COLD IN-PLACE RECYCLING WITH EXPANDED ASPHALT MIX (CIREAM)

by

SAMUEL OLUWATOSIN ABIODUN

A thesis submitted to the Department of Chemistry

in conformity with the requirements for

the degree of Master of Science

Queen's University

Kingston, Ontario, Canada

(April, 2014)

Abstract

Cold in-place recycling with expanded asphalt mix (CIREAM) has become an accepted road rehabilitation technique in Ontario and other parts of the world given its advantages over regular cold in-place recycling (CIR) and other methods. Although CIREAM offers early strength advantages and extended paving periods among other benefits, late season CIREAM can be burdened by distresses such as ravelling, potholing and other moisture-induced damage. Limited information on the behaviour and failure mechanisms of CIREAM has also hindered its utilization in spite of the numerous benefits.

This research investigated effects of additives on the foam properties of roofing asphalt flux (RAF) binder in order to evaluate the suitability of the binder for CIREAM. The study also investigated how mixture variables and test protocols affect performance properties that relate to early strength and moisture resistance of CIREAM versus CIR. Indirect tensile strength testing with moisture conditioning was used to assess the effects of asphalt cement type (80, 300 pen grades and polymer modified asphalt), conditioning time, and additives such as Portland cement, foam stabilizers, polymers and fibers. Uniaxial cyclic compression with partial confinement was used to assess effect of additives on deformation resistance of recycled mixes. Although a siloxane-based stabilizer significantly improved the stability of RAF foam, the binder may not be suitable for CIREAM due to its limited expansion. The optimum binder content was found to be around 2 percent, which is significantly higher than the minimum 1 percent currently used in Ontario. Both Portland cement and the siloxane additive exerted significant positive effects on strength behaviour and moisture resistance of the recycled mixes. In regular CIR mixes, 2 percent binder content gave desirable early strength and strain performance compared to 1 percent.

Application of controlled amounts of additives (e.g. Portland cement, foam stabilizers) and case-by-case evaluation can improve the performance properties of CIREAM and address the associated problems. The entire research effort described in this thesis was designed to provide advice on potential improvements in the CIREAM process as it is currently carried out in Ontario, and also help in developing quality control standards in CIREAM and other cold mix processes.

Acknowledgement

My sincere gratitude goes to my supervisor, Dr. Simon A. M. Hesp for his continuous support and guidance throughout the entire period of my study. I am forever thankful for his unending and valuable advice, and more importantly for the opportunity he availed me to work on this project and co-authored a paper from this research. I also thank my supervisory committee members, Dr. Donal Macartney and Dr. Gary W. Vanloon for their help towards a successful completion of my degree.

Special thanks to Zachary Moore and Stephanie Smith with whom the ITS tests was carried out. I am also grateful to Christine Gorsuch of AkzoNobel Surface Chemistry, for conducting and reporting the foam stability experiments. I would not hesitate to thank all the members of the Hesp Research Group, and all faculty, staff and students of the Department of Chemistry at Queen’s University.

I also wish to thank the Ministry of Transportation of Ontario (MTO) and the National Sciences and Engineering Research Council of Canada (NSERC) for their financial support towards this research.

My heart-felt gratitude is extended to my wife Victoria Abiodun, and my parents for their unending love, support and encouragement. Most importantly, I give God all the glory for making this entire pursuit a success.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

AASHTO	American Association of State and Highway Transportation Officials
AC	Asphalt Cement
ASTM	American Society for Testing and Materials
CIR	Cold In-place Recycling
CIREAM	Cold In-place Recycling with Expanded Asphalt Mix
COV	Coefficient of Variation
DIC	Digital Image Correlation
EPV	Electronic Proportional Valve
ER	Expansion Ratio
ESBO	Epoxidized Soy Bean Oil
HIR	Hot In-place Recycling
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Strength
KPa	Kilo Pascal (Pa)
MTO	Ministry of Transportation of Ontario
MTS	Material Testing System
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
PCC	Portland Cement Concrete
PET	Poly Ethylene Terephthalate
PG	Performance Grade
PTI	Pavement Technologies Inc.

PVC	Polyvinyl Chloride
RAF	Roofing Asphalt Flux
RAP	Recycled Asphalt Pavement
TSR	Tensile Strength Ratio
UCCTC	Uniaxial Cyclic Compression Test with Confinements

Symbols

Cp	centipoise
$\tau^{1/2}$	Half-life
μm/cycle	micrometer per load cycle
%	Percent
P	Peak Load
D	Specimen Diameter
H	Specimen Height
Π	pie (3.142)
°C	Degrees celcius

CHAPTER 1

INTRODUCTION

A considerable amount of government money is spent each and every year on road construction, maintenance and repair all over the world. Traffic levels are increasing yearly and the general population demands better roads. Due in part to budget constraints, government agencies and contractors perform road maintenance and rehabilitation work at lower costs. In recent times, the focus has shifted from building new roads to maintaining and preserving existing pavement surfaces. Hence, the need to adopt cost-effective and environmentally friendly techniques of rehabilitating road pavement layers cannot be over-emphasized [1, 2]. The traditional method of road rehabilitation involves preparing the old pavement and placing a new layer of hot mix asphalt (HMA) pavement on a reconstructed base or milling off one or two top layers of the old pavement (if the road is seriously deteriorated) and then reconstructing the road with new asphalt. Although this traditional rehabilitation process (use of hot mix overlay) is very popular and provides excellent new surfaces, it is associated with a number of disadvantages. One is the long construction period. The ever-increasing road users have to put up with delays caused by long periods of road closures to traffic during the rehabilitation [3, 4]. Other disadvantages include excessive material and energy requirements. In addition to the high cost of reconstructing the base layer and the energy required to produce the hot mix, the traditional mill and pave method is characterised by a heavy release of particulates and greenhouse gases. These issues have motivated the design and utilization of more economical alternatives, which are not only more effective but also eliminate traffic and construction delays and do not impact the environment adversely [4-6]. Recycling techniques have become accepted road rehabilitation processes in many parts of the world as they offer these aforementioned advantages [7].

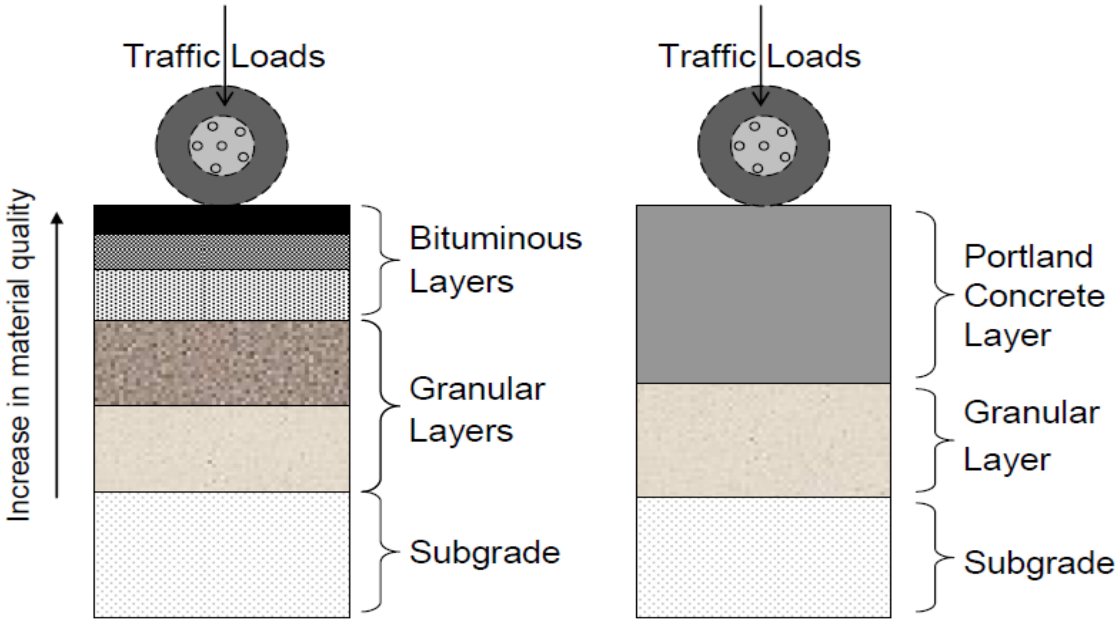
Recycling methods for asphalt pavements comprise a number of techniques which include hot-in-place recycling (HIR), cold mix techniques or cold recycling technology, partial and full depth reclamation [5]. The cold mix techniques, which involve removing and milling about three-quarters of the existing pavement, include cold-in-place recycling (CIR) and cold-in-place recycling with expanded asphalt mix (CIREAM). In the former, the pulverized pavement material is mixed with a bituminous emulsion while the latter involves mixing the milled material with foamed bitumen, after which the mixture is placed on the road in an in-situ operation without any heat application.

1.1 Road Pavement

A pavement is the road structure consisting of stratified layers of structural materials placed on top of the natural (in-situ) soil or sub-grade, with the primary function of sustaining traffic loads safely, efficiently and economically. By distributing the applied traffic loads, the pavement protects the natural sub-grade. Essentially, a pavement is designed to provide a surface of suitable ride quality, sufficient skid resistance, and favourable light reflection. The primary purpose of the pavement is to sufficiently distribute and reduce the stresses transmitted from wheel loads, so that they do not exceed the sub-grade strength. It is desirable to design a pavement having an extended functional life with minimal maintenance and repair actions. Based on the structural performance there are two types of pavements, namely flexible pavements and rigid pavements [8, 9].

In flexible pavements, the surface course is made of asphaltic concrete and it distributes wheel loads to the sub-base or sub-grade. The wheel load is transmitted through the structural particles down to a wider area with the stress decreasing with depth. Hence, flexible pavements consist of many layers with better materials on top where stresses are high, and weaker materials at the bottom where stresses are much reduced. In flexible pavements, the deformation of the lower layers (for example undulation in the sub-grade) is reflected on the surface layer as the pavement is capable of adjusting its position to the deformation of the underlying layers with minimal change or damage [8-10].

Rigid pavements are constructed with Portland cement concrete (PCC) as the surface course, which is placed directly on the prepared sub-grade or on a single layer of granular material. Rigid pavements are stiffer than flexible pavements and behave like an elastic plate (concrete slab) lying on a viscous material, distributing the wheel loads over a relatively wider area of soil underneath [9, 10].



(a) (b)

Figure 1.1 (a) Flexible Pavement and (b) Rigid Pavement (after Gonzalez, 2009) [10].

1.2 Pavement Cross Section

A typical asphalt pavement is a multi-layered structure comprising the surface course, binder course, base course, sub-base and sub-grade.

- Surface course: The surface course is usually constructed with dense graded, hot mix asphalt concrete (HMA). It is the layer directly in contact with the traffic and should have sufficient stability and durability to withstand distortion under traffic loads and the adverse effects of air, water and temperature changes without showing any signs of failure. Surface courses should prevent water from infiltrating into the underlying layers and provide sufficient smoothness and skid resistance.

- Binder course: The binder course is an intermediate layer that distributes loads to the base course. It is made of coarse aggregate with a moderate amount of asphalt cement (AC) to provide stability and durability.

- Base course: The base course is often considered the most important structural layer of a pavement. It distributes the traffic load and protects the underlying unbound layers from excessive stresses and strains.

- Sub-base: The sub-base lies beneath the base course and it provides structural support to the sub-grade. It also reduces intrusion of fines from the sub-grade. Together with the sub-grade, the sub-base forms the foundation of the road structure. However, the sub-base may not be needed if the pavement is constructed over a stiff and superior quality sub-grade.

- Sub-grade: This consists of unbound materials such as the native soil, crushed and uncrushed aggregates. It is the layer that absorbs the stresses transmitted from the layers above. The sub-grade should be compacted to a sufficient density and should not be overstressed [8, 11].

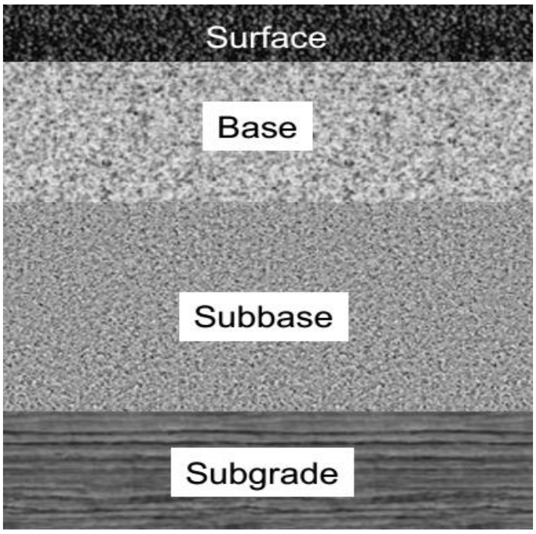


Figure 1.2 Cross section of a typical flexible pavement [11].

1.3 Pavement Distresses

With appropriate maintenance actions, a typical asphalt pavement should last longer than fifteen to twenty years depending on the traffic load and environmental factors [5]. However, major rehabilitation is required as the road approaches the end of its service life. This is due to a number of distress modes observed in the pavement. Four major categories of surface distresses are found in asphalt pavements. These include cracking (e.g., fatigue, low temperature and random cracking), surface deformation (i.e., permanent deformation or rutting), disintegration (potholes), and surface defects (e.g., ravelling and bleeding).

- Fatigue cracking: Fatigue cracking is a progressive distress caused by the failure of the surface course or base due to repeated traffic loads. Usually it starts as longitudinal cracks which later join, forming transverse cracks and eventually resulting in a cracking pattern similar to an alligator skin. Hence, fatigue cracking is also known as alligator cracking. Fatigue cracking can be minimized by adequate compaction during construction. It is often seen in stiffer hot mix asphalt since softer materials generally possess higher fatigue cracking resistance.

- Low temperature cracking: This type of cracking results from pavement shrinkage in cold weather (low temperatures) as tensile stresses develop. Low temperature cracking is common when hard asphalt cement is used. Extreme aging (oxidation), due to a high air void content or overheating during construction, can also lead to low temperature cracking. Soft binders prevent low temperature cracking due to their low viscosity.

- Permanent deformation: Rutting is a result of densification caused by the displacement of pavement materials which occurs each time a load is applied. Rutting is caused by over-stressing the underlying base or sub-grade layers resulting from thin asphalt or sub-base layers, a weak sub-base, and moisture infiltration into the base or sub-grade. As the underlying layers become weakened by the aforementioned, they deform permanently under repeated traffic loads. Rutting normally occurs in the early years (less than five years) of a pavement's life when the asphalt binder is relatively soft. It is less likely a problem after the asphalt binder has aged or oxidized. Rutting is usually accelerated during summer months when high temperatures soften the asphalt cement.

- Disintegration: In extreme situations, fatigue cracking may result in disintegration and formation of potholes as the fragments are displaced by traffic. Disintegration is the progressive breaking up of the pavement into small unbound pieces. As the small fragments of the surface layer are dislodged, potholes are formed. This is common in areas with poor drainage.

- Ravelling: Ravelling can be explained as the loss of material from the surface of a pavement. It results from insufficient binding of the asphalt cement and the aggregates. Ravelling starts as fine aggregates break loose, leaving small rough patches on the pavement surface. Larger aggregates break loose as the disintegration continues resulting in a rough surface. Traffic and freezing weather accelerate ravelling. Sometimes improper construction techniques cause ravelling in chip seals which could lead to bleeding. These types of distresses can be repaired with a wearing course overlay [2].

1.4 Pavement Recycling

Recycling of pavements comprises a range of techniques by which materials from an existing deteriorated pavement is reprocessed for the construction of a new layer. The distressed pavement is modified and transformed into a homogeneous structure capable of supporting the traffic loads. Essentially, it involves pulverizing the existing pavement to a pre-defined depth (typically between 65 and 165 mm), and subsequently adding binder, water, additives, and aggregates. The binder can be an asphalt cement binder, sometimes a bituminous emulsion (CIR) or expanded asphalt cement (CIREAM). The water is added to facilitate hydration, mixing and to aid in compaction. These operations are performed on site.

The resulting homogeneous mixture is compacted and allowed to cure to form a base or layer with the desirable structural support for the new pavement. The recycled layer is then covered with a seal coat to protect it against traffic during the process. A layer of asphalt concrete (hot mix) is later applied in order to ensure the desired bearing capacity so that the performance of the pavement is guaranteed. Typically, the road is reopened to traffic within one or two hours. Asphalt cement bound recycling significantly increases the bearing capacity of the pavement, while pavement deflections, sub-grade stresses and strains are being reduced and existing ruts corrected, if the thickness of the bound layer is sufficiently increased [6].

Hot-in-place recycling involves heating the existing distressed pavement in order for it to be softened enough to allow it to be milled to a specified depth. The asphalt pavement is then re-blended and mixed with virgin hot mix asphalt (aggregate), new binder, and subsequently placed. The technique is used for pavements showing minor surface distresses such as cracking and ravelling but with a sound base. Partial depth reclamation is used for a structurally sound pavement of which the surface layer has deteriorated. When the deterioration in the road extends beyond the pavement layers, full depth reclamation is used. Full depth reclamation processes the entire existing pavement and a predetermined portion of the underlying material (base and sub-base). Because the old pavement is completely removed, deep cracks are erased, thereby eliminating any tendency of reflective cracking and restoring the pavement's profile and cross-fall. A new layer of asphalt is laid after the base is fully prepared or rebuilt. The process usually takes two to three days after which it can be reopened for traffic [5, 12].

1.5 Aims and Scope

In the last decade, cold in-place recycling (CIR) and cold in-place recycling with expanded asphalt mix (CIREAM) have been utilized in many road projects in Ontario and North America [5, 13]. Several studies have been carried out to review the performance of these two cold mix recycling techniques of pavement rehabilitation. Cold in-place recycling (CIR) is an established technique that processes an existing pavement, sizes it, mixes it with emulsified asphalt, and lays it back without off-site hauling and treatment. Cold in-place recycling with expanded asphalt mix (CIREAM), which is a recent development in CIR technology utilizes foamed asphalt, rather than emulsified asphalt in binding the mix [13]. CIREAM was originally designed to minimize the curing time in cold mixes prior to overlaying with the aim of providing an extended paving period as it is less sensitive to moisture and other weather effects [14]. The process has shown several benefits over conventional CIR and other techniques of road rehabilitation and is becoming increasingly popular in many parts of the world. Foamed bitumen technology offers an energy efficient, environmentally friendly, and cost-effective solution for road-building and rehabilitation [13]. However, limited information on the behaviour and failure mechanisms of these cold mixes has promoted the utilization of traditional techniques in spite of the numerous benefits of CIREAM [10]. The current CIREAM processes in cold and wet climates such as those that exist in most of Ontario are still characterized by field problems related to low early strength and moisture damage, manifesting as severe ravelling and potholing of the recycled pavement surface prior to placing the overlay especially during late fall [14]. The lack of standardized design procedures has also been considered to limit the adoption of the technique in many parts of the world. There is insufficient data on the performance of foamed asphalt in road pavements. Hence, the need to further study, understand and improve the effects of foamed asphalt on the performance behaviour and field properties of these cold mixes through sustained research and field trials cannot be over-emphasized. Besides, more work needs to be done in relating laboratory test results with field performance.

The work reported in this thesis examined the strength performance and behaviour of CIREAM that relates to low temperature cracking, high temperature rutting, and foam stability. Specifically, this research project was initiated to study:

- The early strength performance of CIREAM and associated problem such as moisture susceptibility, by investigating the effects of mixture variables such as moisture, asphalt type, binder content, conditioning time, and test protocols, on performance properties that relate to early strength and moisture resistance of foamed asphalt treated recycled mix.

- The study also investigates the high temperature deformation behaviour of CIREAM designs by evaluating the effects of binder content, asphalt type, and additives, on high temperature deformation resistance of mix.

- Foam stability of 300 penetration grade asphalt cement blended with different additives such as surfactants and waxes are examined in order to assess the effects of these additives and temperature on the characteristics of the foamed asphalt.

The entire research effort was designed to provide advice on potential improvements in the CIREAM process as it is currently carried out in Ontario.

CHAPTER 2

BACKGROUND ON PAVEMENT RECYCLING

2.1 Cold-in-Place Recycling

The cold-in-place (CIR) recycling process has been used to rehabilitate and upgrade all types of road pavements over the past two decades. The technology recovers and re-uses material from an existing pavement without the application of heat in an in-situ operation using a specialised recycling machine rather than hauling the material recovered from the road to a central depot (in-plant). The reclaimed material from the existing pavement is pulverized and mixed with binder (or stabilizing agent) after which it is placed, compacted and allowed to cure. A number of stabilizing agents are typically used, these include bitumen (emulsion and foamed asphalt), surfactants or wetting agents (e.g., sulphonated oils), modified waxes, cement stabilizers (e.g., Portland cement and/or lime), natural or synthetic polymers, petroleum resins, or hygroscopic salts (e.g., calcium chloride) [15]. The CIR recycling process utilizes a train of asphalt recycling equipment consisting of the milling drum housed in a mixing chamber which is usually coupled with supply tankers that add stabilizing agents (such as bitumen emulsion) and water to the reclaimed material through spray nozzles.

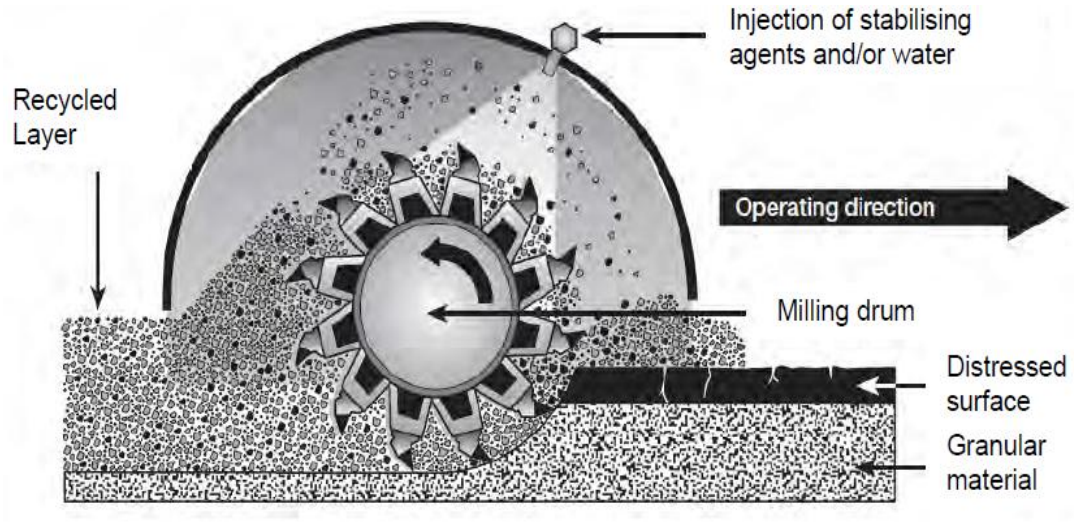


Figure 2.1 Pavement recycling in the mixing chamber (from Wirtgen, 2012) [15].

