450	410	290	190	650	590
0.125	1630	1510	670	1280	520	460	320	220	710	680
0.135	1770	1660	780	1360	580	540	380	250	800	750
0.15	2010	1860	930	1510	680	630	460	310	910	860
0.165			1100	1640			550	370	1030	970
0.175	2160	2120	1160	1690	870	820	590	410	1100	1050
0.19				1690					1190	1160
0.2	1870	2000	1400	1630	1050	1010	750	520	1280	1240
0.225	1730	1510	1580	1530	1220	1190	910	630	1450	1380
0.235				1450						
0.25	1630	1350	1590	1350	1360	1350	1070	770	1610	1560
0.265				1310						
0.275		1230	1490	1290	1490	1480	1210	890	1740	1700
0.3	1070	1180	1310	1270	1510	1550				
0.325	960	1140	1220	1250			1360	1020	1880	
0.335					1360	1410	1500	1140	1960	1850
0.35	900	1110	1180	1250	1330	1300	1620	1250	1970	1960
0.375	880	1090	1160	1200	1310	1220	1710	1360	1910	2090
0.4	880	1040	1150	1090	1300	1160	1680	1490	1790	2140
0.425	920	950	1160	1010	1300	1120	1550	1590	1720	2070
0.45	930	870	1190	990	1310	1100	1500	1660	1710	2010
0.475		850	1220	980	1330	1100	1490	1670	1700	2000
0.5	920	870	1260	980	1360	1090	1490	1620	1710	2010
0.525	730	900	1300	950	1370	1110		1560	1740	2040
0.55		930	1370	880	1370	1120	1530	1530	1780	2070
0.575	720	970	1420	820	1360	1160	1570	1530	1830	2100
0.6	740	990	1490	800	1360	1250	1600	1540	1890	2110
0.625	760	1020	1560	800	1370	1250	1650	1570	1970	2070
0.65	820	1070	1600	830	1410	1300	1700	1600	2040	2000
0.675			1590	860		1360	1750	1630	2110	1960
0.7			1600	900			1820	1670	2160	1940
0.725			1600				1870	1710	2180	1930

CBR data at OMC of Fine Sand S2 with Ground Shingles

Deformation (in.)	Load (lb)	
	0% shingles	0% shingles
0.015	30	10
0.025	50	20
0.035	80	50
0.05	130	70
0.065	210	120
0.075	300	150
0.09	410	220
0.1	510	260
0.115	640	330
0.125	750	390
0.135	860	440
0.15	1010	530
0.175	1320	690
0.2	1600	830
0.225	1880	1000
0.25	2140	1160
0.275	2410	1290
0.3	2660	1450
0.325	2890	1580
0.35	3110	1720
0.375	3300	1850
0.4	3400	1980
0.425	3450	2220
0.45	3400	2360
0.475	3390	2470
0.5	3360	2580
0.525	3370	2700
0.55	3420	2800
0.575	3500	2900
0.6	3600	3080
0.65	3600	3160

Proctor Data for RCA1

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.677	10.931	10.975	10.969	10.96
Mass of mould (kg)	6.202	6.202	6.202	6.202	6.202
Mass of wet soil (kg)	4.475	4.729	4.773	4.767	4.758
Bulk wet density (kg/m^3)	2106.71	2226.29	2247	2244.18	2239.94
Dry density (kg/m^3)	1974.24	2049.80	2048.31	2040.35	2036.31
Dish number	1	2	4	5	6
Mass of wet soil + dish (g)	246	261.9	293.3	305.4	314.1
Mass of dry soil + dish (g)	232.3	243.5	269.9	280.3	288.2
Mass of water (g)	13.7	18.4	23.4	25.1	25.9
Mass of dish (g)	28.2	29.7	28.6	29.1	29.1
Mass of dry soil (g)	204.1	213.8	241.3	251.2	259.1
Water content %	6.71	8.61	9.7	9.99	10

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Proctor Data for RCA1 with 3% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	10.637	10.844	10.91	10.916	10.918	10.917
Mass of mould (kg)	6.202	6.202	6.202	6.202	6.202	6.202
Mass of wet soil (kg)	4.435	4.642	4.708	4.714	4.716	4.715
Bulk wet density (kg/m^3)	2087.88	2185.33	2216.4	2219.23	2220.17	2219.7
Dry density (kg/m^3)	1972.30	2016.36	2025.22	2019.32	2015.40	2012.97
Dish number	1	2	3	4	5	6
Mass of wet soil + dish (g)	252.3	240.5	240.4	244.5	255	273
Mass of Dry soil + dish (g)	239.9	224.1	222.1	225	234.1	250.2
Mass of water (g)	12.4	16.4	18.3	19.5	20.9	22.8
Mass of dish (g)	28.4	28.5	28.3	28	28.3	28.1
Mass of dry soil (g)	211.5	195.6	193.8	197	205.8	222.1
Water content %	5.86	8.38	9.44	9.9	10.16	10.27

