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

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ABSTRACT: Late season cold-in-place recycling with expanded asphalt mix (CIREAM) can be burdened by distresses such as ravelling, potholing and other moisture-induced damage. This study investigated how mixture variables and test protocols affect performance properties that relate to early strength and moisture resistance. Indirect tensile strength testing with moisture conditioning was used to assess the effects of asphalt cement type (80 versus 300 pen grades), conditioning time, and additives such as Portland cement, foam stabilizers, polymers and fibers. Uniaxial cyclic compression with partial confinement was used to assess rutting susceptibility. The optimum binder content was found to be around 2 percent, which is significantly higher than the minimum one percent as currently specified in Ontario. Both Portland cement and a siloxane-based foam stabilizer exerted significant positive effects on performance properties. With an appropriate choice of CIREAM materials important benefits can be realized over regular cold-in-place (CIR) recycling processes.

KEY WORDS: CIREAM, CIR, early strength, moisture sensitivity, expansion ratio, half life

1. INTRODUCTION

Cold in-place recycling has become an accepted road rehabilitation process worldwide by providing economic and environmental advantages over other pavement rehabilitation techniques [1]. The process utilizes aggregates from the entire existing distressed pavement, rather than new aggregates, in creating improved and strengthened pavement layers through in-situ mixing with binder, water and additives at ambient temperatures [2, 3]. Binders such as foamed bitumen, bitumen emulsion and cement slurry can be used to transform the reclaimed aggregates into a homogenous structure capable of supporting the traffic requirements [4]. The cold-in-place recycling with expanded asphalt mix (CIREAM) process, which utilizes expanded (foamed) asphalt as the stabilizing agent, offers a number of benefits over regular cold in-place recycling (CIR) processes. Kendall et al. [5] observed that foamed asphalt stabilized material offers strength characteristics comparable to that of cement treated materials while remaining flexible and, as such, should be relatively fatigue resistant. In addition to being less susceptible to moisture and other weather effects, CIREAM rapidly develops sufficient structural strength for immediate trafficking right after placement and compaction, unlike emulsion stabilized cold mixes which require longer times of hot and dry weather for curing [6, 7].

Asphalt foaming technology was first developed in 1956 by Csanyi [8] who injected steam in hot asphalt cement which caused the material to foam. However, the original steam process was impractical for in-place foaming operations but it was suitable for use in 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 systems and efficient mixing processes.
CIREAM was originally designed to minimize the curing time compared to emulsion stabilized cold mixes (CIR) prior to overlaying with the aim of providing an extended paving period as it is less sensitive to moisture and other weather effects. However, current CIREAM processes in cold and wet climates are still characterized by field issues 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. These challenges are considered to be caused by cold weather conditions during placement, rainfall after placing the overlay and poor compaction [9]. The work presented in this paper investigates the effects of mixture variables and test protocols on performance properties that relate to early strength and moisture resistance of foamed asphalt treated recycled mix. The high temperature deformation behaviour of CIREAM mixes is examined by evaluating the effects of binder content, asphalt types and additives on the deformation resistance of the mix.

2. BACKGROUND

Road pavements are designed to take, transmit and distribute stresses from wheel loads over a large area of the subgrade. The characterization of asphalt mixes is complex due to temperature and time dependent plastic and viscoplastic effects. Pavements are not only required to have sufficient strength to withstand traffic loads but also transmit such loads by viscoelastic deformation without failure. Vasconcelos et al. [10] stated that the performance behaviour of asphalt mixtures is dependent on factors such as stress state, moisture, temperature, strain rate, and more notably binder type. It is imperative to mention that binder properties, or more specifically the foamed asphalt cement properties, together with the effects of additives, are crucially important to improve the performance of foamed asphalt treated mixtures (CIREAM). Chiu and Lewis [11] considered the cost-effectiveness of foamed asphalt as its most significant advantage because the CIREAM process produces high quality mixtures using ordinary penetration graded asphalt with cold, damp aggregate. Foaming increases the surface area of the bitumen and reduces the viscosity significantly to improve its workability with, and dispersion on cold and moist aggregates. The foamed asphalt coats the fine particles forming a mastic mortar material between aggregates to provide strong binding cohesion (strength) to the mix [7, 12]. Foamed bitumen is characterized by the expansion ratio (which is the ratio of the maximum volume of foamed asphalt to the original volume before foaming) and half-life (time in seconds taken for the foam to collapse to half its maximum volume). A suitable combination of expansion ratio and half-life is needed to ensure effective dispersion and coating of the fines by foamed asphalt. Vasconcelos et al. [10] explained that softer asphalts provide lower structural capacity at high service temperatures potentially leading to rutting. On the other hand, hard asphalts are brittle at low service temperatures potentially leading to cracking under load. Thus, the strength and permanent deformation (rutting) behaviour, among others, will provide a good assessment of asphalt mixture behaviour including that of recycled pavements in the field.