2.2 Cold-in-Place Recycling with Bitumen Emulsion (CIR)

Bitumen emulsion consists of bitumen emulsified in water using an emulsifying agent. Usually, the emulsion contains about 60 percent bitumen and 40 percent water. The bitumen is dispersed in the water in a way similar to an oil-in-water type of emulsion. The emulsifying agent used determines the charge of the bitumen emulsion. Cationic bitumen emulsion has a positive charge while anionic bitumen emulsion has a negative charge [15]. Emulsifying agents are “chemicals that are used to stabilize a suspension of asphalt in water” [16]. By migrating to the asphalt-water interface, emulsifying agents keep the bitumen droplets from coalescing thereby stabilizing the emulsion. Emulsifying agents are chemicals which consist of large organic molecules made up of two structural segments. These include the polar or charged, and hence, water-soluble part called the “head”, and the non-polar and water-insoluble “tail” which consists of long chain organic group that is soluble in organic materials such as oils and bitumen. The head consists of a group of atoms with positively and negatively charged areas [17].

In anionic emulsions, the “tail” segment of the emulsifying agent aligns with the bitumen while the positively charged part of the head interacts with the water and the negatively charged part of the head remains at the surface of the droplets. This leaves a negative charge on all the droplets which repel each other thereby keeping the bitumen droplets suspended or dispersed in water. A typical example of such emulsifying agent is one formed by reacting fatty acids and lignins derived from wood with sodium hydroxide to form soap which become negatively charged in water to give anionic bitumen emulsion, e.g. $C_{17}H_{35}COO^-Na^+$ [17, 18].

Cationic emulsifying agents function like the anionic; the negative part of the head interacts with the water leaving a positively charged head thereby imparting a positive charge on all the droplets. These positively charged droplets repel each other and remain suspended in the medium. A typical example are amines derived from wood acids or animal fats which form soaps and become positively charged in water to give cationic bitumen emulsion, e.g. $C_{18}H_{37}NH3^{+}Cl^{-}$ [17, 18].

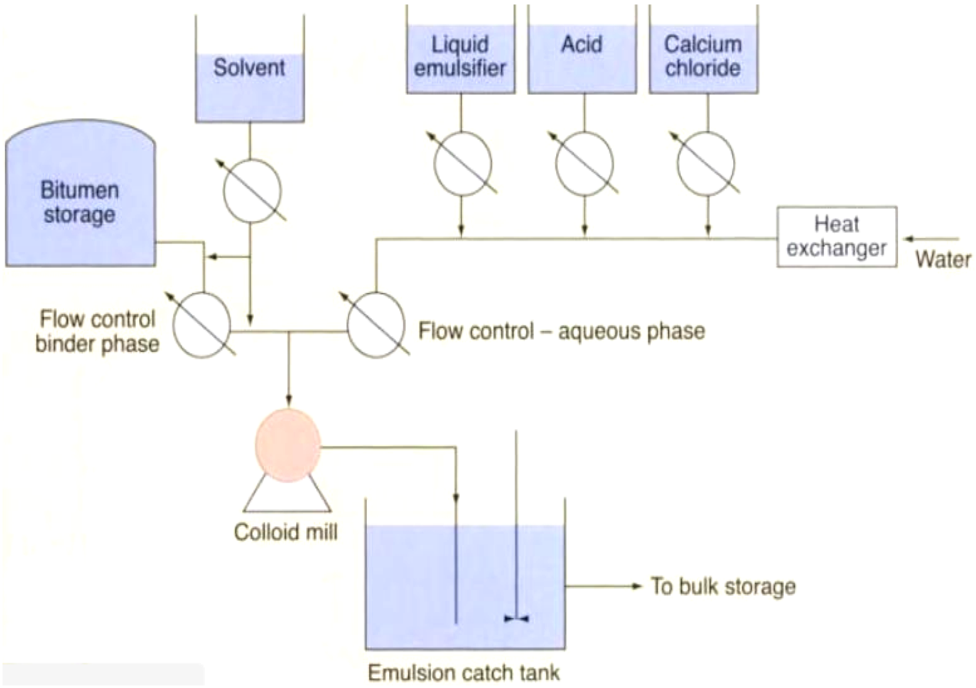


Figure 2.2 Schematic of a bitumen emulsion manufacturing process (reproduced from Reference [19]).

To produce bitumen emulsion, hot asphalt is mixed with water and emulsifier in a high-speed mixer known as a colloid mill. The high shear and emulsifier break the asphalt into droplets which are then dispersed in water. As the bitumen emulsion is mixed with the aggregate of the reclaimed material, the charged bitumen droplets attach to the oppositely charged aggregate particles, mostly the smaller particles due to their larger surface area and charge concentration feature. The dispersion of the bitumen emulsion and the separation of bitumen from water during mixing are dependent on moisture and the type of aggregate. Essentially, the bitumen should separate from the water only after the material is compacted because the emulsion also acts as a lubricating agent [15].

Bitumen emulsion has the advantage of being a liquid at ambient temperatures and so can be mixed with aggregates without the need for application of heat as required in hot mix asphalt [7]. Cold-in-place recycling with bitumen emulsion (CIR) provides structural improvement without altering the pavement geometry. The technology is used to correct many types of pavement distresses such as ravelling and rutting. Besides being environmentally friendly, the process eliminates hauling cost and also avoids premature aging of bitumen since no heat is applied [20]. However, emulsion treated recycled mix requires relatively longer curing periods. The porous nature of the mix necessitates the use of seal coat or hot mix overlay to prevent premature water damage [21].

2.3 Cold-in-Place Recycling with Expanded Asphalt Mix (CIREAM)

Cold-in-place recycling with expanded asphalt mix (CIREAM), like CIR, involves partial milling of an existing distressed asphalt pavement, and then sizing and mixing it with expanded (foamed) asphalt. This cold recycled mixture is then placed and compacted in-situ in one single operation [22]. The foaming technology was first developed in 1956 by Csanyi who injected steam into hot asphalt cement which caused the material to foam [23]. However, the original steam process was impractical for in-place foaming operations but it was suitable for asphalt plants where steam is readily available. The technology was later modified by Mobil Oil in Australia in the late 1960s by adding a mist of cold water (instead of steam) into a stream of hot asphalt in a low pressure expansion chamber. The technology has since been improved with the design of various simplified asphalt foaming system and efficient mixing processes. In the current technology, a small quantity of water is injected into hot bitumen at temperatures between 150°C and 180°C. The water evaporates and the vapour forms numerous tiny bubbles thereby causing instantaneous expansion (foaming) of the bitumen in the saturated steam to about 15 to 20 times its original volume. The foaming process increases the surface area of the bitumen and significantly reduces the viscosity thereby improving its mixing with, and dispersion on cold and moist aggregates. “Liquid asphalt binder at high temperature without foaming would immediately become globules when it contact cold aggregates and thus cannot be thoroughly dispersed” [24]. In the foamed state, the asphalt is mixed vigorously with the aggregates to ensure sufficient dispersion of the foamed asphalt before the foam finally dissipates and the bitumen regains its original properties. Several factors such as the temperature of the asphalt cement, volume of air and water added, and the pressure in the expansion chamber should be controlled to produce an effective foaming process. As the material is mixed, the foam bitumen coats the fines forming a mastic material (mortar) between aggregates which binds and stabilizes the mix [22, 25, 26].

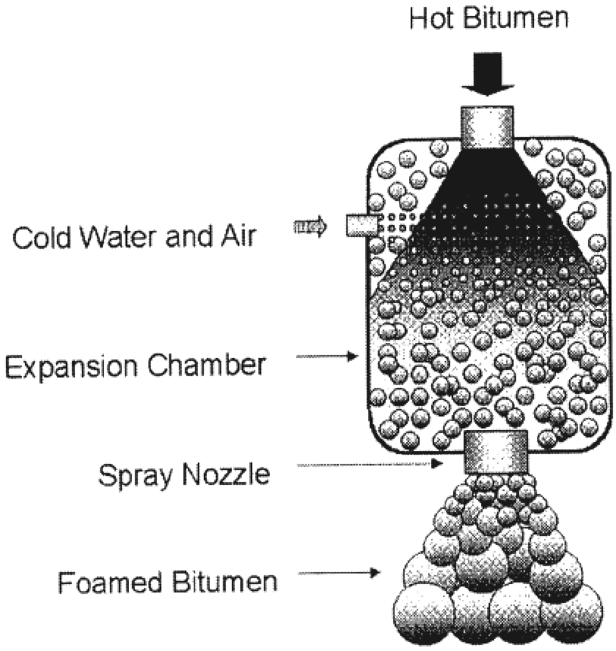


Figure 2.3 Asphalt foaming or expansion chamber (reproduced from Reference [27]).

2.4 Material Properties of Foamed Bitumen

Different bitumens behave differently when subjected to foaming processes due to their compositional differences which can be attributed to the source (origin) of the material. The foamability of an asphalt binder is the property which describes its potential of producing good quality foam. It is however different from the characteristics of the asphalt foam. Under different conditions such as temperature, foaming water content among others, a given asphalt binder can be processed to produce foams showing distinct properties. It is possible to produce foam with inferior foam characteristics from asphalt with good foaming potential if the foaming conditions are not well optimized. Hence, it is important to identify asphalt binders with good foaming potentials and also select optimum foaming conditions to produce good quality foam from the given asphalt [24]. The bitumen used for CIREAM is usually ordinary penetration-graded asphalt cement. The temperature must be controlled to get a suitable volume of foam from the foaming process. Sometimes, depending on the type of bitumen, a foaming agent is needed to counter the effect of antifoaming agent (silicone) added during the refining process of bitumen [26]. The characteristics of the asphalt foam have been studied by many researchers and practitioners. Foamed bitumen is characterized by two terms namely; expansion ratio and half-life. The expansion ratio is defined as the ratio of the maximum volume of the foamed bitumen to the original volume before foaming while the half-life is the time (in seconds) taken for the volume of the foam to collapse to half of its maximum volume. A suitable combination of expansion ratio and half-life is required to ensure effective dispersion and adequate coating of the fines by bitumen. “Foam with a higher expansion ratio has a larger surface area per unit mass and lower overall viscosity due to the thinner asphalt film” [24]. Consequently, such type of foam will not only coat more aggregate, but coat finer aggregates easily. The stability of the foam is indicated by the half life. More stable foams have more time to interact with the aggregates and so provide better aggregate coating. Abel [28] found out that softer asphalt (with a lower viscosity) foams more easily with high expansion ratio and a longer half-life than high-viscosity asphalts which on the other hand provide improved aggregate coating. The question arising is if softer asphalt which is more suitable for CIREAM can perform well during summer without premature and/or excessive rutting. The half-life and expansion ratio of any foamed bitumen is dependent on the amount of water used, temperature of foaming, and volume of foam produced. Increasing the foaming temperature and foaming water content results in higher expansion ratios but a shorter half-life [29]. Hence the choice of the optimum amount of foaming water is a trade-off between expansion ratio and half-life. Maccarone and coworkers [30] reported that by adding surface-active additives, they were able to produce foamed asphalt with high expansion ratios and a half-life greater than 15 and 60 seconds respectively. Iwanski and Chomicz-Kowalska [31] determined an optimum foaming water content of 2.5 percent as the amount needed to obtain the maximum expansion ratio and the longest half-life of foamed bitumen. Foaming properties (expansion ratio and half-life) are dependent on factors such as:

- Foaming temperature (temperature of the base bitumen);
- Type and/or chemical composition of bitumen;
- Foaming water content;
- Foaming agent used;
- Anti-foaming agent;
- The working pressure of bitumen, air and water; and
- Temperature of mixing chamber or vessel.

The foaming water content can be varied readily to improve the foaming properties of foamed asphalt [25].

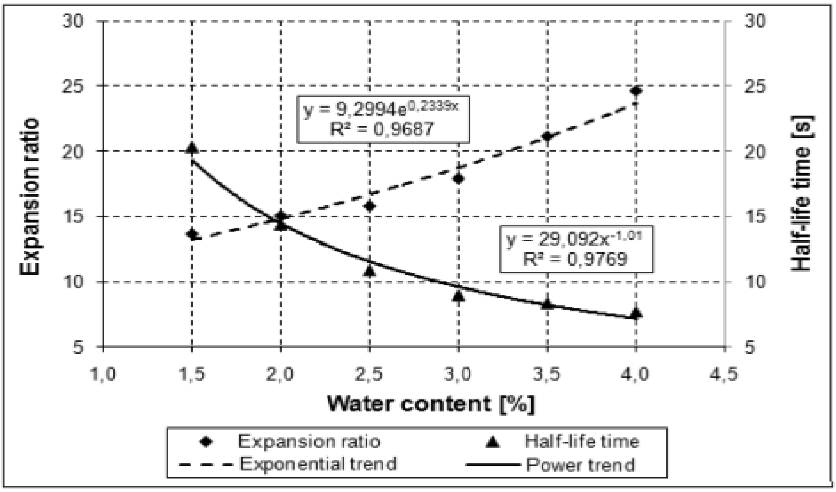


Figure 2.4 Dependence of asphalt foam characteristics on foaming water content [31].

2.5 Factors that affect CIREAM process

Essentially, the CIREAM process should reduce the moisture susceptibility, and increase the fatigue resistance, cohesion and stability of the untreated aggregate to desirable levels [32]. A number of factors should be considered for effective foamed bitumen stabilization of recycled pavements. These include bitumen binder properties (foaming potential and viscosity), foamed asphalt (binder) content, aggregate properties (temperature and fines content), processing conditions (such as moisture and temperature conditions), mixing techniques and additives (such as surfactant, Portland cement, polymer and lime). Some of these factors are discussed below;

- Bitumen binder properties: From the preceding discussion on the material property of foamed bitumen, it can be deduced that effective dispersion of foamed bitumen binder within the mix can be promoted by maximizing the expansion ratio and half life of the foam. By carefully selecting the foaming process conditions (such as temperature, pressure and foaming water content), more stable and highly expanded foam can be produced. Addition of surfactant to the binder prior to foaming will reduce the surface tension of the foams formed thereby increasing the half life and hence, the stability of the foam for better distribution and increased aggregate coating.

- Binder content: Due to its high affinity for fine aggregate, foamed bitumen selectively mixes with and coats finer aggregate particles. The foam interacts with the fines and filler to form a mastic material which binds and stabilizes the mix. Therefore the viscosity of the binder-fines mortar is critical to the mix stability and is dependent on the binder content and aggregate gradation. It is important to determine the optimum binder content needed to produce a mortar viscosity required for the desired strength and stability of the mix. Excess binder can result in a loss of stability (due to the lubricating property of the binder) while insufficient binder increases the water susceptibility of the mix [27, 32].
- Aggregate properties: It is imperative to consider the fines content of the aggregate in CIREAM processes. The material formed by the asphalt foam and fines has a higher viscosity than the raw bitumen and acts as a mortar between the aggregates to increase the mix strength. Sakr and Manke [33] explained that foamed asphalt mix with higher percentage of fines exhibit higher stability. In their work, they reported that aggregate interlock affects the stability of CIREAM more than the binder viscosity.

  The aggregate temperature before mixing also significantly affects the equilibrium mix temperature which in turn affects the rate at which the viscosity increases during mixing [27]. The rate of collapse (or stability) of the foam is influenced by the heat transfer from the foam at higher temperature to the aggregate at lower temperature. Bowering and Martin [34] suggested an optimum mixing temperature (13°C to 23°C) of aggregates for

CIREAM depending on the aggregate type and below which can lead to poor quality mixes.

- Moisture conditions: Many researchers consider the moisture content before and during mixing and compaction as the most critical factor in CIREAM process. Beside softening and breaking down the aggregate lumps, moisture also supports binder distribution during mixing and compaction. During mixing, the bubble rapidly collapse as the foam is agitated into the moist aggregate, partially coating the aggregate and leaving tiny bitumen droplets in the mix. Insufficient water reduces the mix workability because lumps of fine aggregate and binder are formed. Addition of appropriate amount of moisture to the mix produces a mastic (filler-binder) material with stiffness sufficient to impact the desirable strength and stability on the mix. However, excess water will not only extend the curing process and reduce the strength and density of the mix but also reduce the aggregate coating and early-life stability of the mix [27, 30, 32]. The moisture content at which the aggregate has its maximum bulk volume (fluff point) is recommended as the optimum moisture content for CIREAM (65%-85% of Modified AASHTO Optimum Moisture Content) [35, 36].
- Additives: The strength behaviour of CIREAM is dependent on moisture due to the relatively lower binder contents and high void contents (high permeability) of foamed asphalt treated mix. Franco et al. [37] reported that additive such as Portland cement and lime reduce the sensitivity of the mix to moisture. Ramanujam et al. [26] reported that lime acts as anti-stripping agent to aid dispersion of the foamed bitumen in the mix. It also agglomerates the clay fines in the material and stiffens the bitumen binder to increase the initial stiffness and early rut resistance of the compacted mix.

2.6 Curing in CIREAM

Injecting foamed asphalt on to agitated moist and cold aggregate causes the foamed asphalt to bind partially with the fines to form asphalt mastic or binder-fines mortar which is seen as small droplets in the loose mix. Before compaction, aggregate particles in the loose mix are mostly coated with a thin film (membrane) of water because most rocks are hydrophilic. After compaction, the binder-fines mortar droplets tightly bond with the aggregate particle but a limited bonding develops between asphalt and granular particles due to the water membrane because asphalt is hydrophobic. As the water evaporates, substantial bonding develops between asphalt and aggregate. Water in larger voids evaporates first as it is more difficult for water to evaporate from small voids due to lower thermodynamic potential at the asphalt mastic-aggregate particle interface. The mix develops strength as water evaporates and more bonds are formed between the aggregate particle and asphalt mastic droplets [38].

2.7 CIREAM Advantages

Whereas CIR could take as long as 14 days to cure, CIREAM rapidly develops sufficient structural strength for immediate trafficking after placement and compaction. The recycled base can be opened to traffic shortly after compaction to minimize traffic and construction delays [24, 25, 32]. Thus, CIREAM offers improved early strength characteristics. Some trials have shown that CIREAM requires a very small percentage of added asphalt cement to notably improve early strength [25]. It also allows for an extended construction season (paving period) as the process is less dependent on warm and dry weather as required for curing in CIR [24, 25, 32].

The CIREAM process offers strength characteristics comparable to that of cement treated materials and remains flexible; hence it is relatively more fatigue-resistant [39]. In addition, the mix has high air voids which significantly reduces reflection cracking [22]. Unlike emulsion stabilized CIR mixes, CIREAM requires less moisture and so, wet spots are much reduced. Kendall et al. [39] reported that after completion, CIREAM can tolerate rainfall with minimum surface damage when trafficked. Hence, CIREAM is less susceptible to moisture and other effects of weather than other techniques of stabilization.

In terms of economy, CIREAM significantly reduces the cost of energy (fuel) in two ways. One is saving fuels for haul vehicles. It eliminates the need of hauling away the reclaimed material from the cold planning operations to stockpiles because aggregates in the distressed pavement are 100% re-used. In addition, the need to transport hot mix asphalt (HMA) to replace the entire reclaimed materials removed plus additional pavement thickness is eliminated. Second, CIREAM saves the cost of generating energy to produce HMA, which is required for firing burners to heat up aggregates or asphalt cement [25, 32].

The technology is associated with minimum or negligible atmospheric pollution; it doesn’t involve evaporation of volatiles from the mix. The CIREAM process promotes the conservation of a non-renewable resource. CIREAM uses lower optimum binder contents. It can be stockpiled without leeching and the problem of ageing of binder in the plant is avoided. It has a wide range of applicability of materials because it can be used with a wider range of aggregate types than other cold recycling techniques [10, 32]. The CIREAM technology is carried out in-situ and so it is much quicker than other techniques of rehabilitation such as conventional HMA overlay.

2.8 CIREAM Disadvantages

In spite of the numerous benefits provided by CIREAM technology, there are still a number of difficulties associated with the process. A frequently observed issue is late season ravelling and potholing. Typically in Ontario, paving is carried out mid-year (summer) through the third quarter (fall season) of the year when the weather is relatively dry to keep a recycled pavement stable and suitable for traffic. However, during late fall, as the weather becomes wetter due to rain and cold temperatures, CIREAM is prone to low early strength and moisture damage which manifest as ravelling, coarse aggregate loss and potholes. A few examples are provided below with images courtesy of the Ministry of Transportation of Ontario.

(a) (b)

Figure 2.5 (a) CIREAM, several days after placement (b) CIREAM opened to traffic for less than one day.

Figure 2.5 (a) above shows CIREAM several days after placement and not yet opened to traffic. The surface appeares to be granular and loose, the aggregate can easily be removed.

Figure 2.5 (b) shows CIREAM opened to traffic for less than a day. Raveling in wheel paths and at the pavement edge was observed as the surface deteriorates and repair is required.

Figure 2.6 (a) is a newly processed and compacted CIREAM mat with an observable mid-lane streak as well as segregation on the right side of the paver. Figure 2.6 (b) is an enlarged image of the segregated area at the right side of the mat from Figure 2.6 (a).

(a) (b)

Figure 2.6 (a) Freshly processed and compacted CIREAM mat and (b) Close-up of medium to severely segregated area at the right side of the mat from Figure 2.5 (a).

(c) (d)

Figure 2.6 (c) Severe ravelling on CIREAM from Figure 2.6 (a) trafficked a few days after compaction and (d) shows very severe coarse aggregate loss (potholes).

Severe ravelling was observed on the late season processed CIREAM from Figure 2.6 (a) after it was opened to traffic for several days (Figure 2.6 (c)) probably caused by insufficient cohesion on the surface (unbound granular) due to the wetness that characterized the late fall season.

(a) (b)

Figure 2.7 (a) Severe ravelling and coarse aggregate loss and Figure 2.7 (b) Potholes occurring at construction joints.

CHAPTER 3

MATERIALS AND EXPERIMENTAL PROCEDURES

3.1 Materials

The recycled asphalt pavement (RAP) material used in this study was sampled from a contract on Highway 17 near Cobden, Ontario. The material consists of negatively charged dry surface (alkaline type) dolomite rock grains. The material was separated into small pieces and passed through a 26.5 mm sieve prior to use.

The bitumen emulsion used was a standard cationic medium setting emulsion from McAsphalt Industries of Scarborough, Ontario.

The asphalt cements used included an 80/100 penetration grade Cold Lake asphalt obtained from the Imperial Oil refinery in Strathcona, Alberta, a 300 penetration grade roofing flux asphalt (RAF) obtained from the Imperial Oil refinery in Nanticoke, Ontario, and a polymer modified asphalt (655-1) obtained during the construction of a pavement trial north of Timmins, Ontario.

3.2 Additives

Various mix property-modifying additives such as Portland cement concrete (PCC), polyethylene terephthalate (PET) fiber, epoxidized soybean oil (ESBO), a siloxane-based surfactant of proprietary composition, waxes and other asphalt modifiers (warm mix additives) were used in the study. The Portland cement used was a St. Marys® ordinary Portland cement (OPC) added at 1% and 2% by weight of the mixture to impact early strength of the samples and reduce moisture susceptibility of the mix. Portland cement is a hydraulic binder used as a basic ingredient of concretes and mortars. According to ASTM

C150, Portland cement is defined as “hydraulic cement (cement that not only hardens by reacting with water in a process known as hydration, but also forms a water-resistant product) produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate (or gypsum) as an inter ground addition". The clinker consists of a mixture of industrial minerals which include about 63 percent by mass of Alite and Belite (tricalcium silicate Ca_3SiO_5, dicalcium silicate Ca_2SiO_4 respectively), the remainder being aluminium- and iron-containing phases and about 5 percent by mass of magnesium oxide (MgO) [40]. Unlike CIREAM which cures by loosing water, PCC cures through the hydration reaction that requires water, therefore water lose and sometimes temperature must be controlled to enable the concrete gain strength and develop abrasion and cracking resistance.