Proctor Data for RCA1 with 5% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	10.622	10.755	10.85	10.862	10.857	10.77
Mass of Mould (kg)	6.202	6.202	6.202	6.202	6.202	6.202
Mass of wet soil (kg)	4.42	4.553	4.648	4.66	4.655	4.568
Bulk wet density (kg/m^3)	2080.82	2143.43	2188.16	2193.81	2191.45	2150.5
Dry density (kg/m^3)	1978.96	2011.10	2026.45	2017.67	2000.05	1917.18
Dish number	1	2	3	4	5	6
Mass of wet soil + dish (g)	265.7	251.2	252.6	232.4	233.8	256.6
Mass of dry soil + dish (g)	224.8	219.4	222.2	233.2	215.9	231.8
Mass of water (g)	40.9	31.8	30.4	-0.8	17.9	24.8
Mass of dish (g)	28.9	28	38.5	28.2	27	28
Mass of dry soil (g)	195.9	191.4	183.7	205	188.9	203.8
Water content %	5.147	6.58	7.98	8.73	9.57	12.17

Proctor Data for RCA1 with 8% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	10.569	10.762	10.781	10.724	10.723	10.701
Mass of mould (kg)	6.207	6.207	6.207	6.207	6.207	6.207
Mass of wet soil (kg)	4.362	4.555	4.574	4.517	4.516	4.494
Bulk wet density (kg/m^3)	2053.52	2144.38	2153.32	2126.49	2126.02	2115.66
Dry density (kg/m^3)	1921.15	1966.96	1939.23	1902.73	1904.01	1845.00
Dish number	1	2	3	4	5	6
Mass of wet soil + dish (g)	221.6	211.5	225.1	218.8	260.1	295.2
Mass of dry soil + dish (g)	209.2	196.2	205.3	198.8	235.9	261
Mass of water (g)	12.4	15.3	19.8	20	24.2	34.2
Mass of dish (g)	29.3	26.6	26	28.8	28.3	27.9
Mass of dry soil (g)	179.9	169.6	179.3	170	207.6	233.1
Water content %	6.89	9.02	11.04	11.76	11.66	14.67

Proctor Data for RCA1 with 10% Processed Shingles

Trial No.	1	2	3	4	5	6	7	8
Mass of mould + Granular Material (kg)	10.513	10.706	10.777	10.784	10.738	10.745	10.722	10.669
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.31	4.503	4.574	4.581	4.535	4.542	4.519	4.466
Bulk wet density (kg/m^3)	2029.04	2119.9	2153.32	2156.62	2134.96	2138.26	2127.43	2102.48
Dry density (Kg/m^3)	1898.96	1955.63	1964.35	1963.24	1929.47	1929.32	1908.86	1844.12
Dish number	1	2	3	4	5	6	7	8
Mass of wet soil + dish (g)	226.1	232.8	229.7	234	226.6	235.4	242.9	247.7
Mass of dry soil + dish (g)	213.4	216.9	212	215.6	207.5	215.1	220.8	220.7
Mass of water (g)	12.7	15.9	17.7	18.4	19.1	20.3	22.1	27
Mass of dish (g)	28	27.7	28.1	28.8	28.2	27.6	27.8	28
Mass of dry soil (g)	185.4	189.2	183.9	186.8	179.3	187.5	193	192.7
Water content %	6.85	8.4	9.62	9.85	10.65	10.83	11.45	14.01

Proctor Data for RCA1 with 15% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	10.498	10.68	10.679	10.686	10.626	10.626
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.295	4.477	4.476	4.483	4.423	4.423
Bulk wet density (kg/m^3)	2021.97	2107.66	2107.18	2110.48	2082.23	2082.23
Dry density (kg/m^3)	1898.21	1949.01	1921.73	1894.00	1849.88	1831.18
Dish number	1	2	3	4	5	6
Mass of wet soil + dish (g)	240.4	238.3	238.5	222.6	228.5	237.9
Mass of Dry soil + dish (g)	227.4	222.5	220	202.6	206.1	212.6
Mass of water (g)	13	15.8	18.5	20	22.4	25.3
Mass of dish (g)	28	28.5	28.2	27.6	27.8	28
Mass of dry soil (g)	199.4	194	191.8	175	178.3	184.6
Water content %	6.52	8.14	9.65	11.43	12.56	13.71

Proctor Data for RCA2

Trial No.	1	3	4	5	6
Mass of mould + Granular Material (kg)	10.882	11.0496	11.078	11.017	11.012
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.681	4.8486	4.877	4.816	4.811
Bulk wet density (kg/m^3)	2203.69	2282.59	2295.96	2267.25	2264.89
Dry density (kg/m^3)	2054.53	2098.93	2105.61	2059.83	2040.26
Dish number	1	3	5	4	6
Mass of wet soil + dish (g)	865.3	924.3	889.7	969.9	968.1
Mass of dry soil + dish (g)	814.9	859.7	826	892.2	884.1
Mass of water (g)	50.4	64.6	63.7	77.7	84
Mass of dish (g)	120.6	121.16	121.19	120.33	121.5
Mass of dry soil (g)	694.3	738.54	704.81	771.87	762.6
Water Content %	7.26	8.75	9.04	10.07	11.01