2.1 Indirect tensile strength (ITS) test

The indirect tensile strength (ITS) test protocol [13] 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 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 size 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 [14, 15]. Vasconcelos and coworkers [10] 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 mixes 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.
2.2 Uniaxial cyclic compression test with partial confinement (UCCTC)

Uniaxial cyclic compression testing with partial confinement (UCCTC) [16] is a reliable and rapid laboratory procedure to investigate the deformation behaviour of compacted bituminous mixtures. This test was initially developed by Schellenberg [17] in the early 1980s to assess the deformation resistance of asphalt mixtures and was later described under the German Technical Regulations for Testing Asphalts for Road Construction [18]. According to Karcher [18], the UCCTC involves subjecting a cylindrical asphalt specimen with plane-parallel base surfaces to a haversine, pulse-shaped cyclic compression load of a centrally positioned die. A die of about 56 mm diameter is suitable being smaller than the diameter of the specimen (providing some 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. 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 of the specimen. The deformation can also be evaluated using the penetration depth (in mm) as a function of the number of cycles.

3. MATERIALS AND METHODS

Recycled asphalt pavement (RAP) from a contract on Highway 17 near Cobden, Ontario was manually separated into small pieces and screened with a 26.5 mm sieve, material retained on the 26.5 mm sieve was discarded. The screened material was then prepared for briquette manufacture according to procedures specified in Test Method LS-297 [19] 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 amount of additives and cement binder (foamed asphalt and asphalt emulsion) to make mixtures of different compositions. A moisture content of 80 percent of the 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. For example, a mix made with 2 percent foamed asphalt binder and modified with 2 percent Portland cement was conditioned by adding 244 grams of water (that is 544-100-200) to the aggregate followed by 200 grams of Portland cement and then 200 grams of foamed asphalt was injected into the mixture while continuously being mixed for about two minutes to ensure a reasonable degree of binder dispersion and homogeneity. 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 water, asphaltic emulsion (1% and 2%), foamed asphalt and additives, which included Portland cement, PET fiber of 0.5 inch and 4 denier, a siloxane-based surfactant of proprietary composition (Tego Addibit FS 725 A), and epoxidized soy bean oil (ESBO). Cold Lake asphalt, 80 pen grade and 300 pen grade roofing asphalt flux (RAF), were used in making the foam for the CIREAM mix. Each core sample of 150 mm diameter was compacted to a height of 45 mm using pre-defined amounts of the mixture sufficient to obtain comparable air void contents in identical samples (of the same batch). A number of samples of 47 mm in height were also made to probe the effect of air voids on mixture performance.
3.1 Specimen conditioning and testing protocols

Samples were subjected to different condition protocols after compaction. The conditioning included 24 hours under water, 24 hours in a freezer at -15°C, 72 hours in an oven at 50°C, and the reference standard conditioning method which involved air drying at room temperature (20-25°C) for 24 hours. Samples were prepared for digital image correlation (DIC) [20] 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 an hour prior to testing. The indirect tensile strength was determined by measuring the ultimate load to failure of the specimen under a constant loading (deformation) rate of 5 mm/min at 10°C. 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 the UCCTC testing, samples of 150 mm diameter and 45 mm height were conditioned at ambient temperature for seven days. The specimens were also conditioned for two hours at 50°C prior to testing. Conditioning ensured specimens were fully cured in order to simulate prevailing field conditions. The tests were terminated either at 5 mm deformation or after 3000 cycles, depending on the completion criteria first attained.

4. RESULTS AND DISCUSSIONS

The aim of the research was 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 relative to the regular cold in-place recycling process. The results reported here are mean values and the values of dispersion around these averages were determined using coefficient of variation (ratio of standard deviation to the mean values) in order to assess the uniformity of the test. The mean values for the ITS and strain rates had coefficient of variation less than 14 percent for every mixture composition and conditioning protocol. Indirect tensile strength (ITS) testing during the same day as the sample preparation and with moisture conditioning were used to assess early strength and moisture sensitivity of the CIREAM mixtures. As recommended by Muthen [6], the optimum binder content was selected based on the relationship between indirect tensile strength and foamed asphalt content. The ITS results are presented in Figures 1 and 2.