A 0.5 inch length and 4 denier PET fiber obtained from the Edgefield Manufacturing Company in South Carolina was used in this study. Polyethylene terephthalate (PET) is a thermoplastic polymer resin of the polyester family [41]. PET consists of repeated units of polymerized ethylene terephthalate monomers. The polymer is strong, flexible and readily crystallizes above its transition temperature due to its structural regularity. The benzene ring in the main chain makes the chain stiffer resulting in higher glass transition (80°C) and crystalline melting (254°C) temperatures for the polymer. PET has poor chemical resistance to alkalis but good resistance to ultra-violet light. For environmental reasons, conventional PET products such as PET bottles are now recycled and reused for applications with little or no purity requirement such as in building materials like concrete and fiber concrete. PET fibers have been reported as a secondary concrete reinforcement material in the concrete industry for reducing plastic shrinkage or cracking tendency [41].

The epoxidized soy bean oil (ESBO) used in this study was obtained from a commercial source in Ontario. ESBO is a low cost vegetable oil (yellowish liquid) used as plasticizer and stabilizer in plastic materials especially polyvinyl chloride (PVC) and its copolymers. It is produced by oxidizing soybean oil with hydrogen peroxide and either acetic or formic acid. The application of ESBO as an asphalt modifier has been reported to lower the softening point and penetration of asphalt, while significantly increasing the ductility of the asphalt cement [42, 43]. ESBO was added (together with polyphosphoric acid catalyst) at 5% by weight of the binder.

The siloxane-based surfactant used was an organo-modified siloxane foam stabilizer obtained from a commercial source in Ontario. The surfactant was added at 1% by weight of the binder which was anticipated to improve the initial foam height and half life of the foam produced.

A number of additional additives were also employed in the foam stability test. These include two types of amine-based surfactant and a wax surfactant asphalt modifiers which are all hot and warm mix additives that reduce mixing and paving temperatures [44], two types of amine-based surfactant that also reduce mix temperature but exerts no effect on penetration and viscosity of the asphalt binder, and a paraffin-based wax which is capable of reducing bitumen viscosity as well as mixing and handling temperatures [45], all of which were obtained from different commercial sources with proprietary compositions. Others include a tall oil fatty acid surfactant (another asphalt modifier) and a naphthenic wax (warm mix additive) which both lower the mixing and paving temperatures of mix and obtained from commercial sources.

3.3 Experimental Procedures

3.3.1 Asphalt Foam Stability Studies

One of the critical factors in the CIREAM process is the bitumen binder properties. The optimisation of the material properties of foamed bitumen promotes effective binder dispersion which results in better field performance. Essentially, the foam stability studies of asphalt binder include among other things, viscosity measurement and the assessment of the foam characteristics (expansion ratio and half-life) of both unmodified asphalt binder and asphalt binder treated with different additives at several foaming temperatures and water contents. Other variables such as working pressure of bitumen and air should also be put into consideration.

Table 3.1 Asphalt binder blended with various warm mix additives for foam stability studies.

	COMPOSITION	SAMPLE TYPE
1	RAF	Control sample
2	RAF + 1% Tall oil fatty acid surfactant	Modified sample
3	RAF + 1% of 4 types of Amine surfactant	Modified sample
4	RAF + 1% Wax/surfactant additive	Modified sample
5	RAF + 1% Paraffin wax	Modified sample
6	RAF + 1% Siloxane foam stabilizer	Modified sample
7	RAF + 1% Naphthenic wax	Modified sample

In this work, several compositions of asphalt materials containing blended mixtures of 300 pen roofing asphalt flux (RAF) and 1 percent of various warm mix additives were prepared and shipped to the Akzo Nobel Surface Chemistry laboratory in Brewster NY, where the foaming experiments were carried out by Ms. Christine Gorsuch who also wrote a report on the foam stability test. Her effort is hereby acknowledged and appreciated. Twelve one gallon containers of asphalt binders were sent for the project and were prepared as shown in Table 3.1 above.

This study includes a preliminary work carried out with the control binder (unmodified RAF sample) and the assessment of several samples of warm mix modified RAF asphalt binder. In the preliminary studies, the viscosity of the RAF binder was measured with a Brookfield DV-I+ viscometer, spindle 31 and with Thermosel for temperature control in order to determine the mixing temperature range for the RAF binder. This was followed by the foaming process using a foamer designed by Pavement Technologies Inc. (PTI) as shown in Figure 3.1 below.

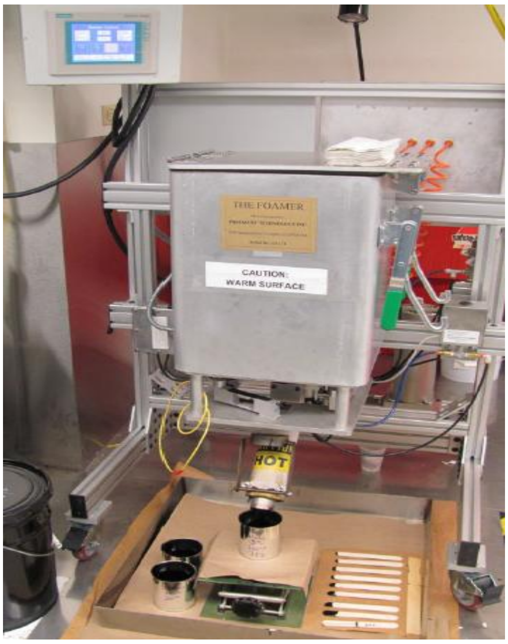


Figure 3.1 Pavement Technologies Foamer.

The test was initiated by entering the experimental variables (temperature, water content and batch size) in the control panel. The asphalt tank, housed by a large metal enclosure sits on a load cell which allows for the control of batch size. At the tank bottom is a valve which opens at the start of the test and closes when the mass change equals the target batch size (gravity flow). The viscosity of the asphalt binder at the test temperature determines the batch time. The foamer produces foam through a nozzle system comprising asphalt nozzle and water-air nozzle. The water-air nozzle receives air from the back and water from the bottom while the nozzle directs the combined atomized air-water spray downward toward the foam chamber. The asphalt stream and the air-water stream combine in the nozzle to form the foam which flows through a heated exit tube at the bottom of the foamer. The PTI foamer produces small batches of foam, typically a batch of 100 g in 6-12 seconds which is much slower than a Wirtgen lab foamer. Air supply is controlled at about 30 psi while water flow is regulated by an electronic proportional valve (EPV) from the water tank pressurised with air to about 30 psi. The foaming water content was varied from 1 percent to about 5 percent while samples were tested at 115°C, 125°C, 135°C and 145°C. The foam batches were dispensed into quart metal cans preheated to about 60-70°C.

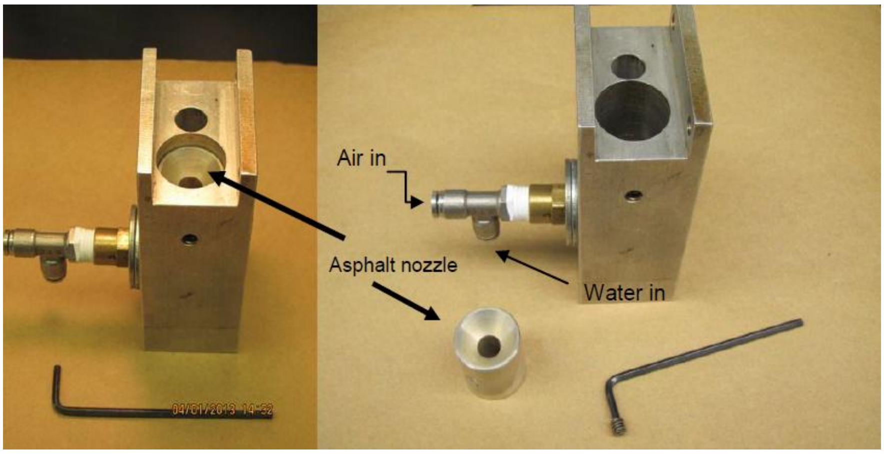


Figure 3.2(a) Asphalt nozzle.

Figure 3.2(b) Water-air nozzle (from bottom).

The foam expansion ratio (ER) and half life were measured for each foam test. Expansion ratio (ER) is the increase in volume of the foam which was determined by measuring the maximum height of foam divided by the minimum height. The minimum height for a 100 g batch size in the quart can containers was 1 cm in these experiments; the maximum height was observed from a paper ruler pasted on the inner wall of the container. Half-life is the time in seconds, taken by the foam to collapse to half of its maximum height. The half-life was measured by taking photos of the foam experiments every 1 second with a GoPro camera and then measuring the foam height in the photos by visual estimation and using Image J software. Depending on the choice of time zero, the half-life can be calculated in different ways which include starting from the time the foaming starts, starting from the time the foaming stops (nozzle off) and starting from the point of maximum expansion. The half-life was calculated in two ways for these experiments. One was from the time the foam nozzle shuts off and the other was from maximum expansion. The foam continues to expand after the nozzle shuts off giving a shorter half-life measurement when starting from maximum expansion.

Figure 3.3 Sample can for half-life measurement.

The preliminary study was followed by an assessment of the foam properties of several samples of warm mix modified RAF asphalt binder. These samples were also foamed with the PTI foamer and tested under the same conditions as the control RAF binder. The mixing temperature range was determined to be 134°C-140°C for the RAF binder in the preliminary study and the highest expansion ratio was obtained at 135°C with 3 percent foaming water content. About 5 warm mix-modified samples were selected and tested in foamed asphalt binder produced at 135°C and 115-125°C with 3-4% water content for comparison with the neat control RAF binder. The selected samples included RAF samples modified with 1% siloxane based surfactant, 1% amine type surfactant (A), 1% Tall oil surfactant (B) and 1% of two different types of amine-based surfactants labelled (C) and (D). The foam properties and binder viscosity were measured as described for the neat control RAF binder.

3.3.2 Indirect Tensile Strength (ITS) Testing

The indirect tensile strength (ITS) test protocol [46] according to ASTM D693, is a useful experimental method developed to evaluate the strength and creep properties of compacted bituminous mixes. In addition to being simple and easy to set up, the ITS procedure provides a rapid rate of testing and as such it is frequently employed in civil engineering. The test involves applying a monotonic load to cylindrical specimens up to the maximum stress of failure. Typically, the ITS test consists of two vertically positioned compressive forces applying a single load parallel to and along the plane of the specimen diameter. The diameter of the specimen is usually 100 or 150 mm and the thickness about 45 or 75 mm (± 5 mm). The loading configuration induces a relatively uniform horizontal tensile stress perpendicular to the direction of the applied load until the specimen fails by splitting along the vertical plane or diameter [10, 47]. The load is applied at a specified deformation rate (e.g. 50

mm/min) and the peak load at failure is used to determine the ITS of the specimen. Breen and Stephen [48] stated that the indirect tensile strength (ITS) test can be applied to materials having an ultimate compressive strength three times their ultimate tensile strength. They suggested that asphaltic mix meets this condition at low temperatures. Due to the compressive stress along the transverse direction during ITS testing, the stress state is not uniaxial and the stress is redistributed due to the non-linearity of materials [49]. Vasconcelos and coworkers [50] explain that the peak load at failure is used to determine the indirect tensile strength of the specimen using the elasticity theory without considering the effect of multi-axial states of stress. The authors explained that the ITS value gives an assessment of the bituminous mixtures and determines the potential to moisture damage by evaluating results of both moisture-conditioned and dry specimens. The susceptibility of cold mixes to water damage is quite important in the behaviour of mixes under wet conditions during and just after significant rainfall. Water hinders the effective binding of the aggregate by the cement (foamed asphalt cement or emulsion) resulting in a loss of strength. Asphalt binder viscosity is sufficiently low at high temperatures to allow relaxation of the tensile stresses by accompanying flow. On the other hand, at low temperatures the binder will have low ductility and the tensile stress will build up until the tensile strength is attained and failure (splitting) occurs.

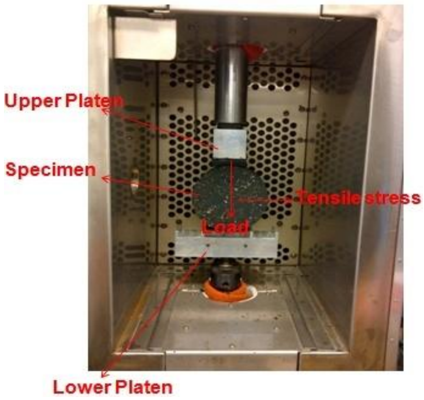


Figure 3.4 Indirect tensile strength (ITS) test.

$$\text{ITS} = \frac{(2 \times P) * 10000}{\pi \times D \times H}$$

P = Peak load (kPa);

D = diameter of briquette (mm); and

H = height of briquette (mm).

The ITS test evaluates the strength and creep properties of compacted bituminous mixes by presenting an analysis of the peak load at failure, peak energy, indirect tensile strength, vertical and horizontal strains among others. The most important requirements of a pavement is the ability to sustain traffic load and then sufficiently distribute and reduce the stresses transmitted from wheel loads, so that they do not exceed the sub-grade strength. The pavement strength is the load-bearing capacity of the structure until the point of failure while the strain measures the ability of the pavement to distribute the stresses over a wider area down the profile through viscoelastic deformation (or movement) without failure (Figure 3.5). The magnitude of the strain tolerated (creep behaviour) by the pavement prior to failure is a measure of its resistance to cracking.

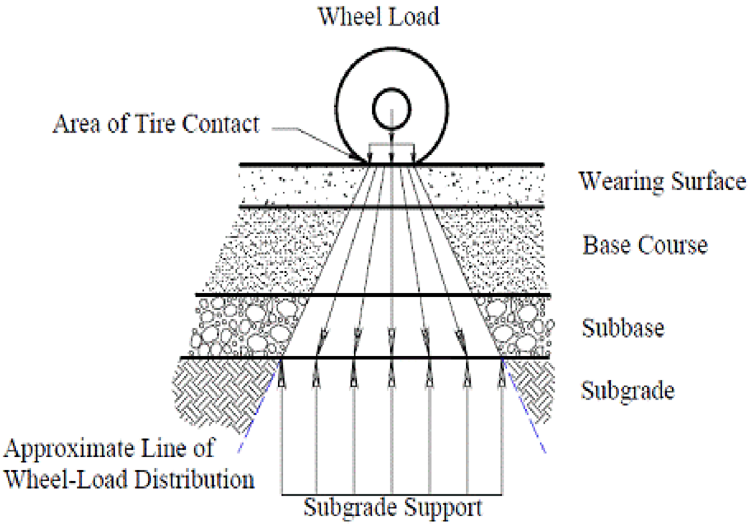


Figure 3.5 Distribution of load stress in flexible pavement [51].

3.3.3 Uniaxial Cyclic Compression Test with Partial Confinement (UCCTC)

Uniaxial cyclic compression testing with partial confinement (UCCTC) [52] is a reliable and rapid laboratory procedure used to investigate the deformation behaviour of compacted bituminous mixtures. This test was developed to assess the deformation resistance of asphalt mixtures under the German Technical Regulations for Testing Asphalts for Road Construction [53]. According to Karcher [53], the UCCTC involves subjecting a cylindrical asphalt specimen (diameter 150 mm, thickness 45 mm) with plane-parallel surfaces to a haversine-shaped cyclic compression load pulse using a centrally positioned die. A die of about 56 mm diameter is suitable being smaller than the diameter of the specimen (providing some lateral confinement) while the test is conducted under isothermal condition of 50°C and dynamic loading to simulate wheel passage. Irreversible deformations of the specimen along the load direction are evaluated based on the axial strain for every load cycle during the test. A test can be completed after 2500 cycles or 5 mm penetration depth as larger penetration results in deformations that are off-limit and can falsify the result [53]. Dołżycki and Judycki [54] found that both cohesion and internal friction of mineral aggregate are responsible for the response of asphalt mix to external load. They considered the prediction of asphalt mix behaviour and evaluation of mix quality based on results of cyclic compression creep test with lateral confinement fully reliable. Asphalt surface layer of a pavement structure is subjected to both vertical compressive stress induced by wheel loads and to horizontal compressive stress created by the response of surrounding medium to external loading. The asphalt material is confined by horizontal compressive pressure which hinders its lateral movement resulting in internal friction of the aggregate. The mobilization of this aggregate internal friction enhances the resistance of the mix to permanent deformation. In test without lateral confinement the lateral movement of material is restricted mostly by bitumen binder cohesion while aggregate internal friction is not fully mobilized. The test without lateral confinement therefore overestimates the role of bitumen binders in mix resistance to permanent deformation at high temperature and may not always provide realistic result [54]. In principle, an impulse creep curve shows three phases. The first phase consists of strong initial deformation with strain rate and creep rate decreasing with load cycles, the strain rate and creep rate are approximately constant with a turning point during the second phase while the third phase is a region of increasing deformation. The pulse creep curve in the second phase is critical in the evaluation of the deformation behaviour of asphalt mix. Usually mixtures having high deformation resistance lack the third phase. The strain rate at the turning point is the most critical parameter for evaluating the deformation behaviour of asphalt mixtures. The higher this strain rate, the lower the deformation resistance of the specimen. The deformation can also be evaluated using the penetration depth (in mm) as a function of the number of cycles.

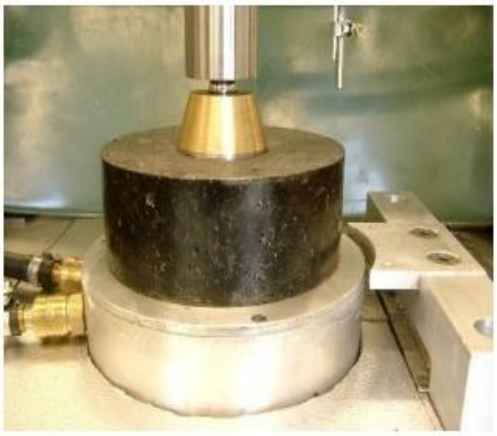


Figure 3.6 Uniaxial cyclic compression test with partial confinement (UCCTC) [53].

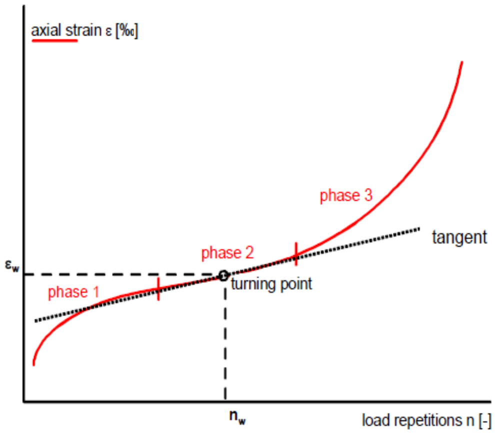


Figure 3.7 Creep curve showing tangent at turning point [53].

3.4 Sample Preparation and Conditioning, and Test Protocols

The screened material was prepared for briquette manufacture according to procedures specified in Test Method LS-297 [55] of the Ministry of Transportation, Ontario (MTO) laboratory testing manual. According to the procedure, about 10 kg of the sieved aggregate was weighed and then mixed with different amounts of additives and cement binder (foamed asphalt and asphalt emulsion) to make mixtures of different compositions. A moisture content of 80 percent of modified AASHTO optimum moisture content (OMC) was selected for the mix design. The asphalt cement and the one percent moisture content of the RAP were considered to be part of the 80% of OMC. Prior to the addition of additives and binder, the agitated material was moisture-conditioned in the mixer by adding a predetermined amount of water calculated as the remainder after 1 percent moisture content of RAP plus the amount (percent) of moisture content of cement binder are subtracted from the 80 percent of optimum moisture content (OMC) which was reported as 6.8 percent of the mixture; OMC being the moisture content at which the maximum density is obtained for a specific compactive effort. The mixture was then agitated continuously for about two minutes in the mixer to ensure a reasonable degree of binder dispersion and homogeneity of the mixture. Finally, 6 portions of equal amounts were weighed from the mixture and compacted to produce 6 core samples using a gyratory compactor. In this manner several batches were made, each containing varying amounts of foamed asphalt, emulsion, cement, and additives in order to study the behaviour of the mix under different conditions. Different compositions of mix were made by mixing the aggregate with varying amounts of water, asphaltic emulsion, foamed asphalt and additives. The 80/100 penetration grade Cold Lake asphalt, 300 pen grade roofing asphalt flux (RAF), and polymer modified asphalt (655-1), were used in making the foam for the different CIREAM mixes. By using a gyratory compactor, the core samples were compacted to 150 mm diameter and 45 mm height to obtain comparable air voids content in identical samples (of the same mixture batch). A number of samples of 47 mm in height were also made to investigate the effect of air voids on mixture performance.

Figure 3.8 Gyratory compactor.

Samples were subjected to different conditioning protocols after compaction. These included placing under water for 24 hours, in a fridge at -15°C for 24 hours, in an oven at 50°C for 72 hours, and reference standard conditioning of air-drying at room temperature for 24 hours. Samples were prepared for digital image correlation (DIC) before actual testing for failure strain analysis. Samples were finally conditioned in the environmental chamber of an MTS

810 servo-hydraulic test frame at 10°C for about an hour prior to ITS testing. For the DIC, one side of each specimen was spray-painted a solid black colour followed by a white speckle pattern. In addition, a centrally positioned square (8 cm x 8 cm) was drawn on the painted side of each sample as shown in Figure 3.9. These preparations were made to enable accurate identification of the failure point during the test. As the test proceeds, a number of pictures of the sample were taken using a Point Grey research camera placed directly in front of the MTS test frame chamber window with all lights facing the machine's window turned off to avoid reflection. These series of pictures are taken in order to monitor and capture the failure point. The camera is connected to and controlled electronically by a computer program which is run simultaneously with the ITS testing.

Figure 3.9 Picture of a sample after ITS experiment, showing the painted side used for the digital image correlation (DIC).

A number of variables are entered into the ITS test system software application. These include rate of applied load (5 mm/min was used in this experiment), platen separation (which is the specimen diameter, typically 150 mm) and maximum strain of 100 percent. Samples are positioned between the actuators such that the 8 cm x 8 cm square is upright while the camera is adjusted to focus directly on the sample. The camera is programmed to take 20 pictures per minute and typically about 30-50 pictures is a suitable amount for the

DIC. The test is stopped when a visible crack is observed. The indirect tensile strength was determined by measuring the ultimate load to failure of the specimen under a constant loading rate of 5 mm/min at 10°C. The rate of capture during the test can be calculated as follows.

(20 pictures/min)/(5 mm/min) = 4 pictures/mm

Therefore, four pictures were taken for every millimetre moved by the compressing actuator. By multiplying the extension at peak load by four, the picture at peak load can be determined and identified in the series of pictures taken during the test. The extension at peak load is determined by magnifying the area around the peak load in the stress-strain curve until an accurate reading of peak load is generated to at least one decimal place. The picture of fracture is identified by a visual inspection of the picture series to choose the one just before the first visible crack. The strain analysis is done using a Vic 2D program to determine the horizontal and vertical strains at peak load and fracture from the picture at peak load and at fracture. Several properties were analyzed from the test result. These included peak load, energy to peak load, indirect tensile strength (ITS), percent vertical and horizontal strain (through DIC), among others.