Proctor Data for RCA2 with 5% Processed Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.8008	10.886	10.89	10.852	10.816
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.5998	4.685	4.689	4.651	4.615
Bulk wet density (kg/m^3)	2165.47	2205.58	2207.46	2189.57	2172.62
Dry density (kg/m^3)	2001.91	2024.95	2004.96	1978.11	1934.83
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	801.55	840.79	808.97	842.72	929.2
Mass of Dry soil + dish (g)	750.1	782	745.8	773	840.7
Mass of water (g)	51.45	58.79	63.17	69.72	88.5
Mass of dish (g)	120.67	122.92	120.48	120.6	120.82
Mass of dry soil (g)	629.43	659.08	625.32	652.4	719.88
Water content %	8.17	8.92	10.1	10.69	12.29

Proctor Data for RCA2 with 10% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	10.673	10.721	10.786	10.758	10.755	10.696
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.472	4.52	4.585	4.557	4.554	4.495
Bulk wet density (kg/m^3)	2105.3	2127.9	2158.5	2145.32	2143.9	2116.13
Dry density (kg/m^3)	1954.96	1961.20	1970.33	1950.47	1931.62	1888.05
Dish number	1		2	3	4	5
Mass of wet soil + dish (g)	777.83	918.72	840.31	868.36	843.3	921.7
Mass of dry soil + dish (g)	730.1	960	777.7	799.7	771.8	835.5
Mass of water (g)	47.73	-41.28	62.61	68.66	71.5	86.2
Mass of dish (g)	109.02	185.8	122.35	112.1	121.1	122.08
Mass of dry soil (g)	621.08	774.2	655.35	687.6	650.7	713.42
Water content %	7.69	8.5	9.55	9.99	10.99	12.08

Proctor Data for RCA2 with 5% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.731	10.9468	10.958	10.894	10.8357
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.528	4.7438	4.755	4.691	4.6327
Bulk wet density (kg/m^3)	2131.66	2233.26	2238.53	2208.4	2180.95
Dry density (kg/m^3)	2010.24	2066.30	2044.88	2003.81	1951.11
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	879.1	836.5	871.8	868.3	923.3
Mass of Dry soil + dish (g)	835.9	783	806.9	799	838.8
Mass of water (g)	43.2	53.5	64.9	69.3	84.5
Mass of dish (g)	120.43	120.6	121.71	120.44	121.54
Mass of dry soil (g)	715.47	662.4	685.19	678.56	717.26
Water content %	6.04	8.08	9.47	10.21	11.78

Proctor Data for RCA2 with 10% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.6774	10.79	10.803	10.7965	10.7535
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.4764	4.589	4.602	4.5955	4.5525
Bulk wet density (kg/m^3)	2107.37	2160.38	2166.5	2163.44	2143.2
Dry density (kg/m^3)	1975.78	1991.13	1967.22	1946.59	1901.35
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	760.3	729.7	723.82	753.02	902.4
Mass of dry soil + dish (g)	719.6	682.06	667.2	689.65	814.29
Mass of water (g)	40.7	47.64	56.62	63.37	88.11
Mass of dish (g)	108.73	121.88	108.5	120.68	121.44
Mass of dry soil (g)	610.87	560.18	558.7	568.97	692.85
Water content %	6.66	8.5	10.13	11.14	12.72

Proctor Data for RCA3 with 0% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.7252	10.7946	10.9367	10.9288	10.9408
Mass of mould (kg)	6.198	6.198	6.198	6.198	6.198
Mass of wet soil (kg)	4.5272	4.5966	4.7387	4.7308	4.7428
Bulk wet density (kg/m^3)	2131.29	2163.96	2230.86	2227.14	2232.79
Dry density (kg/m^3)	1995.78	2010.18	2052.88	2045.31	2010.98
Dish number	1	2	4	3	5
Mass of wet soil + dish (g)	892.1	940.1	938.4	1005.3	941.9
Mass of dry soil + dish (g)	842.3	881.9	873.3	933.2	860.5
Mass of water (g)	49.8	58.2	65.1	72.1	81.4
Mass of dish (g)	108.6	121.1	122.4	122.1	122.2
Mass of dry soil (g)	733.7	760.8	750.9	811.1	738.3
Water content %	6.79	7.65	8.67	8.89	11.03

Proctor Data for RCA3 with 3% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.7599	10.9005	10.9098	10.9131	10.8476
Mass of mould (kg)	6.198	6.198	6.198	6.198	6.198
Mass of wet soil (kg)	4.5619	4.7025	4.7118	4.7151	4.6496
Bulk wet density (kg/m^3)	2147.62	2213.81	2218.19	2219.75	2188.91
Dry density (kg/m^3)	2002.44	2038.12	2023.71	2009.19	1957.88
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	765.7	1526	810	961.6	1142.4
Mass of dry soil + dish (g)	721.3	1459.6	748.5	881.9	1034.7
Mass of water (g)	44.4	66.4	61.5	79.7	107.7
Mass of dish (g)	109.2	688.9	108.6	121.4	122.1
Mass of dry soil (g)	612.1	770.7	639.9	760.5	912.6
Water content %	7.25	8.62	9.61	10.48	11.8