![Graphs](image)

*Figure 1. Effect of (a) binder content and (b) asphalt type on indirect tensile strength (ITS)*

The analysis of the test results presented on Figure 1 shows that the amount of foamed binder exerts a significant impact on the strength of the mix but that the type of binder is less important. The results reveal that the indirect tensile strength (ITS) increases as binder content increases up to 2 percent, after which the ITS declines. This suggests an optimum binder content of 2.0 to 2.5 percent, depending on the nature of the pavement to be recycled. The foamed bitumen 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. Although the results show less than 8 percent difference in ITS values for the two types (grades) of asphalt, the 80 pen grade Cold lake asphalt shows a relatively higher ITS value. Abel [21] found that softer asphalts are more fatigue-resistant having lower viscosity and forming more stable foam. However, by carefully selecting the foaming conditions (foaming water, temperature, foaming agent), a suitable combination of expansion ratio and foam half life can be achieved to ensure desirable strength and stability of the recycled mix. Muthen [6] 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 depends more on aggregate interaction rather than binder cohesion.

Figure 2 presents the effects of variables on strength of CIREAM mixtures subjected to different conditioning protocols before testing and compares these to regular cold in-place recycled (CIR) mixtures. Figure 2(a) shows the effect of mixture variables on strength under reference standard conditioning (air dried at about 20–25°C for 24 hours). The ITS values for the two ordinary CIREAM mixtures (80 and 300 pen) double those of CIR with one and 2 percent Portland cement. The CIREAM mixtures have more asphalt cement and less water than comparable CIR mixtures because the emulsion used contained about 64 percent asphalt cement. 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 2(b) shows the effect of mixture variables made using cold aggregates on the strength performance of the mixtures. The cold aggregate conditioned at -15°C for 72 hours simulates the prevailing low temperature condition associated with cold season paving. The CIREAM mixtures show better strength performance relative to CIR mixtures. Although one percent Portland cement exerted the highest effect on strength, the ITS value of the 80 pen CIREAM is comparable to those of one and 2 percent Portland cement. Softer asphalt has been reported to be less prone to low temperature fatigue cracking because of lower viscosities, yet Cold Lake (80 pen) asphalt gave better strength performance than softer RAF (300 pen).

Figure 2(c) shows the results of tests conducted using specimens soaked under water for 24 hours while Figure 2(d) presents the tensile strength ratio (TSR) determined from the dry and wet ITS values expressed as a percentage of retained strength. This 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 TG 2 of the Asphalt Academy [22]. Figure 2(c) shows that CIREAM mixtures exhibit better strength performance than CIR mixtures, with Portland cement and foam stabilizer improving the ITS significantly. Judycki and Jaskula [23] suggested that mixes are water resistant when the TSR is higher than 70 percent. From Figure 2(d), the CIREAM mix made using the siloxane-based foam stabilizer (specimen H) turned out to be water resistant with a TSR above 70 percent. Other mixtures, including the emulsion treated mixes, did not meet the required criterion as they all showed a TSR below 70 percent. The foam stabilizer reduces the surface tension of the asphalt foam to enhance binder dispersion and increase aggregate coating. This increases the strength and water resistance of the mixes. Two percent of foamed bitumen was used for this test. ESBO is a vegetable oil which has both a softening point and penetration lowering effect on asphalt. Samples modified with ESBO were observed to give off the oil as thin films when soaked under water for 24 hours, probably due to the water-proof and oil-proof nature of ESBO. The result is not presented here as further study of ESBO in foamed asphalt mix needs to be done. Iwanski et al. [2] suggested that higher water resistance can be achieved by increasing the binder content of the recycled composition.