For UCCTC testing, samples where conditioned at room temperature for seven days followed by two hours at 50°C just prior to testing. Such conditioning ensured specimens were fully cured in order to simulate prevailing field conditions. The tests were terminated either at a total of 5 mm deformation or after 3000 cycles, depending on the completion criteria first attained. In the cyclic creep test, cylindrical specimens were subjected to axial loading of maximum 1000 N stress and minimum 62.5 N stress, applied for 0.1 seconds, followed by 0.9 seconds rest periods. The test consisted of the application of 3000 load cycles although a number of specimens failed before the completion of 3000 cycles and such test were considered completed and terminated. The maximum test duration observed was about 5000 seconds. A layer of Teflon sheet is placed between the die and specimens in order to prevent friction which can interfere with the rate of steady loading cycle resulting in deviation from the ideal creep curve pattern. For the type and grade of asphalt mixes tested under the applied load, a penetration beyond 5 mm will create excessive multi-axial stress system which results in multi-directional cracks and/or splitting of the specimen such that an accurate point of failure (usually within the third phase of creep curve) cannot be determined thereby rendering the result invalid.

CHAPTER 4

RESULTS AND DISCUSSION

This study was carried out to investigate the effects of mixture variables such as asphalt binder content, asphalt type and additives on the performance properties that relate to early strength, moisture resistance and rutting susceptibility of CIREAM in comparison to the regular cold in-place recycling process or emulsion-treated mixes (CIR). An assessment of the foam properties of 300 pen RAF binder was also carried out. The results reported in this work are mean values and the uniformity of the test was assessed using the coefficient of variation (COV) to determine the values of dispersion around the averages. Most of the mean values for the ITS, percent vertical and horizontal strain from ITS testing, and strain rates from UCCTC had COV’s less than 15 percent for the various mixture compositions and conditioning protocols. The error bars shown in the results are COVs (ratio of standard deviation to mean values). Standard deviation was also determined for the results of the foam stability tests. Early strength and moisture susceptibility of the CIREAM mixtures were assessed using indirect tensile strength (ITS) testing during same day as the sample preparation and with moisture conditioning respectively. Permanent deformation resistance of the CIREAM mixtures was assessed using strain rates at inflection point and dynamic penetration depth determined from uniaxial cyclic compression test with partial confinement (UCCTC). The optimum binder content was selected based on the relationship between indirect tensile strength and foamed asphalt content as recommended by Muthen [32].

4.1 Asphalt Foam Stability Studies

The viscosity versus temperature profile for the control RAF binder is shown in Figure 4.1. The viscosity was measured to determine the mixing temperature range for the asphalt binder, which is the temperature at which the binder viscosity is 170 +/- 20 cP as laboratory mixing temperature is selected to give a target viscosity of 0.17 +/- 0.02 Pa.s or 170 +/- 20 cP [56]. The measured viscosity of the RAF control binder was lower than values for asphalt binders previously foamed in the Akzo Nobel laboratory and the data was compared with that of a PG 64-22 binder. The mixing temperature range (determined as 134-140°C for the RAF binder) was used as a starting point for foaming of the RAF binder. Experience has shown that a temperature above the mixing range produces better foam properties (greater expansion) but the RAF binder behaves differently.

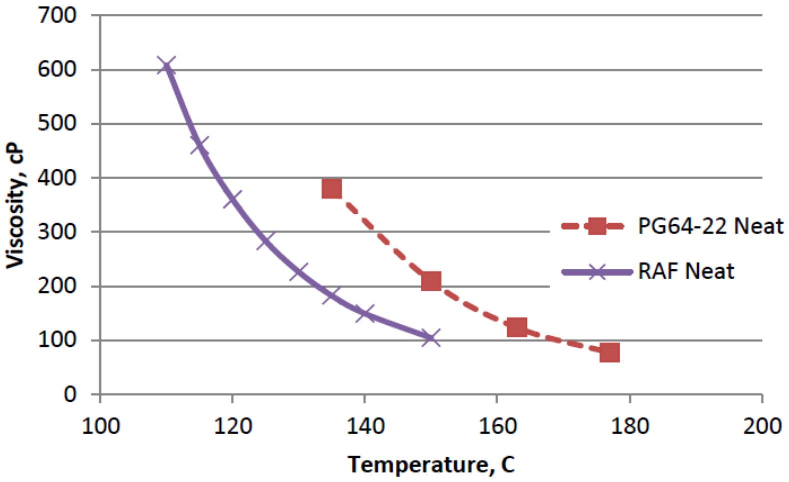


Figure 4.1 Viscosity versus Temperature for RAF control and a PG64-22 binder. (data courtesy of Christine Gorsuch of Akzo Nobel, Brewster, NY)

Figure 4.2 shows the expansion ratio data for the RAF control binder. The sample was tested varying the foaming water contents from 1.0% to 4.8% at 115°C, 125°C, 135°C and 145°C. The highest expansion ratio was obtained at 135°C and with 3% water content. The foam collapsed very quickly resulting in a limited expansion at lower and higher temperatures. At 115°C, the foamed binder leaves the nozzle slowly while at 140-145°C, the foamed binder appeared thin and very fluid. Qualitatively, the foam consistency at 135°C seems to be the best but appeared fluffy and pudding-like at water contents above 3%.

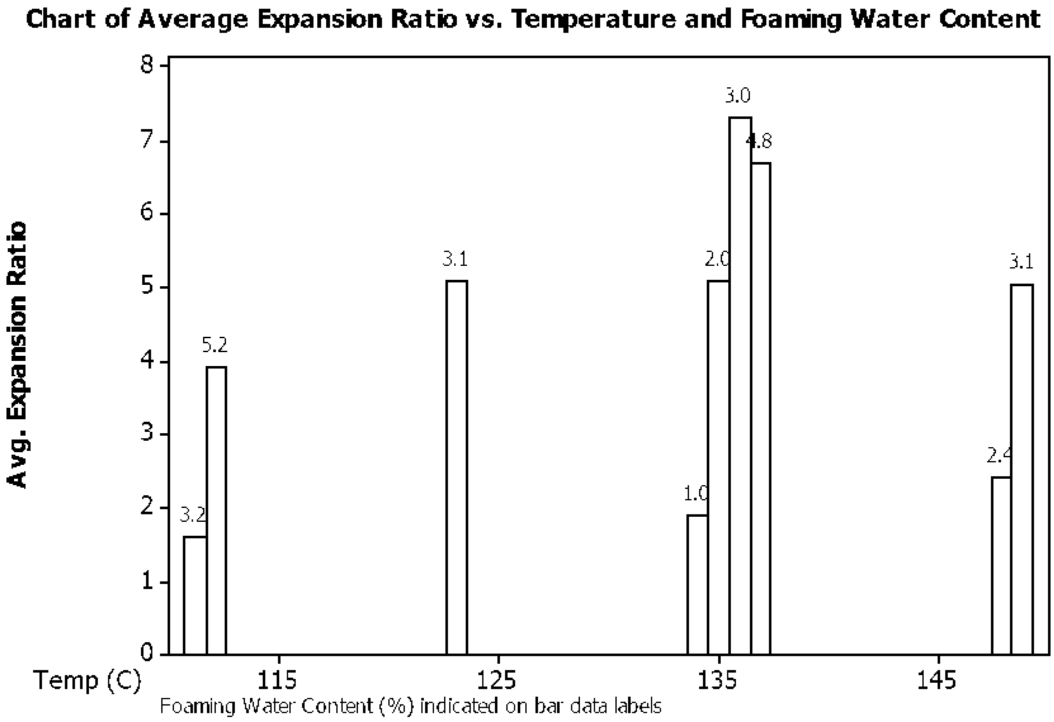


Figure 4.2 RAF Control Binder Foam Expansion Ratio versus Temperature (data courtesy of Christine Gorsuch of Akzo Nobel, Brewster, NY).

Table 4.1 Foam Properties of RAF Control binder (Data courtesy of Christine Gorsuch of Akzo Nobel, Brewster, NY).

Temperature (°C)	Water (%)	Expansion Ratio	Half-life (s), T1, from nozzle off	Half-life (s), T2, from max. height
115	3.2	1.6	NA	NA
115	5.2	3.9	76	61
125	3.1	5.1	30	19
135	4.8	6.7	43	39
135	**3.0**	**7.5**	**40**	**36**
135	2.0	5.1	88	75
135	1.0	1.9	NA	NA
145	3.2	5.1	84	75
145	2.4	2.4	267	255

* Half-life cannot be calculated when the foam expansion ratio was less than 2 cm.

Table 4.1 shows the expansion ratio and half-life data for the RAF control binder. Averages of two to three tests were reported for data at 125°C, 135°C and 145°C at 3% while data at 115°C and 145°C at 2.4% water is one test each. Standard deviations were calculated for samples tested in triplicate. For the 3 runs at 135°C and 4.8%, the standard deviation of the ER is 0.6 cm and 9.5 s for the half-life. For the 3 runs at 135°C and 3% water content, the standard deviation of the ER is 0.7 cm and 11 s for the half-life. A higher expansion ratio can be related to reduced viscosity, better binder dispersion in the mix and hence, better field performance. Half-life measures the foam stability. Iwanski et al. [31] reported that the minimum recommended combination of expansion ratio (ER) and half-life ($\tau^{1/2}$) vary according to industry standards. In California, minimum ER is 10 and minimum $\tau^{1/2}$ is 12 seconds, Asphalt Academy [57] in Pretoria, South Africa recommends 7 for minimum ER and 7 seconds for minimum $\tau^{1/2}$. Wirtgen manual [58] in 2004 recommended minimum of 10 for ER and 8 seconds for $\tau^{1/2}$, in 2010, the manual recommended minimum ER of 10 for aggregate temperature between 10°C to 25°C or minimum ER of 8 for aggregate temperature greater than 25°C and minimum $\tau^{1/2}$ of 6 seconds [59]. Muthen [32] recommends minimum ER of 10 and minimum $\tau^{1/2}$ of 12 seconds. Based on these recommendations, it can be said that the RAF binder exhibits poor foaming properties given its limited expansion.

The viscosity versus temperature profile of the selected warm mix modified RAF binder samples is shown in Figure 4.3 below. As anticipated, none of the warm mix additives change the viscosity of the binder significantly.

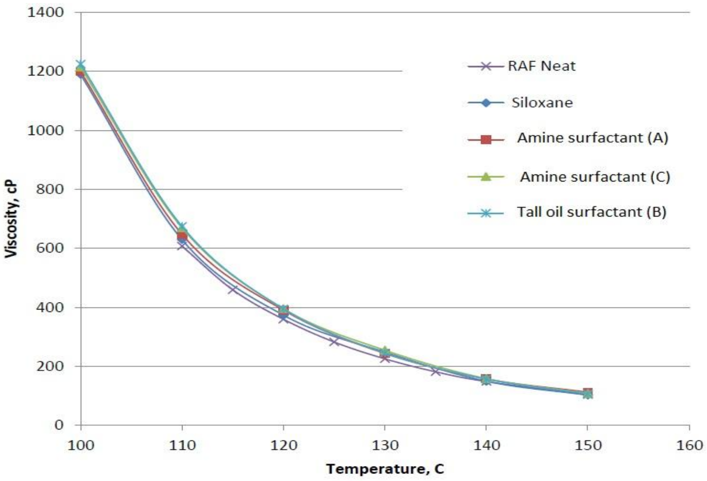


Figure 4.3 Viscosity versus Temperature for warm mix modified RAF and neat control RAF binder. (Data courtesy of Christine Gorsuch of Akzo Nobel, Brewster, NY)

Table 4.2 below shows the foam properties for the binder modified with several warm mix additives. Although 3% water content was targeted for all the experiments, small changes in asphalt flow rates during the tests resulted in some differences in the actual water contents. The data for the siloxane tests at 135°C and for surfactant (C) are not included due to problems with the foamer water nozzle control during the tests. It was observed that the siloxane additive produced foam with a noticeably different structure, thicker, having a meringue-like consistency and finely dispersed small bubbles (see Figure 4.4 for photo). The siloxane foam was thick and fluffy at the two temperatures tested. The thickness retarded the flow of the material into the receiving can and as a result, the recorded expansion ratio was lower than actual for the siloxane foam.

Table 4.2 Foam properties for RAF binder modified with warm mix additives.

Temperature (°C)	Water (%)	Expansion Ratio	Half-life (s), T1, from nozzle off	Half-life (s), T2, from max. height
Neat RAF binder				
125	3.1	5.1	30	19
135	3.0	7.5	40	36
RAF + 1% Siloxane based foam stabilizer				
120	3.7	4.0	110	80
135	-	-	-	-
RAF + 1% Amine surfactant (D)				
120	3.5	6.1	37	19
135	3.5	6.8	37	31
RAF + 1% Amine surfactant (A)				
120	3.5	4.8	67	48
135	3.3	5.3	85	75
RAF + 1% Tall oil surfactant				
120	3.5	5.0	29	11
135	3.2	6.6	41	34

The foam collapses as it piles up slowly and fills the voids settling into an uneven foam surface. A little build-up near the centre was observed for most of the asphalt foam samples tested, much more pronounced for the siloxane modified sample and was not accounted for in the measurement technique. The expansion ratio and half life measured were consistent for the siloxane foam batches at lower temperatures. The standard deviation of the expansion ratio was 0.2 and 17 seconds for half-life. The expansion ratio varied more between runs for the higher temperature tests probably due to a water nozzle problem. The Amine surfactant (D) produced foam with a pudding-like consistency (see photo in Figure 4.4 (b)). The expansion ratio and half-lives of the 135°C batches were consistent, with a standard deviation of 0.2 for the expansion ratio and 4 s for the half-life. For the amine surfactants, the expansion ratio is slightly lower than that of the neat control binder but the half-life is not significantly different. The foam with amine surfactant (A) appeared similar to that produced with amine surfactant (D) (see photo in Figure 4.4 (c)) but less expansion. In the lower temperature tests, the Tall oil surfactant produced foam with thin viscosity and a warm mousse consistency. At higher temperature, the foam produced had a thicker more pudding-like structure and a higher expansion. The results for batches at the two temperatures were consistent in expansion and half-life.

(a) (b) (c)

Figure 4.4 (a) RAF foam with siloxane additive; foam is thicker, more viscous and with visibly finely dispersed bubbles (b) RAF with amine surfactant (D); pudding-like fluffy foam (c) RAF foam with amine surfactant (A); pudding-like fluffy foam.

Overall, the modified binders produced foams with lower expansion ratios than the neat control RAF binder at similar temperature and water contents. Amine surfactant (A) and (D), and the tall oil surfactant produced foam with similar consistencies which appeared pudding-like fluffy with a mixture of bubble sizes. From Figure 4.5, amine surfactant (D) and tall oil surfactant produced the foam with the closest expansion ratio to that of the neat binder. The Siloxane additive produced foam with a noticeably different structure, thicker and finely dispersed small bubbles but with the least expansion of all the samples tested. Siloxane additive extends the half-life (stability) of RAF foam by almost a factor of 3 while amine surfactant (A) doubles the half-life of foamed RAF binder (Figure 4.6). Tall oil surfactant impacts no significant effect on the half-life of foamed RAF binder.

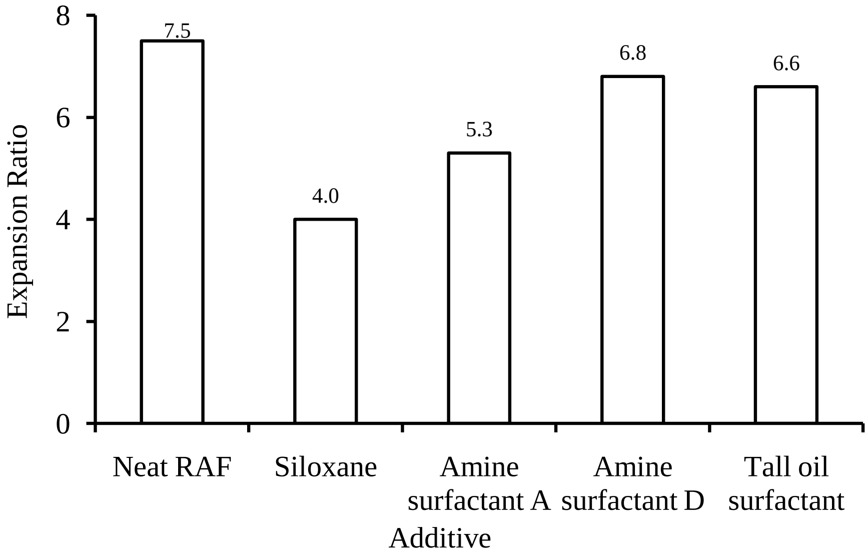


Figure 4.5 Effect of warm mix additive on expansion ratio RAF binder.

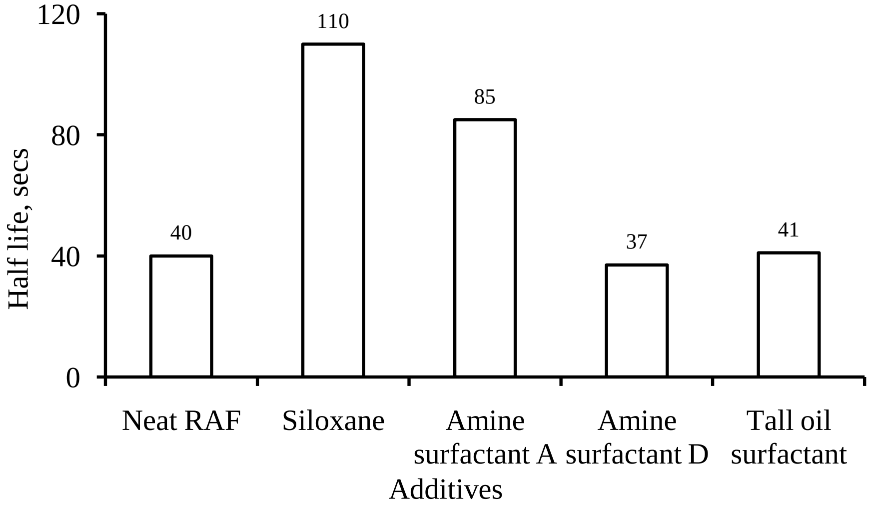


Figure 4.6 Effect of warm mix additive on half-life of foamed RAF binder.

4.2 Indirect Tensile Strength (ITS) Testing

4.2.1 Asphalt Content

Figure 4.7 (a), (b) and (c) show that the foamed asphalt (binder) content used in the CIREAM process exerts a significant impact on the strength performance of the mix. The result in Figure 4.7 (a) reveals that the indirect tensile strength (ITS) increases as binder content increases up to 2 percent, after which the ITS begins to decline. This suggests an optimum binder content of around 2.0 to 2.5 percent, depending on the nature of the pavement to be recycled. The observed trend is in line with results reported in several other studies which suggest an optimum binder content for foamed asphalt stabilized recycled pavement. Many studies have reported an optimum binder content of about 2 percent to 3 percent depending on the nature of aggregate used, e.g. Iwanski et al. [31], Gonzalez et al. [60] and Chiu et al. [61]. The foamed asphalt binder stabilizes the mix within this range but acts as a lubricant on the aggregate when in excess, thereby resulting in a loss of strength and stability.

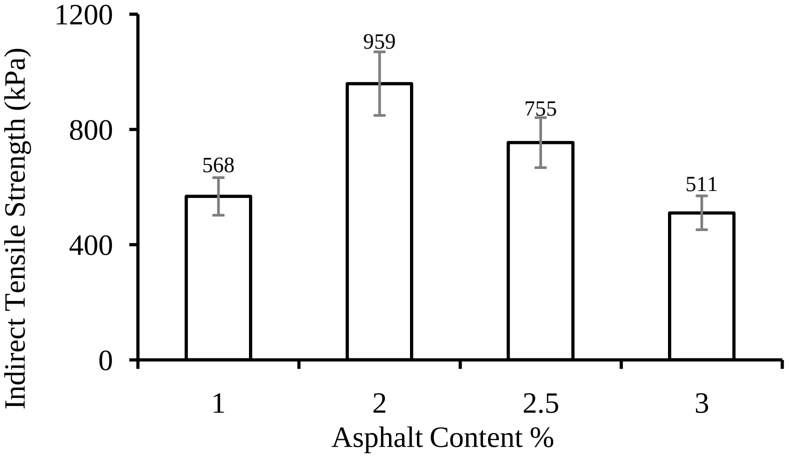


Figure 4.7 (a) Effect of asphalt content (binder content) on ITS.

In Figure 4.7 (b), 3 percent binder content shows the highest percent vertical strain probably because the amount of compressive strain a compacted asphalt mix is capable of withstanding under stress is dependent on the viscoelastic property of and hence, related to the volume (or amount) of asphalt binder used. However, the percent vertical and horizontal strain at 2 to 3 percent binder content are to a large extent identical, confirming an optimum binder content which is significantly higher than the minimum 1 percent presently specified in Ontario.

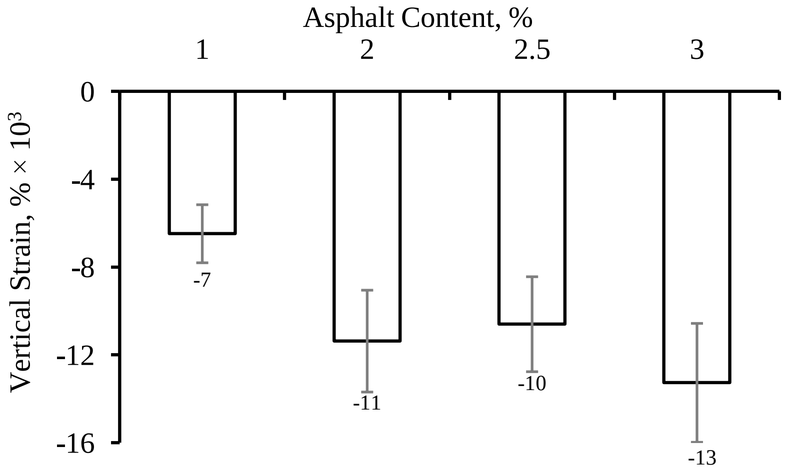


Figure 4.7 (b) Effect of asphalt binder content on percent vertical strain.

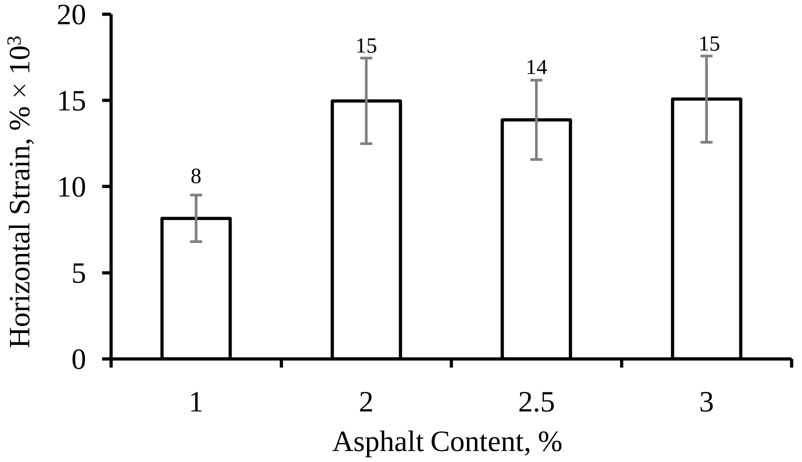


Figure 4.7 (c) Effect of asphalt binder content on percent horizontal strain.