Proctor Data for RCA3 with 5% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.731	10.843	10.8851	10.8912	10.8466
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.528	4.64	4.6821	4.6882	4.6436
Bulk wet density (kg/m^3)	2131.66	2184.39	2204.21	2207.08	2186.09
Dry density (kg/m^3)	1984.05	2009.74	2023.14	2000.98	1949.60
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	911.8	828.4	947.2	1039.5	926.8
Mass of dry soil + dish (g)	857.2	771.9	879.4	953.8	839.6
Mass of water (g)	54.6	56.5	67.8	85.7	87.2
Mass of dish (g)	123.8	122.1	121.5	121.8	120.9
Mass of dry soil (g)	733.4	649.8	757.9	832	718.7
Water content %	7.44	8.69	8.95	10.3	12.13

Proctor Data for RCA3 with 8% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.6965	10.7868	10.8402	10.8419	10.8237
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.4935	4.5838	4.6372	4.6389	4.6207
Bulk wet density (kg/m^3)	2115.42	2157.93	2183.07	2183.87	2175.31
Dry density (kg/m^3)	1969.48	1996.05	2001.71	1982.81	1952.00
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	893.1	883.4	952.6	962.8	984.5
Mass of dry soil + dish (g)	839	826.3	882.5	885.4	896
Mass of water (g)	54.1	57.1	70.1	77.4	88.5
Mass of dish (g)	108.8	121.8	108.7	121.9	122.2
Mass of dry soil (g)	730.2	704.5	773.8	763.5	773.8
Water content %	7.41	8.11	9.06	10.14	11.44

Proctor Data for RCA3 with 10% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.7037	10.7805	10.7886	10.7767	10.7584
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.5027	4.5795	4.5876	4.5757	4.5574
Bulk wet density (kg/m^3)	2119.75	2155.91	2159.72	2154.12	2145.51
Dry density (kg/m^3)	1964.73	1992.52	1979.94	1963.65	1905.60
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	901.5	1065.3	1666.6	1531.9	1457.3
Mass of Dry soil + dish (g)	844.4	993.8	1583.8	1451.7	1365
Mass of water (g)	57.1	71.5	82.8	80.2	92.3
Mass of dish (g)	120.6	121.4	672.2	624.7	631.9
Mass of dry soil (g)	723.8	872.4	911.6	827	733.1
Water content %	7.89	8.2	9.08	9.7	12.59

Proctor Data for LS1 with 0% Processed Shingles

Trial No.	1	2	3	4	5	6
Mass of mould + Granular Material (kg)	11.0307	11.1281	11.236	11.2827	11.302	11.3045
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.8297	4.9271	5.035	5.0817	5.101	5.1035
Bulk wet density (kg/m^3)	2273.7	2319.55	2370.35	2392.33	2401.42	2402.59
Dry density (kg/m^3)	2193.42	2223.07	2249.98	2260.33	2271.71	2232.27
Dish number	1	2	3	4	6	5
Mass of wet soil + dish (g)	235.5	256.3	255.5	284.6	724.8	294.4
Mass of Dry soil + dish (g)	228.2	246.8	244	270.5	691.5	275.5
Mass of water (g)	7.3	9.5	11.5	14.1	33.3	18.9
Mass of dish (g)	28.5	27.7	29.2	28.9	107.9	27.9
Mass of dry soil (g)	199.7	219.1	214.8	241.6	583.6	247.6
Water content %	3.66	4.34	5.35	5.84	5.71	7.63

Proctor Data for LS1 with 5% Processed Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.906	11.04	11.083	11.072	11.109
Mass of mould (kg)	6.203	6.203	6.203	6.203	6.203
Mass of wet soil (kg)	4.703	4.837	4.88	4.869	4.906
Bulk wet density (kg/m^3)	2214.05	2277.13	2297.38	2292.2	2309.62
Dry density (kg/m^3)	2127.46	2165.19	2165.71	2167.16	2098.70
Dish number	1	2	3	4	
Mass of wet soil + dish (g)	622.2	572.7	847.8	660	865.4
Mass of Dry soil + dish (g)	602.1	550.5	806.1	630.6	797.4
Mass of water (g)	20.1	22.2	41.7	29.4	68
Mass of dish (g)	108	121.2	120.6	121.3	120.9
Mass of dry soil (g)	494.1	429.3	685.5	509.3	676.5
Water content %	4.07	5.17	6.08	5.77	10.05

Proctor Data for LS1 with 10% Processed Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.699	10.774	10.806	10.982	10.959
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.498	4.573	4.605	4.781	4.758
Bulk wet density (kg/m^3)	2117.54	2152.85	2167.91	2250.77	2239.94
Dry density (kg/m^3)	2041.59	2063.30	2072.97	2120.77	2074.21
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	692.1	668	698.1	786	795.7
Mass of Dry soil + dish (g)	671.2	645.24	672.8	747.6	745.86
Mass of water (g)	20.9	22.76	25.3	38.4	49.84
Mass of dish (g)	108.7	121.1	120.1	121.2	121.7
Mass of dry soil (g)	562.5	524.14	552.7	626.4	624.16
Water content %	3.72	4.34	4.58	6.13	7.99