Figure 2(e) presents the results of tests conducted only four hours after compaction. This result was used to assess the early strength performance of the mix. ITS values of CIREAM nearly double those of CIR. CIREAM mixtures develop a significant amount of strength within hours of compaction. The CIREAM mixes cure faster because the foamed bitumen in CIREAM contains less water (3%) and more asphalt cement binder while the emulsion in comparable CIR mixes contains more water (36%) and less binder. CIR mixtures will likely take the same time to cure with comparable CIREAM mixtures had the CIR been done with equal amount of water. Chan et al. [24] reported that CIREAM develops full strength within 3 days of compaction whereas CIR requires about 14 days. It is important to mention that one percent Portland cement shows the highest ITS value rather than 2 percent. This amount exerts a desirable impact on the early strength of CIREAM mixes without compromising flexibility. Figure 2(f) shows the strength performance of mixtures after 3 days of curing at 50°C. CIR 1% shows a higher ITS value compared to CIR 2% due to the lower water content in the binder used in CIR 1%. Unmodified CIREAM mixes show comparable ITS values with those modified with one and 2 percent Portland cement after 3 days curing at 50°C. Epoxidized soybean oil (ESBO) and siloxane-based foam stabilizer have no effect after such long period of curing at high temperatures and hence were not tested.
Figure 2. Effects of asphalt type and additives on strength of recycled mixes: A = CIR 1%, B = CIR 2%, C = CIREAM 300 pen, D = CIREAM 80 pen, E = 1% Portland cement, F = 2% Portland cement, G = epoxidized soybean oil (ESBO), H = siloxane-based foam stabilizer. Two percent 80 pen asphalt content was used in mixtures E, F, G and H.

Figure 3. Effect of binder content on rut resistance of CIREAM mixtures.
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 [25]. In their work, Miljkovic and Radenberg [25] stated 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. Hofko and Blab [26] 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 [27]. The UCCTC test assesses the rutting resistance of recycled mixtures using the strain rate at the inflection point and dynamic penetration depth as a function of load cycles. High strain rates at the turning point indicate low rutting resistance.

Figure 3 presents the effect of binder content on the deformation (rutting) resistance of the recycled mixes at high temperature (50°C). For both 300 and 80 pen graded asphalt, 2 percent binder content gave the lowest strain rate at the turning point and therefore highest rutting resistance relative to 2.5 and 3 percent binder content. Miljkovic et al. [25] had reported that rutting resistance decreases with increasing binder content while modifiers can be used to increase the stiffness at critical temperatures at which rutting tendency is determined. However, the 80 pen grade asphalt shows a higher rutting resistance relative to 300 pen asphalt in all the binder contents due to its higher viscosity. 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 (viscous) asphalts [27].

Figure 4 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. Addition of fibre, Portland cement, epoxidized soybean oil 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. It is important to mention that moisture infiltration of the recycled layer into the base or subgrade weakens these layers and results into permanent deformation of these layers under repeated traffic. The rutted condition of these underlying layers then manifests itself on the pavement surface [27]. 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 subgrade or base or throughout the entire asphalt pavement structure can be prevented. Additives such as Portland cement, fibre 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. The permanent deformation behaviour of mixtures is dependent on the material composition of the mix and the test (service life) conditions. Therefore, careful selection of materials with controlled application of additives will significantly improve the rutting resistance of CIREAM mixes.
Figure 5. Representative dynamic creep curves as a function of cycles. Note: A = CIR 1%, B = CIR 2%, C = 300 pen, D = 80 pen, E = 1% Portland cement, F = 2% Portland cement, G = epoxidized soybean oil, H = siloxane-based surfactant, I = PET fiber. Two percent 80 pen asphalt content was used in mixtures E, F, G, H, and I.

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. Figure 5 presents the creep curve for nine (9) mixtures of different compositions. The various compositions tested gave reproducible creep curves and those presented here are representative for the different mixtures tested. The rutting depth of asphalt pavement on the field has been reported to be strongly related to the dynamic penetration depth in the laboratory [28]. Santucci [27] 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 had less than 4 mm penetration depth at about 2500 load cycles. Mixture G had about 3.5 mm penetration depth below 3000 load cycles, mixture D 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. 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. 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 allows for a 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 areas such as bus stops, intersections, congestion area around traffic lights and freeway off ramps [18, 27].
5. CONCLUSIONS

This study was designed to investigate CIREAM and CIR mixes under different conditions. The following conclusions can be drawn from the results:

- The optimum binder content was found to be around 2 percent since the use of higher binder contents resulted in a decrease of indirect tensile strength. This optimum binder content likely depends on the source of the recycled pavement materials and thus testing is recommended 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 asphalt cement.
- 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.
- 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 excess can lead to a loss in flexibility, which would make the mix more prone to low temperature cracking.
- 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 emulsion-treated 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.
- 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 life cycle analysis should be done to assess the overall benefits of the investigated additives.

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