4.2.2 Asphalt Type

In this section, the ITS of CIREAM mixes made using different asphalt binders at 2 percent binder content were determined. Although the result in Figure 4.8 (a) shows only about 5 to 7 percent difference in the ITS values for the three types (grade) of asphalt, the 80 pen grade

Cold Lake asphalt shows a relatively higher ITS value than RAF and 665-1 whose ITS values are almost comparable. Abel [28] found that softer asphalt are more fatigue-resistant having lower viscosity and forming a more stable foam. The percent vertical and horizontal strain behaviour of the asphalts shown in Figure 4.8 (b) and 4.8 (c) somewhat agree with Abel's [28] report. The RAF, being softer asphalt has the highest percent vertical and horizontal strain probably because its lower viscosity allows more visco-plastic deformation under stress than the 80 pen grade and 655-1 asphalt with relatively higher viscosity. However, by carefully selecting the foaming conditions (e.g. foaming water, temperature and foaming agent among others), a suitable combination of expansion ratio and foam half life can be achieved for the various asphalt grades to ensure desirable strength and stability of the recycled mix. Muthen [32] reported that asphalt type or grade probably has little effect on strength of foamed asphalt mix because the shear and tensile strength of the mix depend more on aggregate interaction rather than binder cohesion. Sakr and Manke [33] in a limited study showed that the stability of foamed asphalt-treated mixes is dependent more on aggregate interlock than the viscosity of the binder. Hence, the asphalt type (grade) is not critical for the strength performance of foamed asphalt mixes.

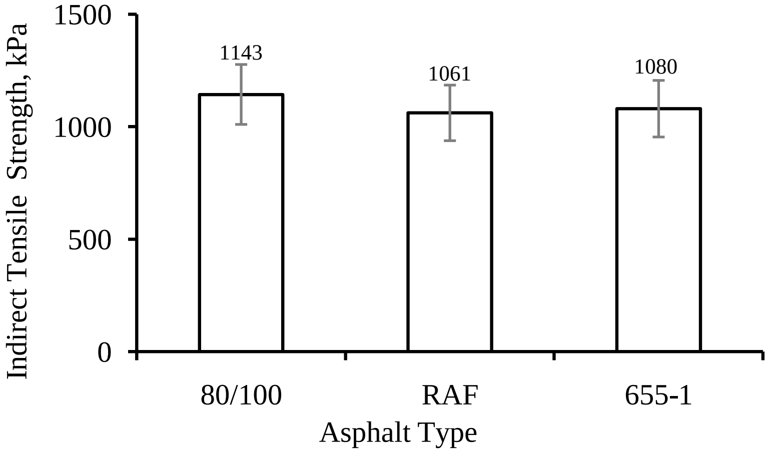


Figure 4.8 (a) Effect of asphalt type on ITS.

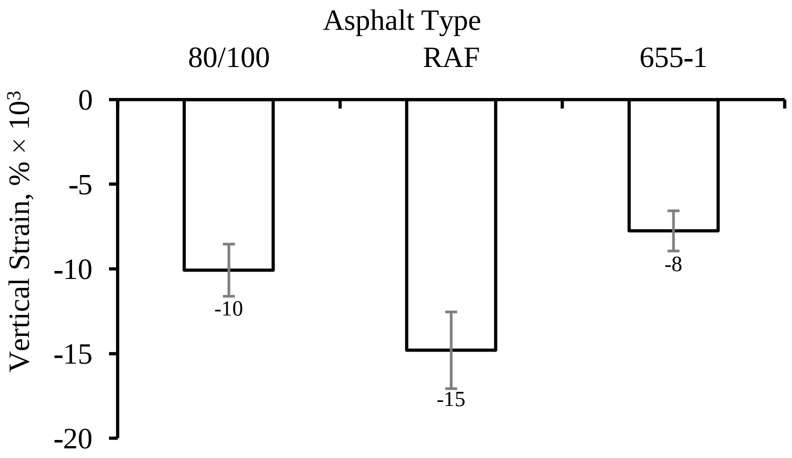


Figure 4.8 (b) Effect of asphalt type on percent vertical strain.

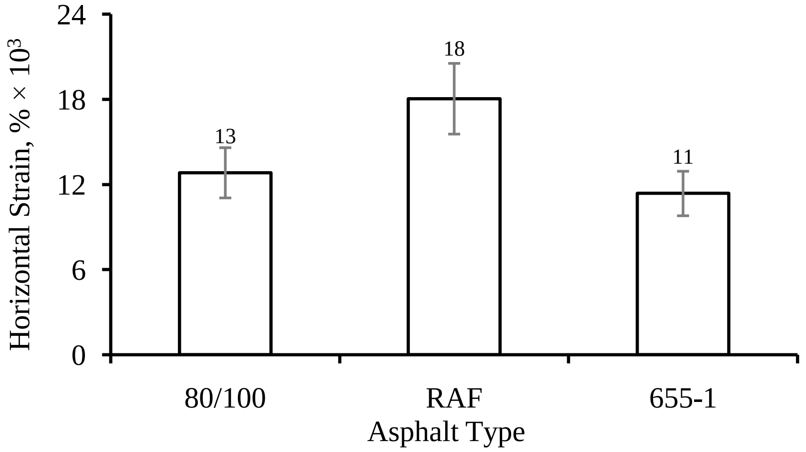


Figure 4.8 (c) Effect of asphalt type on percent horizontal strain.

4.2.3 Curing Time

The results in Figure 4.9 (a), (b) and (c) show the effect of curing time (degree of curing) on the strength behaviour of CIREAM. As the curing time increases, the ITS values increase because the binder-filler mortar material stabilizing the mix hardens and the stiffness increases. However, the ability of the mix to allow viscoplastic movement (or deformation) under load increases hours after compaction till about a day and then declined after about four days due to increased stiffness as shown by the percent vertical and horizontal strain behaviour in Figure 4.9 (b) and 4.9 (c) respectively. After four days of curing, the material is relatively hard and stiff and allows less viscoplastic flow or movement under load.

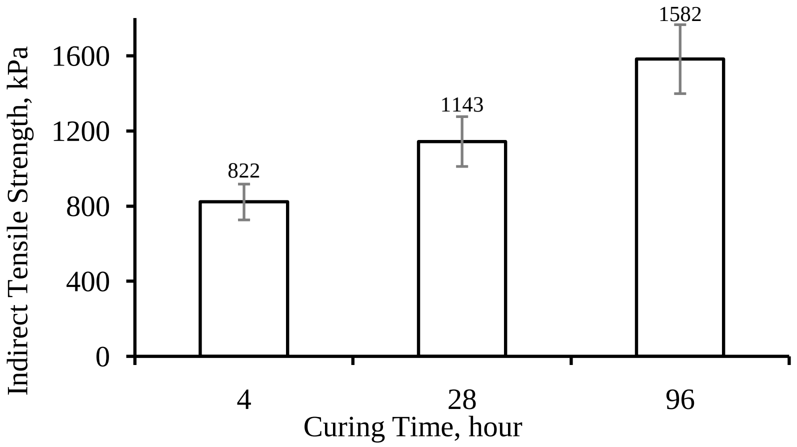


Figure 4.9 (a) Effect of curing time on ITS.

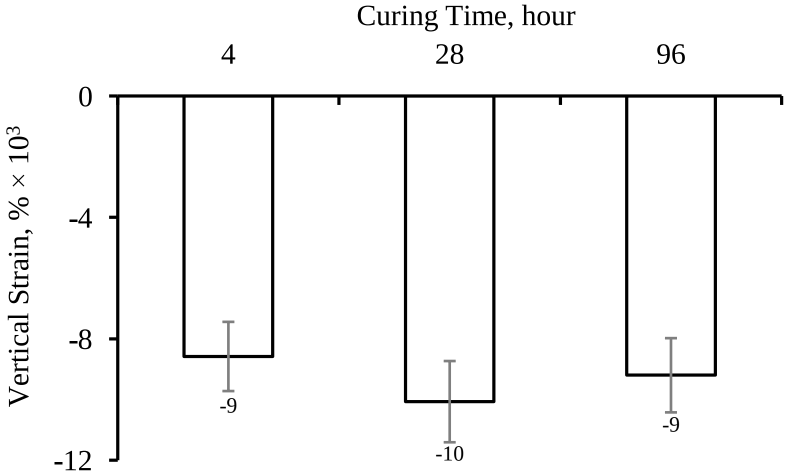


Figure 4.9 (b) Effect of curing time on percent vertical strain.

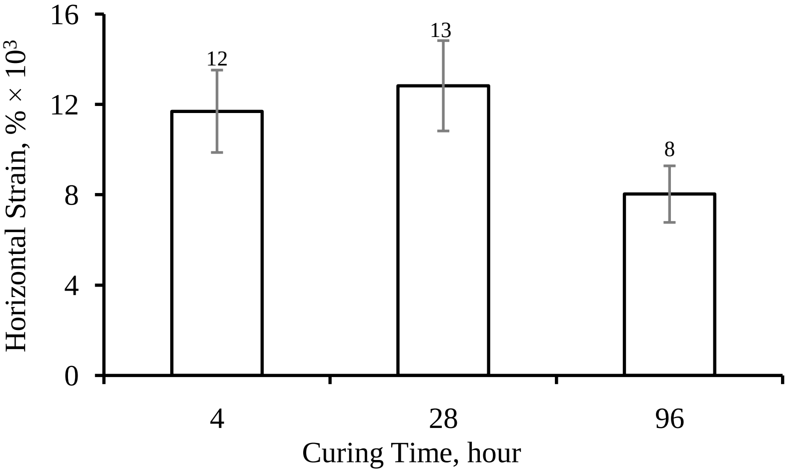


Figure 4.9 (c) Effect of curing time on percent horizontal strain.

4.2.4 Degree of Compaction

Figure 4.10(a), (b) and (c) show the effect of the degree of compaction on the strength performance of CIREAM. Reducing the degree of compaction by increasing the height of compacted specimen from 45 mm to 47 mm increases the voids which in turn increases the permeabilities of the mix and also reduces the density of the mix. This explains why about a 4 percent decrease in the degree of compaction resulted in about a 65 percent decrease in the ITS value as shown in Figure 4.10 (a). In other words, about 4 percent decrease in degree of compaction reduces the ITS by a factor of 3. Similarly, the capacity of the mix to allow compressive and tensile movement (or deformation) under load without failure is also reduced as shown in Figure 4.10 (b) and (c) respectively.

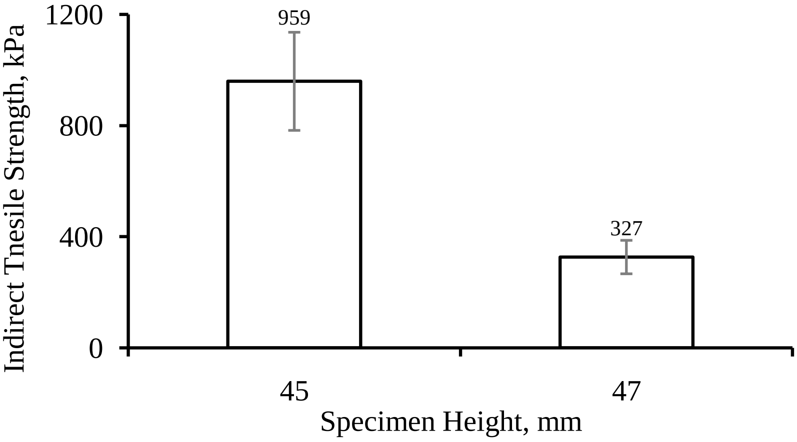


Figure 4.10 (a) Effect of air voids (degree of compaction) on ITS.

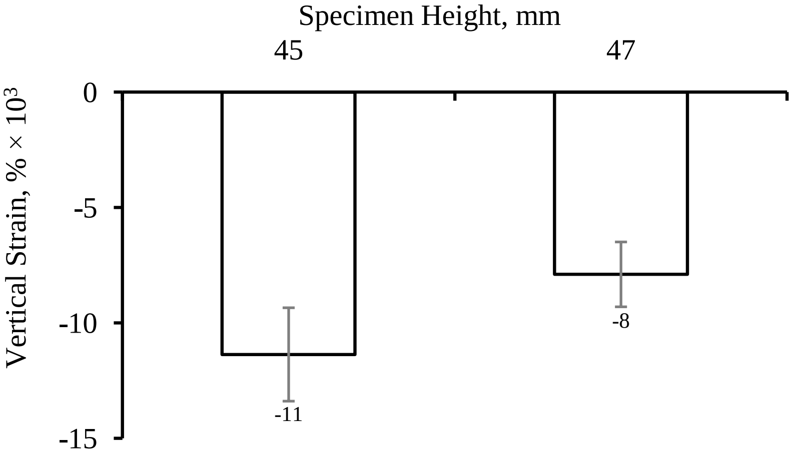


Figure 4.10(b) Effect of air voids (degree of compaction) on percent vertical strain.

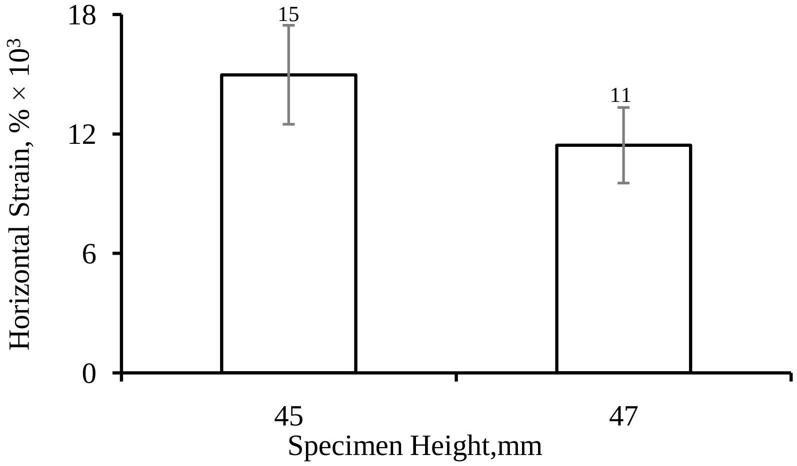


Figure 4.10 (c) Effect of air voids (degree of compaction) on percent horizontal strain.

4.2.5 Water Content

Figure 4.11 (a), (b) and (c) show the effect of water during mixing and compaction on the strength performance of CIREAM. From Figure 4.11 (a), increasing the amount of water added by over 100 percent results in about a 20 percent decrease in the ITS. Appropriate amounts of moisture aid binder dispersion and compaction by softening and breaking down the aggregate agglomeration. Excess water during mixing, extends the curing time and reduces the strength and density of compacted mixes. Excess water also hinders aggregate coating leading to loss of strength and cohesion. Maccarone et al. [30] stated that excess water reduces the early-life stability of mix. The determination of the OMC depends on the property of the mix that is being optimized or monitored, e.g. strength and density of mix [32]. From Figure 4.11 (b) and (c), water contents of 580 g showed the highest percent vertical and horizontal strain. However, the effect of water on the creep behaviour of CIREAM (percent strain) needs to be further studied.

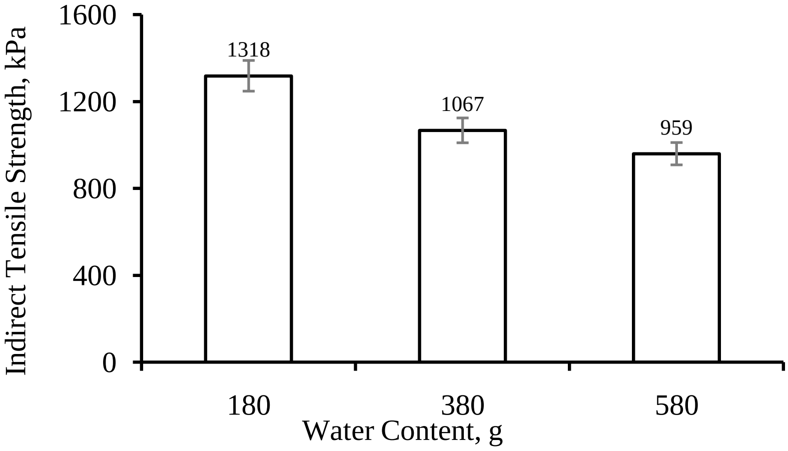


Figure 4.11 (a) Effect of water content on ITS.

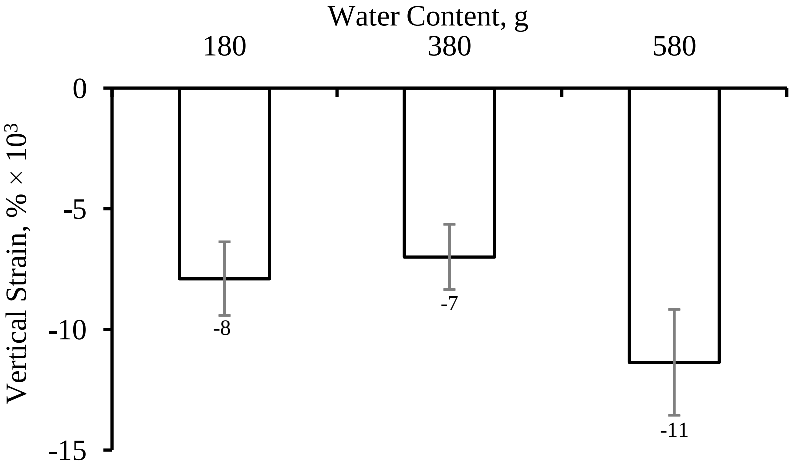


Figure 4.11 (b) Effect of water content on percent vertical strain.

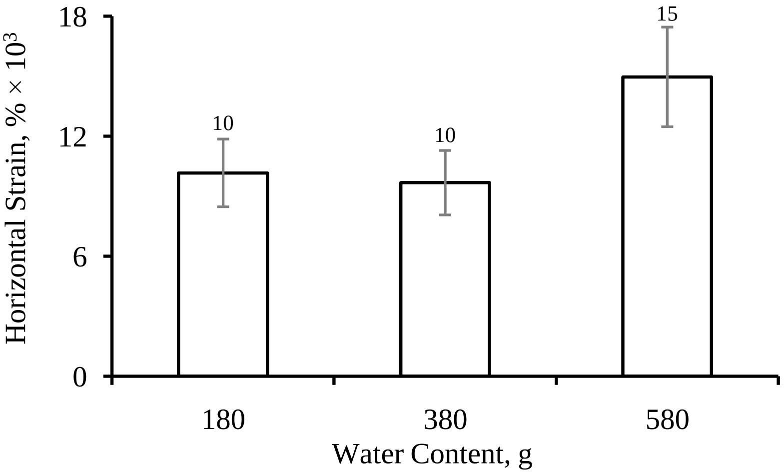


Figure 4.11(c) Effect of water content on percent horizontal strain.

4.2.6 Water Susceptibility

The strength behaviour of CIREAM after compaction is highly moisture-dependent because CIREAM has lower binder contents and higher void contents relative to regular CIR mixes [32]. This is shown in Figures 4.12 (a), (b) and (c) where specimen (B) tested after being soaked under water for one day showed about a 50 percent drop in ITS relative to specimen (A) tested after one day dry conditioning. Similar behaviour was observed in specimen (D) tested after being conditioned for three days at 50°C when compared with specimen (E) tested after being conditioned for three days at 50°C and then soaked under water for a day, although there was a more modest 20 percent drop in ITS in this case. This behaviour can be explained by the sensitivity of fines as well as the coating of aggregate to moisture. Additives such as cement and lime reduce the moisture susceptibility of the mixes. Increasing the bitumen content can also reduce the moisture susceptibility as higher densities are achieved, which in turn results in lower permeability or lower void contents and ultimately, increased coating of the fines with binder [32, 37].

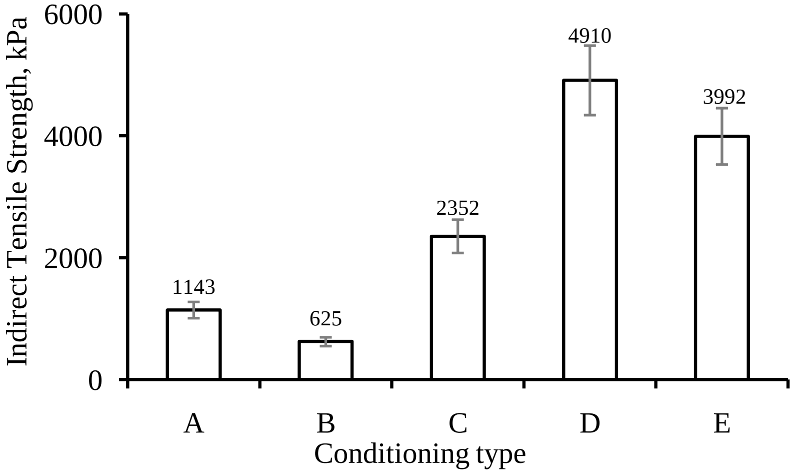


Figure 4.12 (a) ITS and water susceptibility of CIREAM, A (1 day dry), B (1 day wet), C (1 day with 50 mm/min loading rate), D (3 days at 50°C) and E (3 day at 50°C + 1 day wet).

The results in Figure 4.12 (b) and (c) show that the ability of the specimen to undergo compressive and tensile deformation (creep) under load is increased after being soaked in water for specimen conditioned at 50°C for three days compared with specimen conditioned same way and then soaked under water for one day. This can be observed in the increased percent vertical and horizontal strain of specimens D and E. However this behaviour needs to be further studied. The effect of loading rate on the ITS of CIREAM was studied to a limited extent in this work and also needs to be further investigated. Higher loading rates simulate higher traffic load cycles, e.g. on highways. The result herein shows that the ITS value was doubled, while the strain capacities reduced when the loading rate was raised from 5 mm/min to 50 mm/min at a test temperature of 10°C (specimens A and C). Li and co-workers [62] investigated the effect of loading level and loading rate on the strength of asphalt mixes tested at three low temperatures. They reported that the tensile strength increases as the loading rate increases for all test temperatures but the effect becomes less pronounced at lower temperatures. Muthen [32] stated that the viscoelastic behaviour such as the stiffness of bituminous materials is affected by the loading rate.

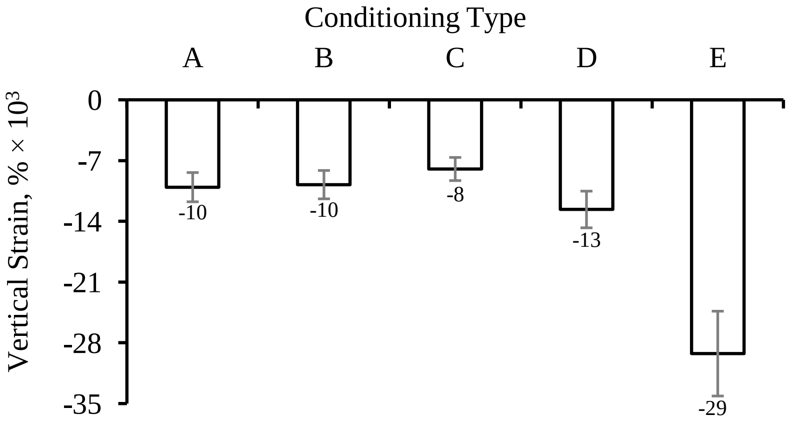


Figure 4.12 (b) Percent vertical strain and water susceptibility of CIREAM. A (1 day dry), B (1 day wet), C (1 day with 50 mm/min loading rate), D (3 days at 50°C) and E (3 day at 50°C + 1 day wet).