Proctor Data for LS1 with 3% Ground Shingles

Trial No.	1	2	3	4	5	6	7
Mass of mould + Granular Material (kg)	11.066	11.1859	11.2549	11.285	11.258	11.2945	11.2653
Mass of mould (kg)	6.201	6.202	6.202	6.202	6.202	6.202	6.202
Mass of wet soil (kg)	4.865	4.9839	5.0529	5.083	5.056	5.0925	5.0633
Bulk wet density (kg/m^3)	2290.32	2346.29	2378.77	2392.94	2380.23	2397.42	2383.67
Dry density (kg/m^3)	2194.84	2231.16	2253.26	2266.26	2252.09	2262.36	2244.93
Dish number	1	2	3	6		5	4
Mass of wet soil + dish (g)	252.6	236.9	243.8	605	692.8	289.1	252.5
Mass of Dry soil + dish (g)	243.3	226.6	232.3	579.4	661.3	274.4	239.5
Mass of water (g)	9.3	10.3	11.5	25.6	31.5	14.7	13
Mass of dish (g)	29.7	26.8	26	121.1	108.1	28.2	29.3
Mass of dry soil (g)	213.6	199.8	206.3	458.3	553.2	246.2	210.2
Water content %	4.35	5.16	5.57	5.59	5.69	5.97	6.18

Proctor Data for LS1 with 5% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	11.053	11.1178	11.183	11.231	11.234
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.852	4.9168	4.982	5.03	5.033
Bulk wet density (kg/m^3)	2284.2	2314.7	2345.4	2367.99	2369.41
Dry density (kg/m^3)	2187.51	2203.85	2214.73	2228.91	2210.06
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	626.5	583.7	650.2	751.5	803.1
Mass of Dry soil + dish (g)	605.1	560.9	620	714.4	757.2
Mass of water (g)	21.4	22.8	30.2	37.1	45.9
Mass of dish (g)	120.7	107.9	108.3	119.9	120.2
Mass of dry soil (g)	484.4	453	511.7	594.5	637
Water content %	4.42	5.03	5.9	6.24	7.21

Proctor Data for LS1 with 8% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.917	11.022	11.115	11.155	11.108
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.716	4.821	4.914	4.954	4.907
Bulk wet density (kg/m^3)	2220.17	2269.6	2313.38	2332.21	2310.09
Dry density (kg/m^3)	2137.45	2161.52	2182.64	2180.65	2134.23
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	641.5	662.4	639.3	631.5	710.5
Mass of Dry soil + dish (g)	621.6	636.6	609.3	598.3	665.6
Mass of water (g)	19.9	25.8	30	33.2	44.9
Mass of dish (g)	107.9	121	108.3	120.4	120.6
Mass of dry soil (g)	513.7	515.6	501	477.9	545
Water content %	3.87	5	5.99	6.95	8.24

Proctor Data for LS1 with 10% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.945	11.063	11.098	11.127	11.095
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.744	4.862	4.897	4.926	4.894
Bulk wet density (kg/m^3)	2233.35	2288.9	2305.38	2319.03	2303.97
Dry density (kg/m^3)	2142.71	2170.60	2173.45	2167.52	2153.24
Dish number	1	2	3	4	5
Mass of wet soil + dish (g)	635.9	658.4	647.1	690.4	672.6
Mass of Dry soil + dish (g)	615	630.6	617	653.2	636.5
Mass of water (g)	20.9	27.8	30.1	37.2	36.1
Mass of dish (g)	121	120.7	121.2	121.3	120.6
Mass of dry soil (g)	494	509.9	495.8	531.9	515.9
Water content %	4.23	5.45	6.07	6.99	7

Proctor Data for LS1 with 15% Ground Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	10.918	10.978	11.043	10.976	11.011
Mass of mould (kg)	6.201	6.201	6.201	6.201	6.201
Mass of wet soil (kg)	4.717	4.777	4.842	4.775	4.81
Bulk wet density (kg/m^3)	2220.64	2248.89	2279.49	2247.95	2264.42
Dry density (kg/m^3)	2125.22	2131.04	2127.58	2064.80	2141.09
Dish number	1	2	4	5	6
Mass of wet soil + dish (g)	646.8	603.1	664.5	693.8	647.5
Mass of Dry soil + dish (g)	624.2	577.8	628.3	647.1	618.8
Mass of water (g)	22.6	25.3	36.2	46.7	28.7
Mass of dish (g)	120.5	120.7	121	120.9	120.5
Mass of dry soil (g)	503.7	457.1	507.3	526.2	498.3
Water content %	4.49	5.53	7.14	8.87	5.76

Proctor Data for Natural Gravel

Trial No.	1	2	3	4	5	6	7
Mass of mould + Granular Material (kg)	10.9567	11.0225	11.1426	11.2635	11.3227	11.3312	11.3311
Mass of mould (kg)	6.1969	6.1969	6.1969	6.1969	6.1969	6.1969	6.1969
Mass of wet soil (kg)	4.7598	4.8256	4.9457	5.0666	5.1258	5.1343	5.1342
Bulk wet density (kg/m^3)	2240.79	2271.77	2328.31	2385.22	2413.09	2417.09	2417.05
Dry density (kg/m^3)	2194.27	2207.96	2241.78	2282.73	2292.50	2275.34	2263.37
Dish number	1	2	3	4	5	6	7
Mass of wet soil + dish (g)	810.5	770	852.9	913.8	807	828.1	1005.7
Mass of Dry soil + dish (g)	795.9	751.8	825.7	879.8	772.7	786.7	949.4
Mass of water (g)	14.6	18.2	27.2	34	34.3	41.4	56.3
Mass of dish (g)	108.6	121.5	121.7	121.9	120.9	121.8	120.6
Mass of dry soil (g)	687.3	630.3	704	757.9	651.8	664.9	828.8
Water content %	2.12	2.89	3.86	4.49	5.26	6.23	6.79