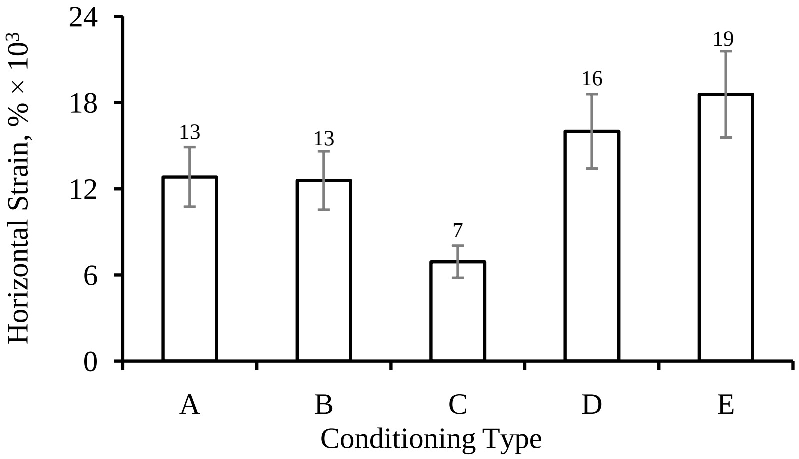


Figure 4.12 (c) Percent horizontal strain and water susceptibility of CIREAM. A (1 day dry), B (1 day wet), C (1 day with 50 mm/min loading rate), D (3 days at 50°C) and E (3 day at 50°C + 1 day wet).

4.3 CIREAM versus CIR and Effects of Additives.

This section presents the effects of asphalt type and additives on strength of CIREAM mixtures subjected to different conditioning protocols before testing and compares these to regular cold in-place recycled (CIR) mixtures. In the figures below, A and B represent regular emulsion-treated cold mix with 1 percent and 2 percent binder content respectively. C and D represent CIREAM mixes made with 2 percent 300 pen RAF and 80 pen Cold Lake asphalt respectively. E and F represent CIREAM mixes treated with 1 percent and 2 percent Portland cement respectively, while G and H are CIREAM mixes modified with epoxidized soybean oil (ESBO) and a siloxane-based foam stabilizer respectively. Two percent 80 pen asphalt content was used in mixtures E, F, G and H.

4.3.1 Reference Standard Conditioning (24 hours dry at ambient temperature)

Figure 4.13 (a), (b) and (c) show the effect of mixture variables on strength under reference standard conditioning at ambient temperature for 24 hours. From Figure 4.13 (a), the ITS values for the two ordinary CIREAM mixtures (80 and 300 pen) double those of CIR with 1 and 2 percent emulsion. The CIREAM mixtures have more asphalt cement and less water than comparable CIR mixtures because the emulsion used contained about 64 percent asphalt cement. Bowering and Martin [34] reported that foamed asphalt mixes exhibit superior strength characteristics compared to those of emulsion-treated mixes at binder contents above 1.5 percent. Portland cement increased the strength of CIREAM mixtures by about 100 percent. Siloxane based surfactant (foam stabilizer) also exerted a significant increase on the ITS.

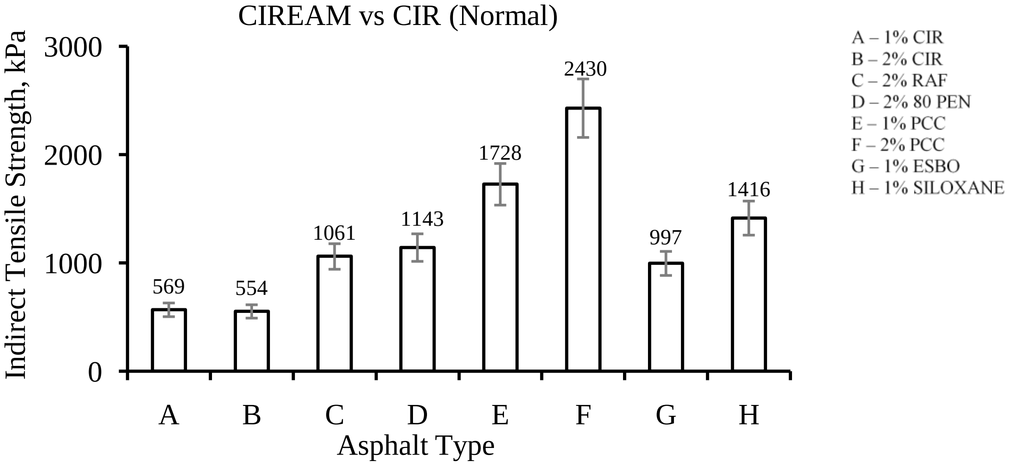


Figure 4.13 (a) Effects of asphalt type and additives on ITS of recycled mixes.

From Figure 4.13 (b) and (c), CIR 1 and 2 percent show higher percent vertical and horizontal strain than ordinary CIREAM mixtures. CIREAM mixture treated with siloxane-based foam stabilizer have percent vertical and horizontal strain comparable with that of CIR 2 percent whose values appeared to be the highest. It can be inferred that the siloxane-based foam stabilizer improves the creep properties of CIREAM by enhancing the viscoelastic behaviour of the mix. The stabilizer therefore enhances the stress distribution and reduction capacity of the pavement under applied load to protect the subgrade.

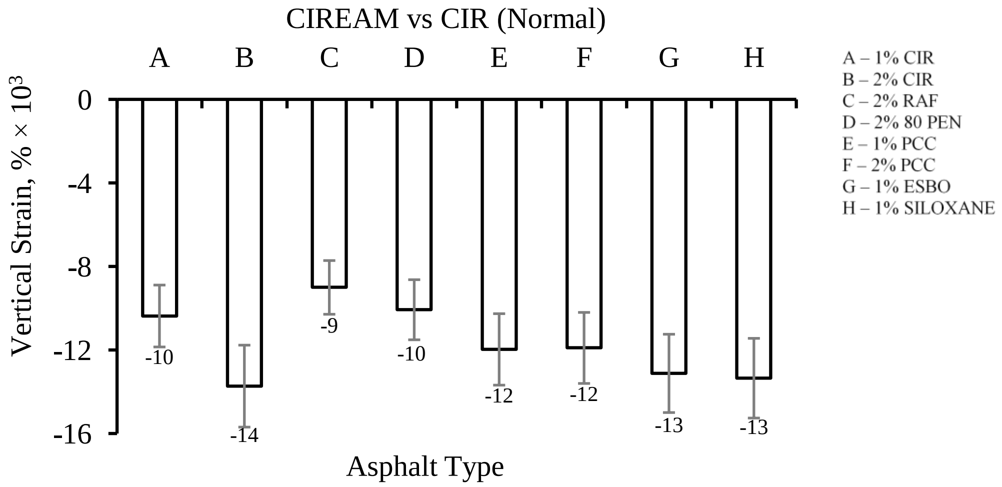


Figure 4.13 (b) Effects of asphalt type and additives on percent vertical strain of recycled mixes.

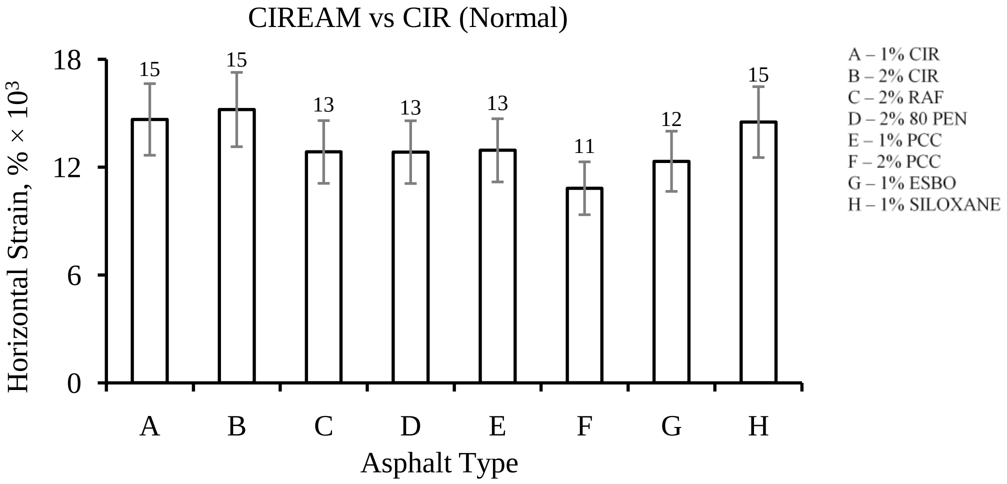


Figure 4.13 (c) Effects of asphalt type and additives on percent horizontal strain of recycled mixes.

4.3.2 Cold Aggregate (conditioned at -15°C for 72 hours)

The cold aggregate conditioned at -15°C for 72 hours simulates the prevailing low temperature condition associated with cold season paving. Figure 4.14 (a), (b) and (c) show the effect of mixture variables made using cold aggregates on the strength performance of the mixtures. It can be observed from Figure 4.14 (a) that the CIREAM mixtures show better strength performance relative to CIR mixtures. The ITS was significantly increased upon the addition of 1 percent Portland cement but reduced when the Portland cement content was increased to 2 percent. This suggests that the amount of Portland cement required to produce the most suitable strength performance in cold season paving should be controlled as excess cement may result in less desirable strength performance in CIREAM. The ITS value of the 80 pen CIREAM is comparable to those of mixtures treated with 1 and 2 percent Portland cement. Softer asphalt have been reported to be less prone to low temperature fatigue cracking because of low viscosity, yet Cold Lake (80 pen) asphalt gave a better strength performance compared to RAF (300 pen) which is softer.

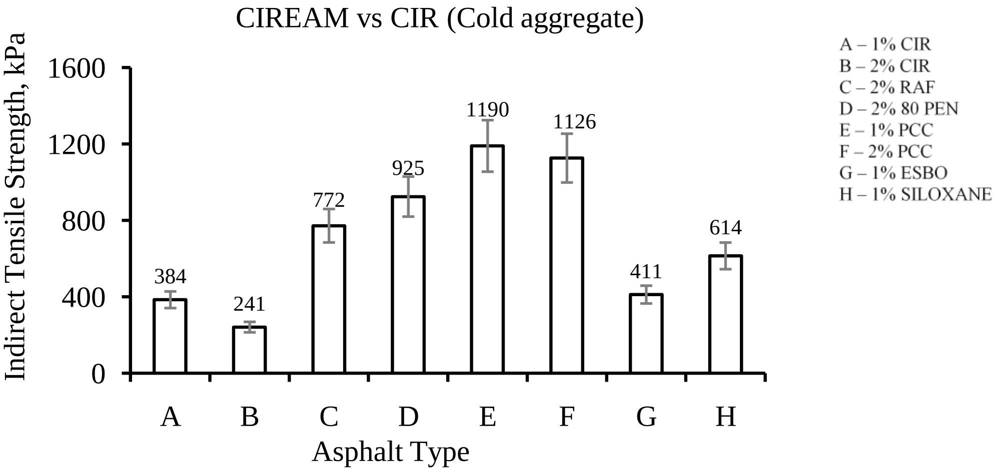


Figure 4.14 (a) Effects of asphalt type and additives on ITS of recycled cold aggregate mixes.

From Figure 4.14 (b), CIR 2 percent, 1 percent Portland cement, ESBO and siloxane based foam stabilizer show comparable percent vertical strain although the foam stabilizer appeared to be the highest. Figure 4.14 (c) shows that CIR 2 percent, 80 pen CIREAM and siloxane based foam stabilizer exhibit comparable percent horizontal strain. It can be explained that the siloxane based foam stabilizer extends the foam half-life to allow good particle interlock after compaction which in turn enhance the strain tolerance of the recycled mix. The application of these additives in controlled amounts enhances the flexibility and creep properties of CIREAM.

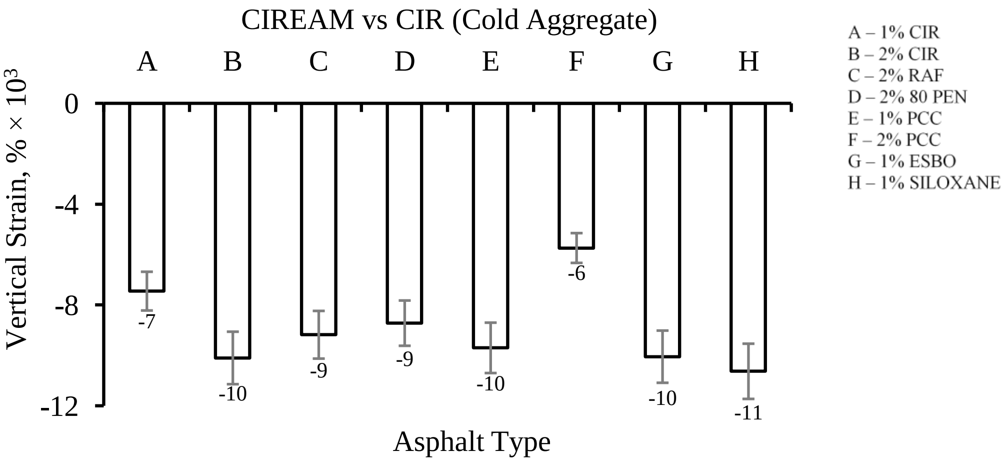


Figure 4.14 (b) Effects of asphalt type and additives on vertical strain of recycled cold aggregate mixes.

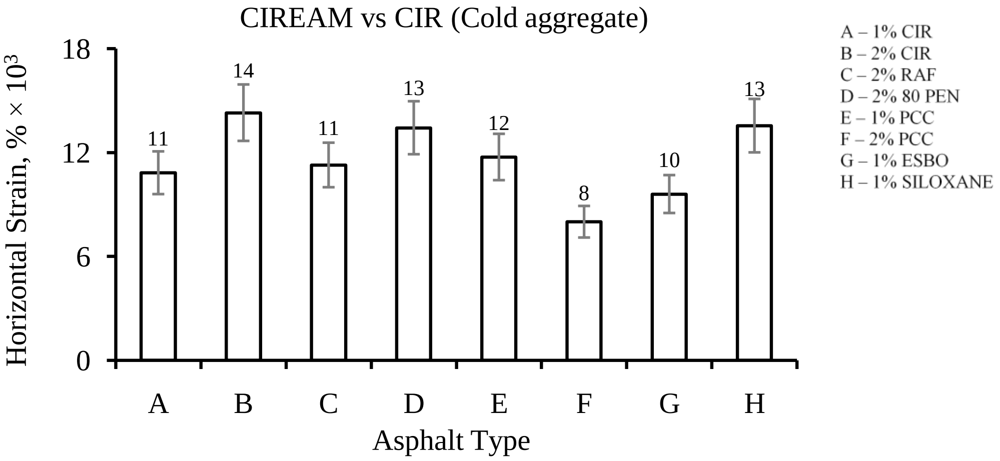


Figure 4.14 (c) Effects of asphalt type and additives on percent horizontal strain of recycled cold aggregate mixes.

4.3.3 Wet Conditioning (specimens soaked under water for 24 hours) and Tensile Strength Ratio (TSR)

Figure 4.16 (a), (b) and (c) show the results of test conducted using specimens soaked under water for 24 hours while Figure 4.15 presents the tensile strength ratio (TSR) determined from the dry and wet ITS values expressed as a percentage of retained strength. The wet conditioning is used along with the TSR to assess the water resistance of CIREAM and CIR mixes, as well as the effect of additives on the moisture susceptibility. The tensile strength ratio (TSR) is determined as the ratio of the average ITS of soaked specimens to the average ITS of dry specimens according to Technical Guideline TG2 of the Asphalt Academy [63]. From Figure 4.16 (a), it is observed that CIREAM mixtures show better strength performance than CIR mixtures, with Portland cement and foam stabilizer improving the ITS significantly. Portland cement increases the viscosity and/or stiffness of the binder-fines mastic mortar in order to improve the strength behaviour of the mix while foam stabilizer enhances the binder foam expansion and stability to give improved binder dispersion resulting in better strength performance of the CIREAM.

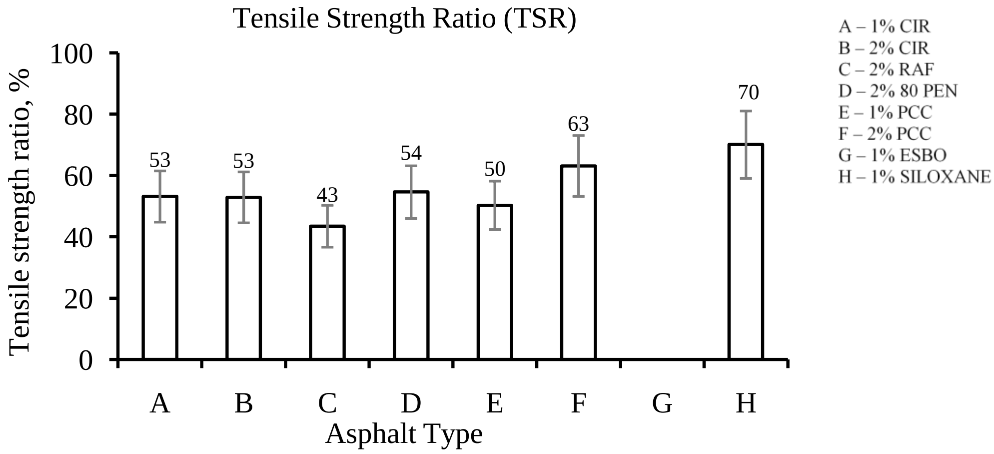


Figure 4.15 Effects of asphalt type and additives on Tensile strength ratio (TSR) of recycled mixes.

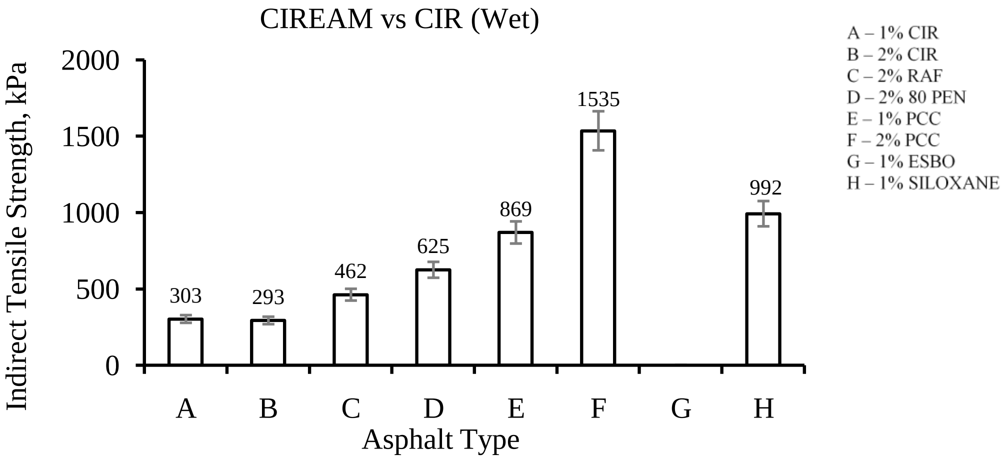


Figure 4.16 (a) Effects of asphalt type and additives on ITS of recycled mixes after wet conditioning.

Judycki and Jaskula [64] suggested that mixes are water resistant when the TSR is higher than 70 percent. From Figure 4.15, the CIREAM mix treated with the siloxane-based foam stabilizer (specimen H) turned out to be water resistant with a TSR above 70 percent according to this criterion. Other mixtures, including the emulsion treated mixes, did not meet this criterion as they all showed a TSR below 70 percent. However, the minimum specified TSR in Ontario is 50%. All the mixes except the 300 pen CIREAM meet this criterion as they showed TSR above 50 percent. The 300 pen CIREAM showed a TSR below 50 percent and therefore, can be considered not suitable for late season paving in Ontario due to its low water resistance. The foam stabilizer reduces the surface tension of the asphalt foam, thereby stabilizing it to enhance binder dispersion and increase aggregate coating. This increases the strength and water resistance of the mixes. As earlier mentioned in section 3.2, the hydration reaction product formed during the curing process in PCC is water-resistant and so, it enhances the water susceptibility of the CIREAM in addition to impacting strength on the mix. It is also important to mention that PCC is compatible with CIREAM because the water needed to sustain curing in PCC is supplied by the CIREAM as it also cures. Two percent of foamed bitumen was used for this test. Iwanski et al. [31] suggested that higher water resistance can be achieved by increasing the binder content of the recycled pavement composition. From Figure 4.16 (b) and (c), CIR 1 and 2 percent show higher percent vertical and horizontal compared to CIREAM. Although the effect of water content on strain behaviour of CIREAM was not extensively studied in this work, it can be mentioned that the two emulsion treated mixes tolerate higher strain prior to failure probably due to the partial miscibility of water with bitumen emulsion.

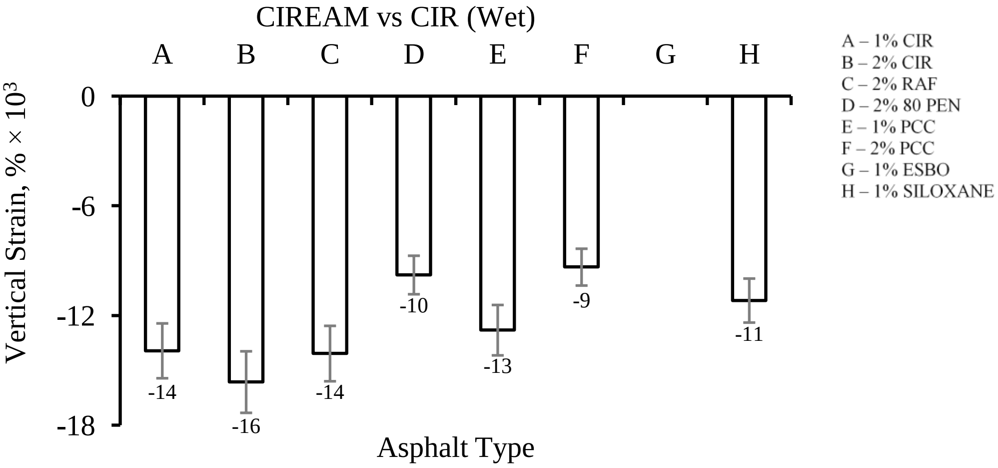


Figure 4.16 (b) Effects of asphalt type and additives on percent vertical strain of recycled mixes after wet conditioning.