Proctor Data for LS2 without Shingles

Trial No.	1	2	3	4	5
Mass of mould + Granular Material (kg)	11.0823	11.2345	8.2372	11.4098	11.2687
Mass of mould (kg)	6.1932	6.1932	3.0676	6.1932	6.1932
Mass of wet soil (kg)	4.8891	5.0413	5.1696	5.2166	5.0755
Bulk wet density (kg/m^3)	2301.66	2373.31	2433.71	2455.84	2389.41
Dry density (kg/m^3)	2228.99	2293.27	2335.61	2342.02	2231.22
Dish number	3	4	1	2	5
Mass of wet soil + dish (g)	794.9	603.2	595.6	651.6	598.6
Mass of Dry soil + dish (g)	773.6	586.9	576	627	567
Mass of water (g)	21.3	16.3	19.6	24.6	31.6
Mass of dish (g)	120.2	119.9	109.1	120.9	121.4
Mass of dry soil (g)	653.4	467	466.9	506.1	445.6
Water content %	3.26	3.49	4.2	4.86	7.09

Proctor Data for LS2 with 12% Shingles

Trial No.	1	2	3	4	5	6	7
Mass of mould + Granular Material (kg)	10.6992	10.7945	10.9282	10.9856	10.9695	10.9554	10.8836
Mass of mould (kg)	6.1912	6.1912	6.1912	6.1912	6.1912	6.1912	6.1912
Mass of wet soil (kg)	4.508	4.6033	4.737	4.7944	4.7783	4.7642	4.6924
Bulk wet density (kg/m^3)	2122.25	2167.11	2230.06	2257.08	2249.5	2242.86	2209.06
Dry density (kg/m^3)	2059.84	2083.36	2129.14	2139.21	2111.41	2098.09	2046.56
Dish number	1	2	4	5		6	
Mass of wet soil + dish (g)	595	581.7	566.2	653.5	554.16	594.5	614.98
Mass of Dry soil + dish (g)	581.09	563.88	546.02	625.7	527.55	563.96	578.67
Mass of water (g)	13.91	17.82	20.18	27.8	26.61	30.54	36.31
Mass of dish (g)	121.3	120.7	119.9	120.97	120.47	121.4	121.24
Mass of dry soil (g)	459.79	443.18	426.12	504.73	407.08	442.56	457.43
Water content %	3.03	4.02	4.74	5.51	6.54	6.9	7.94

Proctor Data for Fine Sand (S1)

Trial No.	1	2	3	4	5	6	7	8
Mass of mould + Granular Material (kg)	9.7915	9.8671	9.9325	9.9748	10.1056	10.2632	10.2075	10.3687
Mass of mould (kg)	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963
Mass of wet soil (kg)	3.5952	3.6708	3.7362	3.7785	3.9093	4.0669	4.0112	4.1724
Bulk wet density (kg/m^3)	1692.53	1728.12	1758.91	1778.82	1840.4	1914.59	1888.37	1964.26
Dry density (kg/m^3)	1632.771	1653.387	1658.723	1660.431	1694.971	1745.615	1719.201	1767.534
Dish number	2	20	21	1	8	6	10	1
Mass of wet soil + dish (g)	677.9	675.7	698.1	720.3	695.2	519.1	795.2	642.2
Mass of Dry soil + dish (g)	658.3	651.7	665.2	679.6	649.8	484	734.8	588.8
Mass of water (g)	19.6	24	32.9	40.7	45.4	35.1	60.4	53.4
Mass of dish (g)	122.1	120.8	120.3	108.9	120.7	121.4	120.9	108.9
Mass of dry soil (g)	536.2	530.9	544.9	570.7	529.1	362.6	613.9	479.9
Water content %	3.66	4.52	6.04	7.13	8.58	9.68	9.84	11.13

Proctor Data for Fine Sand (S1)

Trial No.	9	10	11	12	13	14	15	16
Mass of mould + Granular Material (kg)	10.3524	10.3438	10.453	10.3645	10.4302	10.385	10.3673	10.4732
Mass of mould (kg)	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963	6.1963
Mass of wet soil (kg)	4.1561	4.1475	4.2567	4.1682	4.2339	4.1887	4.171	4.2769
Bulk wet density (kg/m^3)	1956.58	1952.54	2003.94	1962.28	1993.21	1971.93	1963.6	2013.45
Dry density (kg/m^3)	1753.522	1748.491	1775.126	1742.236	1736.397	1704.789	1670.58	1779.138
Dish number	6	2	9	13	20	21		9
Mass of wet soil + dish (g)	705.7	662.1	774	634.6	680.6	743.3	1449.6	706.9
Mass of Dry soil + dish (g)	645.1	605.7	699.5	577	608.5	659	1326.1	638.8
Mass of water (g)	60.6	56.4	74.5	57.6	72.1	84.3	123.5	68.1
Mass of dish (g)	121.7	122.3	121.6	121	121.1	120.9	622.1	121.6
Mass of dry soil (g)	523.4	483.4	577.9	456	487.4	538.1	704	517.2
Water content %	11.58	11.67	12.89	12.63	14.79	15.67	17.54	13.17