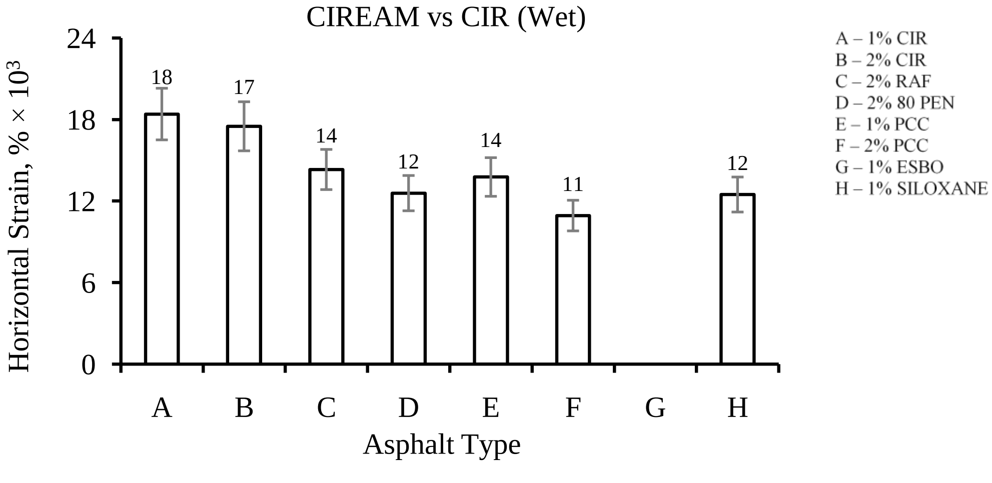


Figure 4.16 (c) Effects of asphalt type and additives on percent horizontal strain of recycled mixes after wet conditioning.

4.3.4 Same Day testing (4 hours after time of compaction)

Figure 4.17 (a), (b) and (c) present the results of tests conducted four hours after the time of compaction. This result was used to assess the early strength performance of the mix. ITS values of CIREAM nearly double those of CIR. CIREAM mixes develop a significant amount of strength within hours of compaction. The CIREAM mixes cure faster than emulsion treated mixes because the foamed bitumen in CIREAM contains less amount (3 percent) of water and more asphalt cement binder while the emulsion in comparable CIR mixes contains more (36 percent) water and less binder. If the emulsion was made with equal amount of water, the CIR mixtures will probably take about same time to cure with comparable CIREAM mixtures because there will not be excess water reaching the desired voids during compaction. Chan et al. [13] reported that CIREAM develops full strength within 3 days of compaction whereas CIR requires about 14 days to fully cure. It was observed that the CIREAM treated with 1 percent Portland cement shows the highest ITS value rather than the CIREAM treated with 2 percent Portland cement. This amount exerts a desirable impact on the early strength property of CIREAM mixes without compromising flexibility.

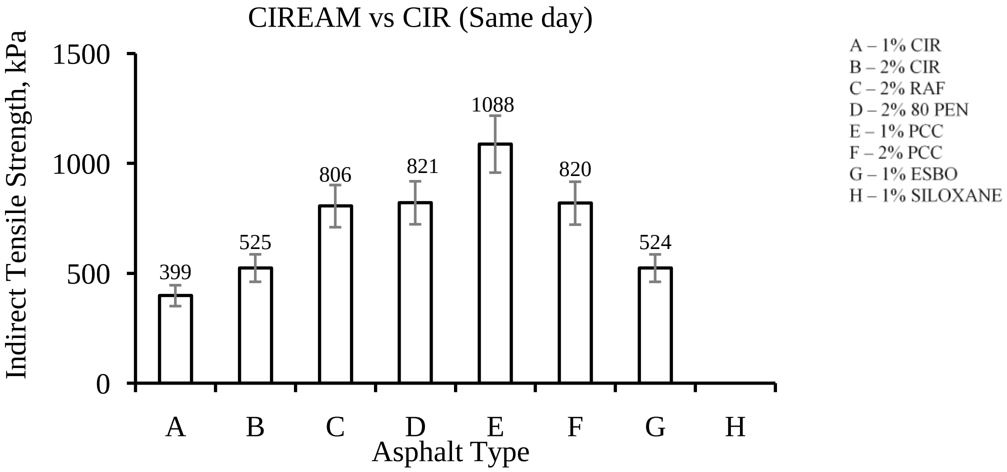


Figure 4.17 (a) Effects of asphalt type and additives on ITS of recycled mixes tested 4 hours after compaction.

To a good approximation, all the recycled mixes showed a somewhat comparable percent vertical and horizontal strain as observed from Figure 4.17 (b) and (c). The vertical strain and horizontal strain are around the magnitude of -0.01 and 0.01 respectively. The ability of all the mixes, including the CIR, to tolerate strain prior to failure is almost comparable.

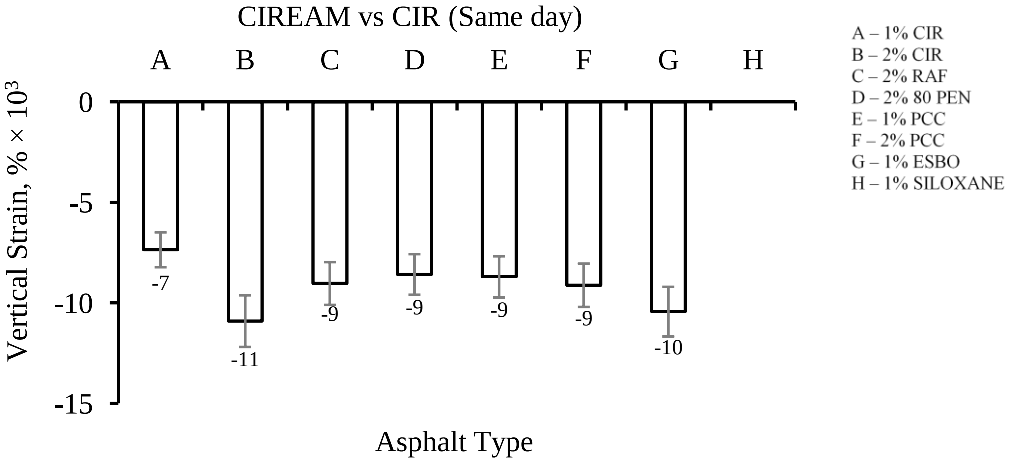


Figure 4.17 (b) Effects of asphalt type and additives on percent vertical strain of recycled mixes tested 4 hours after compaction.

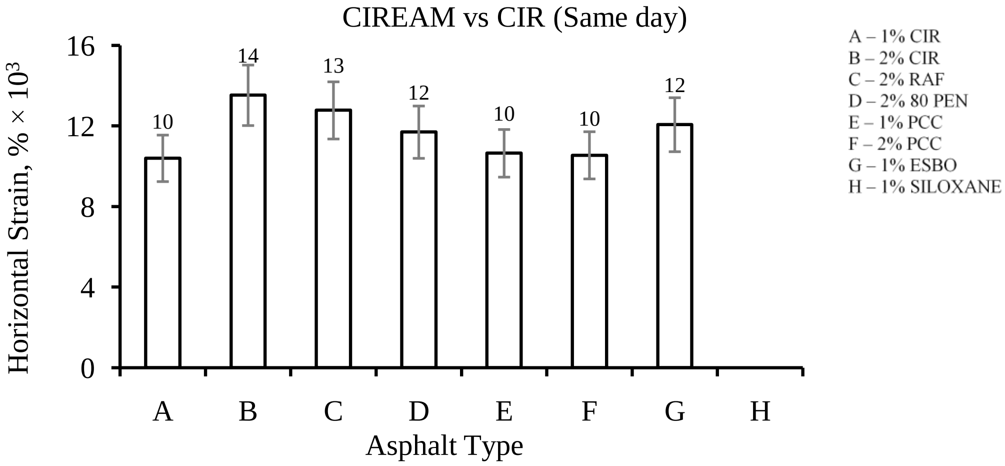


Figure 4.17 (c) Effects of asphalt type and additives on percent horizontal strain of recycled mixes tested 4 hours after compaction.

4.3.5 Three (3) days of curing at 50°C

Figure 4.18 (a), (b) and (c) show the strength performance of mixtures tested after 3 days of curing at 50°C. CIR 1 percent shows a higher ITS value compared to CIR 2 percent due to the lower water content in the binder used in CIR 1 percent. The unmodified CIREAM mixtures show comparable ITS values with those modified with 1 and 2 percent Portland cement after 3 days curing at 50°C as the mixes have all attained full structural capacity at this time. Epoxidized soybean oil (ESBO) and foam stabilizer have no effect after such long period of curing at high temperatures and hence were not tested. Maccarone [30] suggested that 3 days curing at 60°C can be related to 12 months field curing. He explained that oven cured samples gave test results similar to that of field cores taken 12 months after construction.

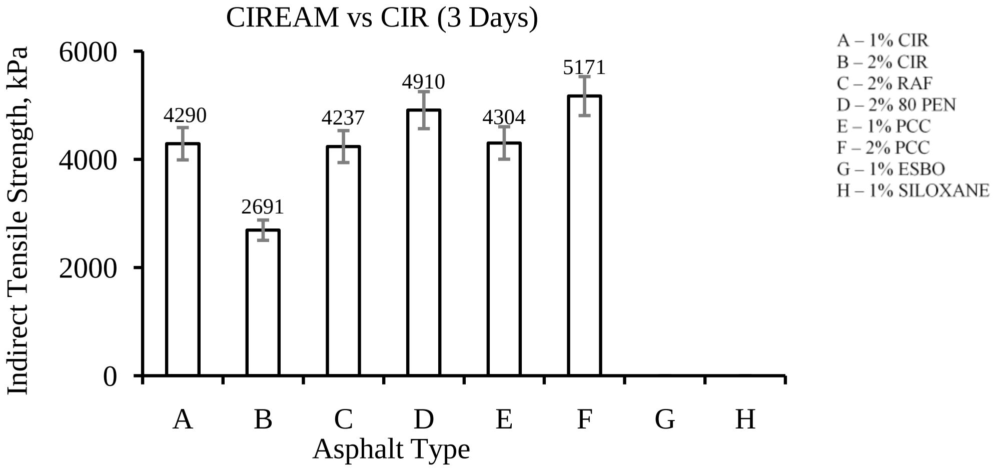


Figure 4.18 (a) Effects of asphalt type and additives on ITS of recycled mixes tested 3 days after compaction.

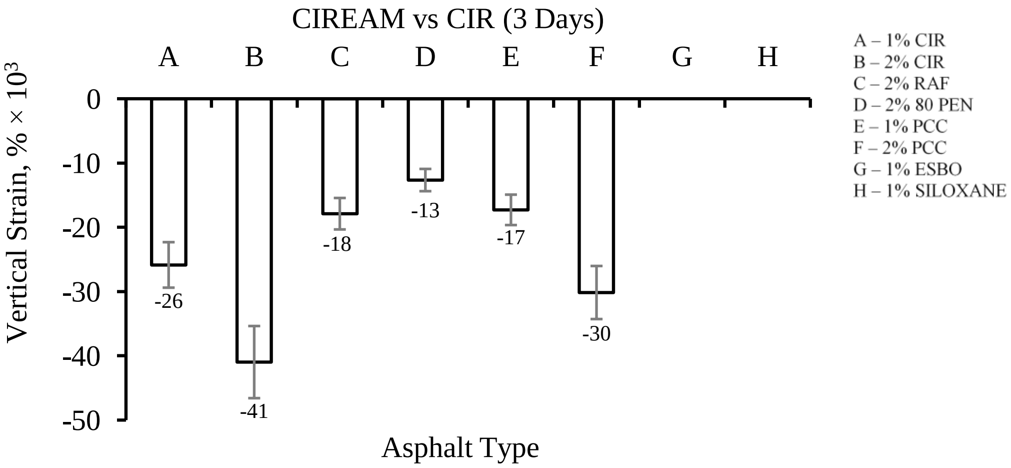


Figure 4.18 (b) Effects of asphalt type and additives on percent vertical strain of recycled mixes tested 3 days after compaction

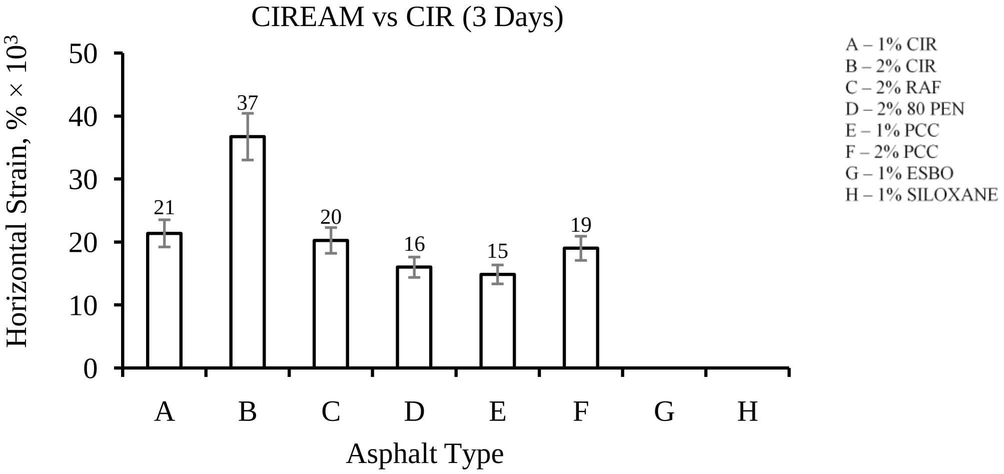


Figure 4.18 (c) Effects of asphalt type and additives on percent horizontal strain of recycled mixes tested 3 days after compaction.

4.4 Uniaxial Cyclic Compression Test with Partial Confinement (UCCTC)

Permanent deformation of asphalt layers results from densification and shear deformation brought about by repeated traffic loads and manifests itself at the pavement surface as rutting [65]. Miljkovic and Radenberg [65] stated in their work, that all flexible pavements undergo some amount of rutting. In addition to void contents and degree of compaction, the performance of asphalt mixtures, which are viscoelastic materials, depends on temperature and frequency of load. Hofbo and Blab [66] also reported that the viscoelastic properties of asphalt mixtures being thermo-rheological materials are dependent on frequency and temperature. Rutting in the asphalt layer can be caused by heavy load (vehicle) traffic, unstable asphalt mixes, and high pavement temperatures [67]. Rutting in the entire asphalt pavement structure results from over-stressing of the underlying base or sub-grade layers caused by thickness design inadequate for the applied traffic load, and weakening of the base or sub-grade due to moisture infiltration. The UCCTC assesses the rutting resistance of recycled mixtures using the strain rate at inflection point and/or dynamic penetration depth measured as a function of load cycles. High strain rates at inflection point indicate low rutting resistance while dynamic penetration measures the extent of deformation under specified load cycles.

Figure 4.19 presents the effect of binder content on the deformation (rutting) resistance of the recycled mixes at high temperature (50°C). For the three asphalt binder tested, 2 percent binder content gave the lowest strain rate at turning point and therefore highest rutting resistance compared with 2.5 and 3 percent binder content. Miljkovic et al. [65] had reported that rutting resistance decreases with increasing binder content and modifiers can be used to increase the stiffness at critical temperatures at which rutting tendency is determined. The polymer modified asphalt 655-1 show the highest rutting resistance followed by the 80 pen grade asphalt and the 300 pen RAF exhibits the least resistance in all the binder contents. The high rutting resistance of 655-1 may be attributed to the increased viscosity and stiffness impacted on the asphalt by the polymer at the test temperature. It is important to mention that the polymer modified asphalt 655-1 showed a high rubbery or elastomeric behaviour which reduces its workability during mixing and limits the foam expansion resulting in reduced aggregate coating. The relatively high resistance of the 80 pen asphalt to rutting can also be attributed to its higher viscosity at the test temperature. Softer asphalts are more prone to rutting. Mixes made with soft asphalt are less resistant to rutting at high temperatures than comparable mixes made with harder and more viscous asphalts [67].

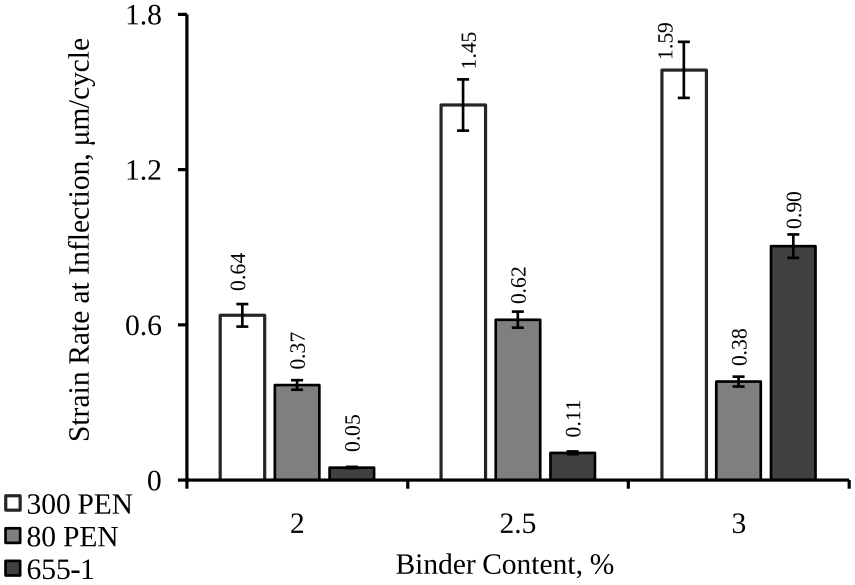


Figure 4.19 Effect of binder content on permanent deformation (rut) resistance of CIREAM mixtures.

Figure 4.20 presents the effect of additives on the rutting resistance of representative recycled mixes. Overall, the CIREAM mixtures showed higher resistance to deformation (lower strain rate at inflection) relative to CIR mixtures. Santucci [67] explained that rutting resistance of asphalt mixes is affected by friction, cohesion and resistance to displacement within the pavement structure. The relatively higher amount of binder in CIREAM mixes relative to comparable CIR mixes provides a higher resistance to mass movement or displacement in

CIREAM and this explains the higher rut resistance in foamed asphalt mixes relative to emulsion treated mixes. Addition of fiber, Portland cement, epoxidized soybean oil (ESBO) and foam stabilizers significantly improved the deformation resistance of the 80 pen grade asphalt but had little or negative impact on the performance of the softer 300 pen grade asphalt.

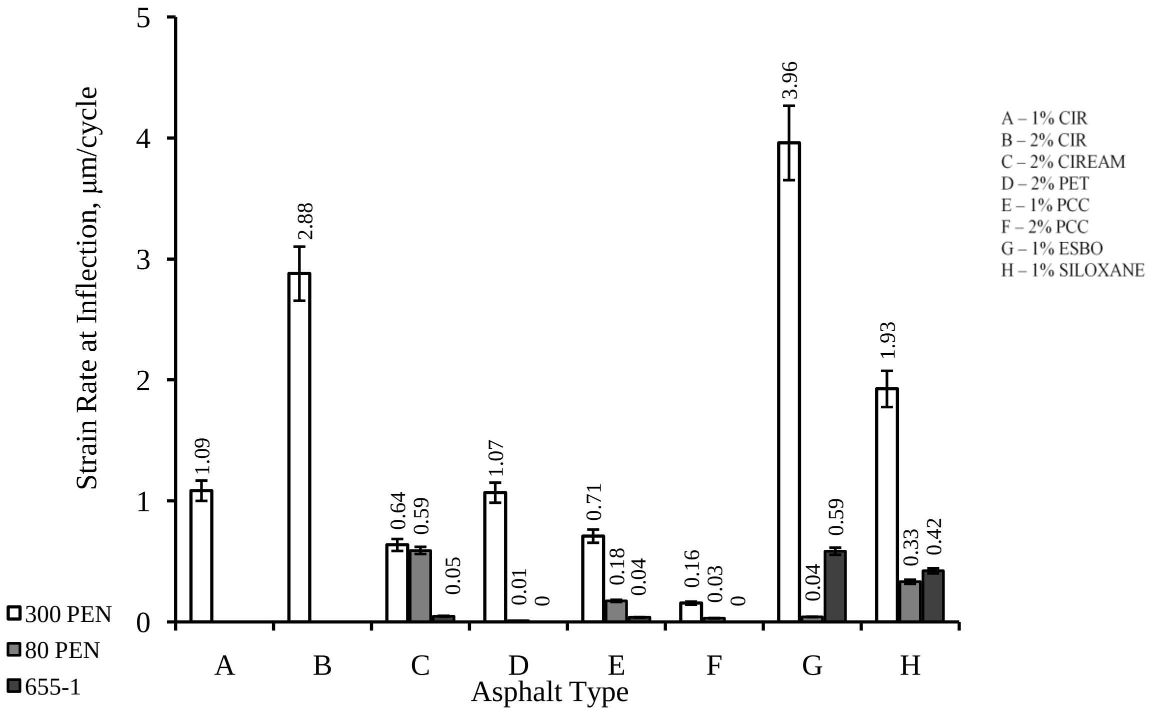


Figure 4.20 Effect of asphalt type and additives on permanent deformation (rut) resistance of recycled mixes. Note: Mixes A and B are CIR 1% and 2% respectively, C are unmodified 300 pen, 80 pen and 655-1 CIREAM, D is fiber-modified, E and F are 1% and 2% Portland cement-treated mixes respectively, G is ESBO-treated, and H is treated with a siloxane-based foam stabilizer.

Moisture infiltration of the recycled layer into the base or sub-grade weakens these underlying layers and result in permanent deformation of these layers under repeated traffic load. The rutted condition of the underlying layers then manifests on the pavement surface [67]. By improving the moisture resistance of the recycled layer through the application of additives such as foam stabilizers and Portland cement, the problem of rutting in the base or sub-grade or throughout the entire asphalt pavement structure can be prevented. Additives such as Portland cement, fiber and ESBO improve the performance of the CIREAM mixtures by increasing the stiffness of the binder, hence increasing the rutting resistance of the compacted mixture. Portland cement also minimizes the voids content in the compacted mix and so reduces the densification of material caused by excessive air voids when subjected to traffic loads. The permanent deformation behaviour of mixtures is also dependent on the material composition of the mix and the service life or test conditions. Therefore, careful selection of materials with controlled application of additives will significantly improve the rutting resistance of CIREAM mixes.

Figure 4.21 presents the representative dynamic creep curves versus load cycles for nine mixtures of different compositions. Mixtures A and B are 1 and 2 percent CIR mixes respectively, C is 300 pen CIREAM, D is 80 pen CIREAM, Mixtures E and F are CIREAM mixtures treated with 1 and 2 percent Portland cement respectively, G is CIREAM mixture modified with epoxidized soybean oil, mixture H was treated with siloxane-based surfactant and I was modified with PET fiber. Two percent 80 pen asphalt content was used in mixtures E, F, G, H and I. The various compositions tested gave reproducible creep curves and those presented here are representative for the different mixtures tested.

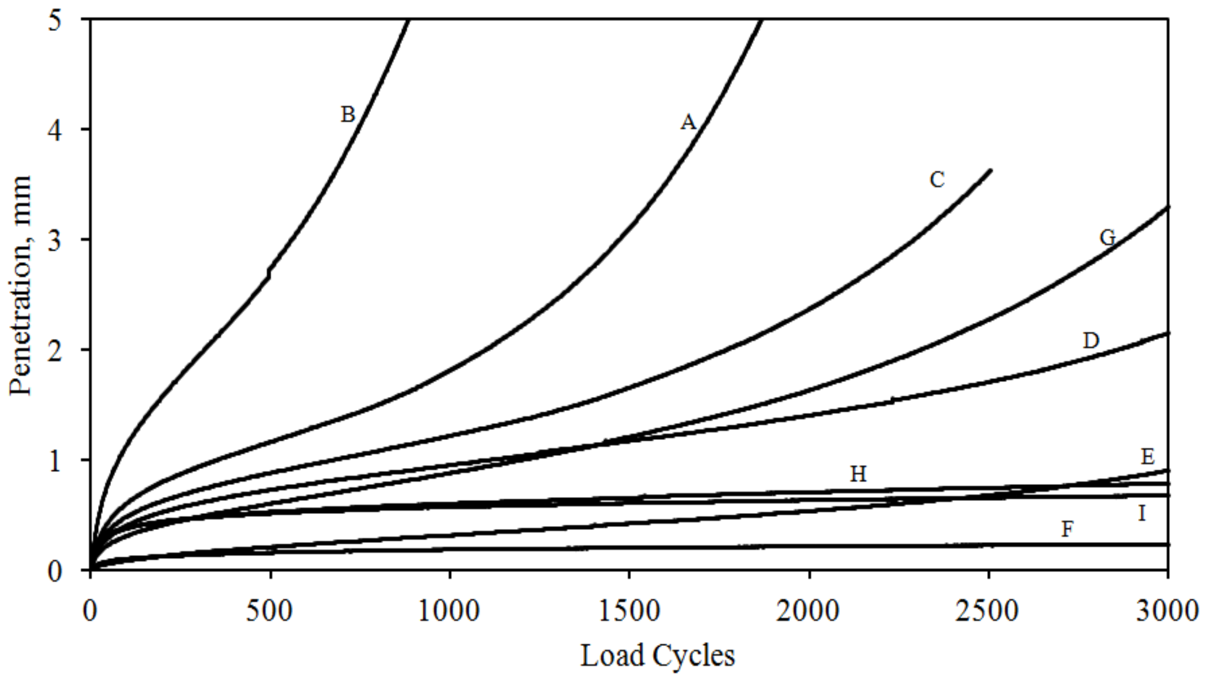


Figure 4.21 Representative dynamic creep curves as a function of cycles.

Karcher [53] explained that the dynamic penetration depth (mm) as a function of number of load cycles offers a reliable way of evaluating the permanent deformation behaviour of asphalt mixtures. The rutting depth of asphalt pavement on the field has been reported to be strongly related to the dynamic penetration depth in the laboratory [68]. Santucci [67] also mentioned that mixes that show high stability in the laboratory will likely have good rut resistance in the field.

The two CIR mixes A and B had penetration depths of about 5 mm and failed below 2000 cycles. Mixture C (300 pen) had less than 4 mm penetration depth at about 2500 load cycles. Mixture G (ESBO) had about 3.5 mm penetration depth below 3000 load cycles, mixture D (80 pen) had about 2 mm penetration depth at 3000 load cycles while mixes E, F, H and I had less than 1 mm penetration depth at 3000 load cycles and did not reach failure when the test was completed. The result shows that the CIR mixes show lower rut resistance in comparison to the CIREAM mixtures. The ordinary 80 pen CIREAM mix exhibits higher resistance to deformation when compared with the 300 pen CIREAM mix and even the ESBO-modified mix. This is consistent with the result of strain rate at turning point discussed earlier. Again, this behaviour can be attributed to the higher viscosity of the 80 pen grade asphalt relative to the 300 pen RAF. CIREAM mixtures modified with Portland cement, siloxane-based foam stabilizer and fibre exhibit significantly higher resistance to deformation with creep curves lacking the third phase (tertiary creep deformation or failure region) at the end of the test. It can be explained that Portland cement and PET fiber increase the mix density and reduces excessive air voids which causes material displacement and further compaction of pavement when subject to traffic loads. Foam stabilizer enhances foam expansion and extends the half life resulting to improved binder dispersion and aggregate coating in the mix. With sufficient compaction, the effects of the foam stabilizer produce adequate cohesion coupled with a mass viscosity induced friction required for the desirable mix stability or resistance to deformation at elevated temperature under applied load. This shows that asphalt performance at elevated temperatures can be improved by using modified binders rather than conventional ones. Given the reproducibility of the dynamic creep curves of the various compositions tested, the curves also show that dynamic penetration depth is dependent on the material composition of the asphalt mix and provides reliable evaluation of the deformation resistance. Experience has shown that mixes with dynamic penetration depth greater than 1.5 mm perform poorly under warm summer conditions with direct sun radiation, and under high loading, rolling or standing traffic. Additive-treated CIREAM mixes (such as mixes treated with Portland cement, PET fiber and foam stabilizer) which exhibit dynamic penetration depth below 1.5 mm perform well in extremely warm summer and under slow rolling and standing heavy traffic areas such as bus stops, intersections, and congestion area around traffic lights [54, 67].

CHAPTER 5

SUMMARY AND CONCLUSIONS

This study was designed to investigate CIREAM and CIR mixes under different conditions. Based on the background, experimental procedures, results and discussions of this thesis, the following summary and conclusions are provided:

- RAF binder exhibited poor foaming properties given its limited expansion.
- Warm mix additives tested showed no significant effect on the viscosity and consistency of the RAF binder but lowered the expansion of the binder at similar temperatures and water contents.
- Siloxane-based additive produced RAF foam with a noticeably different structure, as well as thicker and finely dispersed small bubbles. Siloxane-based foam stabilizer increased the half-life of the RAF foam significantly by a factor of 3.
- An amine type surfactant doubled the half-life of the RAF foam.
- The optimum binder content was found to be around 2 percent. This optimum binder content likely depends on the source of the recycled pavement materials and thus testing is recommended to determine this on a case-by-case basis.
- The 80 pen grade asphalt cement exhibited better performance in terms of strength properties and deformation behaviour in CIREAM mixes over the softer 300 pen grade.
- The indirect tensile strength of the CIREAM mixes, on average, doubled that of CIR mixes in cold and wet conditions. Foamed asphalt ensured high water resistance and favourable strength behaviour at low temperatures. This improved performance is due to the higher asphalt binder and lower water contents in CIREAM compared to CIR.

- Application of Portland cement and siloxane-based foam stabilizer significantly increased the strength and moisture resistance of the CIREAM mix. The tensile strength ratio of the CIREAM mix treated with foam stabilizer exceeded 70 percent, hence the mix was the least susceptible to moisture damage and other problems associated with wet climates. However, all mixes except the RAF CIREAM met the Ontario specification of a minimum 50% TSR.
- Siloxane-based foam stabilizer also enhances the creep behaviour of CIREAM mixes by improving the capacity of the mix to tolerate more strain prior to failure. This enhances the stress-distributing of CIREAM under applied loads and would provide added protection to the sub-grade.
- CIREAM mixes tested four hours after compaction were found to have higher indirect tensile strength in comparison to CIR mixes. One percent of Portland cement positively impacted the indirect tensile strength balanced with desirable flexibility in mixes tested four hours after compaction. Portland cement exerts favourable early strength properties on CIREAM. However, the amount applied should be controlled as an excess can lead to a loss in flexibility, which would make the mix more prone to low temperature cracking.
- CIREAM made with 300 pen grade roofing asphalt flux (RAF) is considered not suitable for late season paving in Ontario due to its low water resistance shown by its low TSR when compared to the 80 penetration grade Cold Lake asphalt CIREAM and CIR mixes.
- All mixes showed comparable strength performance after three days at 50°C, except CIR 2% which showed about a 40 percent decrease in indirect tensile strength compared to all other mixtures. Binder contents that are too high in regular cold in-place mixes should therefore be avoided.

- For both 300 pen and 80 pen grade asphalt cements, 2 percent binder content gave the most favourable permanent deformation behaviour. However, in the three binder contents used, 80 pen grade asphalt cement exerted higher rutting resistance in comparison to 300 pen grade asphalt. The high viscosity and stiffness of the polymer modified asphalt 655-1 reduce its workability, foam stability and aggregate coating to a large extent and may not be considered suitable for CIREAM.
- Additives such as Portland cement, foam stabilizer, epoxidized soybean oil and fibre significantly increased rutting resistance of 80 pen grade asphalt CIREAM. However, these additives had little or no effect on the performance of 300 pen grade asphalt CIREAM.
- Asphalt performance at elevated temperatures can be improved by using modified CIREAM processes rather than those using only conventional asphalts. A cost-benefit analysis should be done to assess the overall benefits of the additives investigated in this study.

REFERENCES

1. Johnson, A. M. Best Practices Handbook on Asphalt Pavement Maintenance. *2000-04, Minnesota Technology Transfer Centre/LTAP Program, University of Minnesota, Minneapolis,* Feb. 2000, pp. 1-8.
2. Orr, D. P., Pavement Maintenance, *Cornell Local Roads Program*. 416 Riley-Robb Hall Ithaca, New York. 2006. pp. 1-27.
3. Cool Asphalt; Hot Trend, Cold-in-place Recycling. *Ontario Good Roads Association (OGRA) Milestones*, Vol. 9, No. 1, Feb. 2007, pp. 47-49
4. Lane, B., T. Kazmierowski, and A. E Alkins. Sustainable pavements: environmental, economic, and social benefits of in-situ pavement recycling. *Quantifying Sustainability in Pavement Rehabilitation Projects Session of the 2008 Annual Conference of the Transportation Association of Canada Toronto, Ontario.* 2008, pp. 1-8.
5. Keeping up Appearances, Municipal Road Maintenance and Rehabilitation. *Ontario Good Roads Association (OGRA) Milestones*, Vol. 7, No. 1, Feb. 2007, pp. 10-15
6. In-situ Pavement Recycling, *European Concrete Paving Association, Activity Areas.* Website: http://www.eupave.eu/documents/activity-areas/in-situ-pavement-recycling.xml?lang=en. Accessed: June 2013
7. Lewis, A. J. N., and D. C. Collings. Cold In Place Recycling: A Relevant Process For Road Rehabilitation and Upgrading. *CAPSA 99, 7th Conference on Asphalt Pavements for Southern Africa*, South Africa, 1999, pp. 1-11.
8. Mathew, T. V., and K. V Krishna Rao. Introduction to Pavement Design. *NPTEL. Introduction to Transportation Engineering*, May 2006, pp. 19.1-19.6.
9. Al-Abdul Wahhab H. I. Introduction to Pavement Structures. *Lecture notes, King Fahd Univ. of Petroleum and Minerals*. Chapter 1 and 2.

10. Gonzalez, A. An Experimental Study on Deformational Characteristics and Performance of Foam Bitumen Pavements. *Ph. D. Thesis, Dept. of Civil and Environmental Engineering,* University of Caterbury, Christchurch, New Zealand. 2009, pp. 1-8.
11. Geotechnical Aspects of Pavements Reference Manual, *U.S. Department of Transportation Publication No. FHWA NHI-05-037***,** *Federal Highway Administration***,** May 2006.
12. Kowalski, T. E., and D. W. Starry, Jr. Cold Recycling using Foamed Bitumen. *Characterization and Improvement of Soils and Materials Session of the 2007 Annual Conference of the Transportation Association of Canada.* Saskatoon, Saskatchewan, Oct., 2007. pp. 1-19.
13. Chan, S., B. Lane, C. Raymond, W. Lee, and T. Kazmierowski. Five-Year Performance Review of Cold-in-Place Recycling and Cold-in-Place Recycling with Expanded Asphalt Mix on Highway 7, Perth, Ontario 2009. *Sustainability of Asphalt Mixes Session, Annual Conference of Transportation Association of Canada*, Vancouver, British Columbia, 2009. pp. 1-16.
14. Moore, T., J. Davidson, A. Kucharek, and M. Esenwa. Early Stage Curing Characteristics of Partial Depth Cold Recycling. *Proceedings of The Fifty-sixth Annual Conference of the Canadian Technical Asphalt Association*, Quebec city, Quebec, Nov. 2011, pp. 171-184.
15. Wirtgen Group. Cold Recycling, *Wirtgen Cold Recycling Manual*. Germany, 2012.
16. Manolis, S. Asphalt Emulsion Manufacturing 101. *2010 Asphalt Emulsion Manufacturing Asociation, Asphalt Emulsion Technologies Workshop*, Niagra Falls, Canada, Nov 2-3, 2010.
17. Bitumen Emulsions. *Bitumina Hi-Tech Pavement Binders.* Website: http://www.bitumina.co.uk/bitumen-emulsions.html. Accessed: June 2013

18. The Chemistry of Asphalt Emulsions. *Asphalt Emulsions Manufacturers Association.* Website: http://www.aema.org/index.php?option=com_content&view=article&id=74:cae&catid=7&Itemid=25. Accessed: June 2013
19. Read, J. And D. Whiteoak. The Shell Bitumen Handbook. 2003. Pp 87-98.
20. Das, A. Cold in-place Recycling with Bitumen Emulsion. *Indo-Belarus Seminar on Bitumen Emulsion and Cold Mix Technologies,* New Delhi, October 19, 2005.
21. Landers, K. Deep rehab for distressed pavements, *Better Roads*, James Informational Media, Inc., July, 2002.
22. Cold in-place Recycling with Expanded Asphalt, *Technical Publication B-335 CIREAM – OPSS 335, Ministry of Transportation Ontario RAQs.* Jan., 2010. pp. 1-6.
23. Csanyi, L. H. Foamed Asphalt in Bituminous Paving Mixes. *Highway Research Board Bulletin*, Vol. 10. 1957. pp. 108-122.
24. Characterizing Foam. *Foamed Asphalt 101.* Website: http://foam101.info/Basics/Characterize_Foam.html. Accessed: June 2013
25. Kowalski, T. E., and D. W. Starry Jr. Cold Recycling Using Foamed Bitumen. *Annual Conference of the Transportation Association of Canada*, Saskatoon, Saskatchewan, Canada, Oct. 14-17, 2007, pp. 1-20.
26. Ramanujam, J. M., and J. D. Jones. Charaterisation of Foamed Bitumen Stabilisation. *Vol. 8, No. 2, International Journal for Road pavement Engineering*. June 2007, pp. 111-122.
27. Van de Ven, M. F. C., K. J. Jenkins, J. L. M. Voskuilen, and R. Van Den Beemt. Development of (half-) warm foamed bitumen mixes: state of the art. *International Journal of Pavement Engineering* 8, No. 2, 2007, pp 163-175.

28. Abel, F. Foamed Asphalt Base Stabilisation, *6th Annual Asphalt Paving Seminar*, Colorado State University, Colorado, USA, 1979.

29. Brennen, M., M. Tia, A. G. Altschaeffl, and L. E. Wood. Laboratory Investigation of the use of Foamed Asphalt for Recycled Bituminous Pavements. *In: Asphalt Materials, Mixtures, Construction, Moisture Effects and Sulfur*. Washington, DC: Transportation Research Board. (Transportation Research Record; 911), 1983. pp. 80-87.

30. Maccarrone, S., G. Holleran, and A. Ky. Cold Asphalt Systems as an Alternative to Hot Mix. *9th AAPA International Asphalt Conference*. 1995. pp. 1-6.

31. Iwanski, M. and A. Chomicz-Kowalska. The Effects of using Foamed Bitumen and Bitumen Emulsion in the Cold Recycling Technology. *The 8th International Conference, Environmental Engineering*, Vilnius, Lithuania, May 19-20, 2011, pp. 1089-1093.

32. Muthen, K. M. Foamed Asphalt Mixes - Mix Design Procedure. *Contract Report Number CR-98/077,* SABITA and CSIR Transportek, Pretoria, South Africa. 1998, pp. 1-11.

33. Sakr, H.A. and P.G. Manke. Innovations in Oklahoma foamix design procedures. *Asphalt Materials, Mixes, Construction and Quality*. Washington, DC, Transportation Research Board. (Transportation Research Record; 1034), pp 26-34.

34. Bowering, R.H. and C.L. Martin. Foamed Bitumen Production and Application of Mixtures, Evaluation and Perfomance of Pavements. *Proceedings of The Association of Asphalt Paving Technologists,* Vol. 45, 1976. pp. 453-477.

35. Lee, D.Y. Treating Marginal Aggregates and Soil with Foamed Asphalt. *Proceedings of The Association of Asphalt Paving Technologists,* Vol. 50, 1981. pp. 211-230

36. Bissada, A.F. Structural Response of Foamed Asphalt-Sand mixtures in hot environment. *Asphalt Materials and Mixtures,* Washington DC. Transportation Research Board (Transportation Research Record; 1115) 1987. pp. 134-149.

37. Castedo-Franco, L.H., C.C. Beaudoin, E.L. Wood and A.G. Altschaeffl. Durability Characteristics of Foamed Asphalt mixtures. *Proceedings of the 29th Annual Canadian Technical Asphalt Association Conference.* Montreal, Canada. 1984.
38. Curing Mechanism of Foamed Asphalt. Website: http://foam101.info/Science/Curing.html. Accessed: July 2013.
39. Kendall, M., B. Baker., P. Evans, and J. Ramanujan. Foamed Bitumen Stabilization. *Proceedings Roads at Work-Developing Southern Queensland, Southern Region Symposium, Qld Department of Main Roads, Goondiwindi*. 1999, Vol. 21, pp. 1-4.
40. Wikipedia. http://en.wikipedia.org/wiki/Portland_cement. Accessed: July 2013.
41. Akers, S.A.S., B. Mtsweni, L. Olivier, J. Fonseca and C. Wadhwani. Potential Use of Polyethylene Terephthalate (Pet) Fibres in Fibre Cement Composite Materials. *International Inorganic-Bonded Fibre Composites Conference IIBCC,* Canberra. Sept. 2012. pp. 155-164.
42. Epoxidized Soybean Oil. The Chemical Company. Website: http://www.thechemco.com/chemical/epoxidized-soybean-oil/. Accessed: July 2013
43. LiLiKun. Preparation and Microstructure and Properties of Modified Oxidized Asphalt with ESO and Fibers. *Master's Thesis, Suzhou University*. 2008.
44. Rediset. Website: http://sc.akzonobel.com/en/asphalt/Pages/product-detail.aspx?prodID=10415. Accessed: July 2013
45. Sasol Wax, Website: http://www.sasolwax.com/Sasobit_Technology.html. Accessed: July 2013.
46. ASTM, D6931 – Standard Test Method for Indirect Tensile Strength of Bituminous Materials. *ASTM International.* USA, 2007.

47. Tran, J., and H. U. G. O. Vanloon. Indirect Tensile Strength of Asphalt Mixes in Southern Australia. *Australian Asphalt Paving Association, Thirteenth International Flexible Pavements Conference,* Surfers Paradise, Queensland, Australia, 2009, pp. 1-3
48. Breen, J.J and J.E. Stephen, *Split Cyclinder Test Applied to Bituminous Mixtures at Low Temperature.* Journal of Materials. 1996. 1(1). pp. 66-67.
49. Castro-Montero, A., Z. Jia, and S.P. Shah, *Evaluation of Damage in Brazilian Test Using Holographic Interferometry.* Journal of Materials. 1995. 92(3) pp. 268-275
50. Vasconcelos, K. L., L. B. Bernucci, and J. M. Chaves. Effect of Temperature on the Indirect Tensile Strength Test of Asphalt Mixtures. *Proceedings, 5th Eurasphalt and Eurobitume Congress,* Istanbul, Turkey, 2012.
51. Flexible Pavement Composition And Structure. Website: http://theconstructor.org/transportation/flexible-pavement-composition-and-structure/5499/. Accessed: August 2013.
52. Technische Prüfvorschriften für Asphalt im Straßenbau (TP Asphalt-StB), Teil 25 A 1: Dynamischer Stempeleindringversuch an Gussasphalt. Forschungsgesellschaft für Straßen- und Verkehrswesen (Hrsg.), 2009.
53. Karcher, C. Evaluation of the Deformation Resistance of Asphalt Mixes by Cyclic Compression Tests. *5th Eurasphalt and Eurobitume Congress,* Instabul, 2012.
54. Dołżycki, B., J. Judycki. Behaviour of asphalt concrete in cyclic and static compression creep test with and without lateral confinement. *Road Materials and Pavements Design.* Volume 9, No 2.2008, pp. 207 – 225.
55. Method of Test for the Determination of Indirect Tensile Strength of Expanded Asphalt Mixes. *Ministry of Transportation, Ontario laboratory Testing Manual.* Test Method LS-297, Ontario, Canada, May 2001, Rev. No. 26, pp. 1-6.

56. BP Performance Grades Recommended Mixing and Compaction Temperatures for Paving Applications. Website: http://www.bp.com/liveassets/bp_internet/bitumen/bp_bitumen_us/STAGING/local_assets/downloads_pdfs/m/mixing-compaction-temperature-guide_jul13.pdf Assessed: August 2013.

57. Asphalt Academy. *Interim Technical Guidelines (TG2): The design and Use of Foamed Bitumen Treated Materials.* Technical Guideline 2 (TG2). CSIR, Pretoria, South Africa, June 2002.

58. *Wirtgen Cold Recycling Manual*. 2nd Edition, ISBN 3-936215-05-7, Wirtgen GmbH, Windhagen, Germany, November 2004.

59. *Wirtgen Cold Recycling Manual.* 3rd Edition, ISBN 3-936215-05-7, Wirtgen GmbH, Windhagen, Germany, 2010.

60. Gonzalez, A., M. Cubrinovski, B. Pidwerbesky, and D. Alabaster. Strength and Deformation Characteristics of Foamed Bitumen Mixes under Suboptimal Conditions. *Journal of Transportation Engineering,* 2011, Vol. 137, pp. 1-10.

61. Chiu, C. T., and A. J. N. Lewis. A Study on Properties of Foamed Asphalt-Treated Mixes. *ASTM Journal of Testing and Evaluation,* Vol. 34, Issue 1, 2002, pp. 5-10.

62. Li, X., M.O. Marasteanu, and R.C. Williams. Effect of Loading Level and Rate in the Indirect Tensile Test. *Proceedings of the 2007 Mid-Continent Transportation Research Symposium.* Ames, Iowa. August, 2007. pp. 1-9.

63. Asphalt Academy. Bitumen Stabilized Materials. A guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilized Materials. *Technical Guideline 2 (TG2).*2nd Edition, ISBN 978-0-7988-5582-2, Asphalt Academy, Pretoria, South Africa, May 2009.

64. Judycki, J., J. Jaskula. Investigation into Water and Frost Resistance of Asphalt Concrete. Road Pavement, Vol. 12, 1997, pp. 374-378.

65. Miljkovic, M., M. Radenberg. Rutting Mechanisms and Advanced Laboratory Testing of Assphalt Mixture Resistance against Permanent Deformation. *Facta universitatis series: Architecture and Civil Engineering*, Vol. 9, No. 3, 2011, pp. 407-417.

66. Hofko, B., R. Blab. Assessment of Permanent Deformation Behavior of Asphalt Concrete by Improved Triaxial Cyclic Compression Testing. *Transportation and Development Institute Congress*, *Integrated Transportation and Development for a Better Tomorrow*, ASCE, 2011, pp. 396-397.

67. Santucci, L. Rut Resistant Asphalt Pavements. *Technology Transfer Program, Technical Topics, Institute of Transportation Studies*, University of California, Berkeley, 2001, pp. 1-8.

68. Schellenberg, K., and H. J. Eulitz. Ansprache des Verformungswiderstandes von Gussasphalt mit dem dynamischen Eindringversuch mit ebenem Stempel – Weiterentwicklung und Bewertungshintergrund [The Deformation Resistance of Asphalt with the Dynamic Indentation with a Flat Stamps – Development and Evaluation Framework. Forschung StraBenbau und StraBenverkehrstechnik, Heft 798, Bonn, 2000 [*Research Road and Traffic Engineering* No. 798, Bonn, Germany].