Mix Design of Hot Mix Asphalt

	sieve size	Gradation	Control mix						3% shingles				
Aggregate	25.4	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	19	2.2	103.40	103.40	103.40	103.40	103.40	103.40	103.40	103.40	103.40	103.40	103.40
	12.7	8.7	408.90	408.90	408.90	408.90	408.90	408.90	408.90	408.90	408.90	408.90	408.90
	9.5	16.3	766.10	766.10	766.10	766.10	766.10	766.10	766.10	766.10	766.10	766.10	766.10
	4.75	24.9	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30	1170.30
	Total	**52.1**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**	**2448.70**
Trap rock	2.36	4.8	225.60	225.60	225.60	225.60	225.60	225.60	210.18	210.18	210.18	210.18	210.18
	1.18	12.4	582.80	582.80	582.80	582.80	582.80	582.80	542.97	542.97	542.97	542.97	542.97
	0.6	10.7	502.90	502.90	502.90	502.90	502.90	502.90	468.53	468.53	468.53	468.53	468.53
	0.3	9.4	441.80	441.80	441.80	441.80	441.80	441.80	411.61	411.61	411.61	411.61	411.61
	0.15	5.4	253.80	253.80	253.80	253.80	253.80	253.80	236.46	236.46	236.46	236.46	236.46
	0.075	1.2	56.40	56.40	56.40	56.40	56.40	56.40	52.55	52.55	52.55	52.55	52.55
	Total	**43.9**	**2063.3**	**2063.3**	**2063.3**	**2063.3**	**2063.3**	**2063.3**	**1922.3**	**1922.3**	**1922.3**	**1922.3**	**1922.3**
Dust		4	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00
3% shingles		0							141	141	141	141	141
Total		100	4700	4700	4700	4700	4700	4700	4700.00	4700.00	4700.00	4700.00	4700.00
Binder		4.3	185.65	211.18	220.44	224.04	229.73	236.97	140.37	165.42	179.57	181.6	190.74
Binder (%)			3.8	4.3	4.48	4.55	4.66	4.8	2.9	3.4	3.68	3.72	3.9

Air Void Calculation

Description	Control Specimen						Shingle Specimen						
Bitumen content (%)	4.48	4.52	4.66	4.66	4.3	4.3	3.68	3.68	3.9	2.9	3.4	4.66	3.68
Gyration	174	109	109	109	174	174	109	109	174	174	174	109	109
Permissible pressure (psi)	600	600	600	600	600	600	600	600	600	600	600	600	600
Height of sample (mm) at 8 gyrations	121.73	122.91	121.71	121.71	121.58	122.21	121.85	121.85	121.11	117.64	117.62	121.71	121.85
Height of sample (mm) at 109 gyrations	111.39	112.53	111.71	111.71	111.79	111.9	111.69	111.69	110.82	112.3	111.79	111.71	111.69
Height of sample (mm) at 111 or 174 gyrations*	109.97	112.41	111.56	111.56	110.46	110.48	111.54	111.54	109.55	111.22	110.69	111.56	111.54
Height of sample (mm) at 181 gyrations	109.82	112.41			110.29	110.31			109.34	110.99	110.48	111.56	111.54
Mass of sample in air	4855.2	4887.9	4888	4888	4870.3	4860.2	4872.8	4872.8	4863.6	4826.5	4858	4888	4872.8
Mass of sample in water	2936.3	2937.5	2943.8	2943.8	2945.9	2936.2	2927.6	2927.6	2952.2	2898.1	2926.1	2943.8	2927.6
SSD	4857.2	4892	4890.4	4890.4	4873.6	4863.7	4877	4877	4866.6	4841	4863	4890.4	4877
BRD (temp)	2.528	2.501	2.511	2.511	2.526	2.522	2.500	2.500	2.541	2.484	2.508	2.511	2.500
Temperature	19	19	19	19	17	20	19	19	17	17	17	19	19
Correction factor	1.0014	1.0014	1.0014	1.0014	1.0017	1.0012	1.0014	1.0014	1.0017	1.0017	1.0017	1.0014	1.0014
BRD (25)	2.531	2.504	2.515	2.515	2.531	2.525	2.503	2.503	2.545	2.488	2.512	2.515	2.503
BRD at 109 gyrations	2.495	2.504	2.515	2.515	2.497	2.489	2.503	2.503	2.511	2.459	2.483	2.511	2.500
Mass of beaker in air	308.1	308	308	789.6	789.5	308	789.5	786.7	308	308.1	789.5	308	308
Mass of beaker + mix in air	1336.8	1351	1394.6	1874.5	1913.9	1314.8	1822.5	1942	1276.6	1320.5	1831.9	1284.1	1300.5
Mass of beaker + mix in water	803.8	813.7	839.8	1356.3	1383	792.8	1325.7	1396.3	764.1	799.8	1331.7	770.8	780.4
Mass of beaker in water	169.8	169.6	169.6	688.8	688.4	169.8	689.7	689.7	169.8	169.8	688.4	169.6	169.6
MRD (temp)	2.606	2.615	2.610	2.599	2.616	2.623	2.602	2.575	2.588	2.647	2.612	2.604	2.600
Temperature	19	19	19	19	23	20.1	19	19	20	23	23	20	20
Correction factor	1.0014	1.0014	1.0014	1.0014	1.005	1.0012	1.0014	1.0014	1.0012	1.005	1.005	1.0014	1.0014
MRD (25)	2.610	2.610	2.613	2.603	2.629	2.626	2.606	2.578	2.591	2.661	2.625	2.607	2.604
Air voids	3.023	4.048	3.773	3.391	3.743	3.878	3.934	2.918	1.776	6.477	4.287	3.685	3.997
Air voids at 109 gyrations	4.390				5.034	5.244			3.088	7.568	5.409		

*111 Gyration for N_{design} and 174 gyration for N_{max}

Air Void Calculation

Description	Control			Shingles		
Bitumen content (%)	4.64	4.64	4.55	3.72	3.72	3.68
Gyration	174	174	109	174	174	109
Permissible pressure (psi)	600	600	600	600	600	600
Height Of sample (mm) at 8 gyrations	121.6	121.6	121.37	121.68	121.68	121.68
Height Of sample (mm) at 109 gyrations	111.54	111.54	111.35	111.58	111.58	111.67
Height Of sample (mm) at 111 or 174 gyrations*	110.16	110.16	111.22	110.33	110.33	111.54
Height Of sample (mm) at 181 gyrations	110.12	110.12	111.22	110.37	110.37	111.54
Mass of sample in air	4872	4872	4871.8	4843.3	4843.3	4853.4
Mass of sample in water	2955.2	2955.2	2934.3	2925.1	2925.1	2912.4
SSD	4874.6	4874.6	4874.4	4847.2	4847.2	4859.2
BRD (temp)	2.538	2.538	2.511	2.520	2.520	2.493
Temperature	19	19	18	19	19	18
Correction factor	1.0014	1.0014	1.0016	1.0014	1.0014	1.0016
BRD (25)	2.542	2.542	2.515	2.523	2.523	2.497
BRD at 109 gyrations	2.509	2.509	2.512	2.496	2.496	2.494
Mass of beaker in air	789.8	308	308	786.9	308	308
Mass of beaker + mix in air	1816	1389	1383.4	1851.6	1311.9	1402.8
Mass of beaker + mix in water	1320.2	836.6	833.3	1343.1	787.1	842.9
Mass of beaker in water	688.8	169.6	169.6	686.8	169.7	169.6
MRD (temp)	2.599	2.611	2.6121	2.607	2.597	2.59739
Temperature	20	20	18	20	20	18
Correction factor	1.0014	1.0012	1.0016	1.0014	1.0012	1.0016
MRD (25)	2.603	2.614	2.616	2.611	2.601	2.602
Air voids	3.590	4.007	3.866	3.345	2.969	4.018
Air voids at 109 gyrations	3.590	4.007	3.978	4.393	4.021	4.130

* 111 Gyration for N_{design} and 174 gyration for N_{max}

Wet Specimen (TSR Specimen Data)

Description	Specimens without Shingle			Control Specimens		
	Specimen No.			Specimen No.		
	1	2	3	1	2	3
Height of specimen at 8 gyrations	102.09	101.16	100.67	102.35	102.16	102.11
Total gyrations	55	41	40	60	59	61
Height of specimens at end	94.93	94.87	94.87	94.97	94.97	94.97

Dry Specimen (TSR Specimen Data)

Description	Specimens without Shingle			Control Specimens		
	Specimen No.			Specimen No.		
	1	2	3	1	2	3
Height of specimen at 8 gyration	101.05	101.99	102.35	1001	100.69	101.03
Total gyrations	46	55	66	44	42	48
Height of specimen at end	94.87	94.87	94.87	94.83	94.95	94.97

Indirect Tensile Strength of Dry Sample

Description	Diameter (mm)	Load (lb)	Load (N)	Stress (N/mm^2)	Average Stress
Control specimen	150	3090	13750	610.73	604.08
Control specimen	150	3020	13438	597.44	
Specimen with shingles	150	3860	17176	763.81	764.88
Specimen with shingles	150	3870	17220	765.95	

Indirect Tensile Strength of Wet Sample

Description	Thickness after	Thickness after						
	freezing	thawing	Diameter (mm)	Load (lb)	Load (N)	Stress (N/mm^2)	Average Stress	TSR (%)
Control Specimen	95.42	95.58	150	2840	12637	562.3	573.31	94.906
Control Specimen	95.43	95.42	150	2950	13127	584.33		
Control Specimen	95.47	95.47	150	3470	15441	686.86		
Specimen with Shingles	95.49	95.42	150	3670	16331	725.74	702.81	91.885
Specimen with Shingles	95.48	95.46	150	3520	15663	695.84		