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Enhancing Sustainable Surface Treatments: A Review of Sasobit® Redux and Nanomaterial for Chip and Cape Seals in Cold Regions

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Abstract **-** Chip and cape seals are commonly used as surface treatment due to their cost-effectiveness as a pavement maintenance strategy. However, freeze-thaw cycles in cold regions cause binders in surface treatment to expand and contract, resulting in deteriorating surface treatments. These surface treatments should prevent water ingress into the pavement and resist damage from freeze-thaw cycles. However, failures such as bleeding, aggregate stripping, brittleness caused by the stiffening effect in bituminous binders and loss in microtexture due to aggregate embedment are common with seals constructed during freezing periods. Conventional materials such as lime and cement used as adhesion promoters in slurries for cape seals have been reported to propagate cracks within the seal. These cracks become fault lines for pavement deterioration in winter; hence, there is a need to seek alternative innovative materials for surface treatments.

This review investigates the potential of incorporating innovative Sasobit® REDUX and nanomaterial as alternatives to conventional materials in constructing chip and cape seals in cold weather. Sasobit® REDUX is widely used as an additive in warm mix asphalt to extend the paving window. Its lower congealing point (72-83ºC), higher penetration (16-30 dmm), and lower crystallisation temperature (60ºC) make this additive effective in resistance against low-temperature cracking in the pavement. It provides better coating over aggregates and ensures better compaction at lower temperatures; however, its benefits in surface treatment have been underexplored. On the other hand, using nanomaterial significantly improves the binder-aggregate adhesion and reduces temperature susceptibility and the likelihood of cracking. This paper analyses the selection procedure for binder, aggregate, and modifiers to ensure a more durable seal in cold regions. The findings indicated that 1% -1.4% dosage of Sasobit® REDUX by weight of bitumen enhances the performance of bitumen at low temperatures while nanomaterial such as anionic nanosilane-modified bitumen emulsion successfully replaced the use of lime and cement in slurry for Cape seal. Both Sasobit® REDUX and nanomaterial offer cost-effective approaches to enhance surface treatments in cold weather; therefore, future studies should explore the large-scale application of these materials in the field.

Keywords**:** Surface Treatments, cold regions, nanomaterial, chip seal, microtexture, Cape seal

1. Introduction

Bitumen is a non-volatile complex mixture of hydrocarbon and their compounds. In the pavement industry, bitumen serves as a vital construction material. About 90% of bitumen is used in pavement construction [1].

Unmodified bitumen performs well in low and moderate traffic loading and temperature changes. However, its performance is greatly influenced by adverse conditions such as extreme traffic loading exceeding 40,000 equivalent light vehicles (per lane, per day), steep grades, extreme temperature fluctuations, and slow-moving vehicles [2, 3].

Failures such as brittle cracking in the bituminous pavement caused by the stiffening effect in bituminous binders are common in chip seals constructed in cold weather. Some transport authorities chose to suspend chip sealing activities during winter to avoid failure and wastage of construction material [3]. Adhesion failures between the binder, aggregate and slurries for Cape seals are frequent in the construction of seals in cold regions [3, 4]. Some studies have reported that using lime and cement in the slurry can propagate cracks in Cape seal. These problems necessitate seeking alternative construction materials to advance sealing in cold weather.

This review aims to identify viable and sustainable construction materials that can enable the construction of chip and Cape seals in cold weather. Sasobit® REDUX and nanomaterials are explored in this review to understand their key benefits in advancing the construction of seals in cold weather. The selection of Sasobit® REDUX and nanomaterial for this study is genuinely based on a thorough literature review.

The method used in this review is systematically identifying and analysing relevant studies from Scopus, Web of Science, and Google Scholar databases. The keywords used were "bitumen modifiers," "surface treatments," "Sasobit® REDUX," and "nanotechnology in pavement." Emphasis was given to the studies published in the last 15 years. The inclusion criteria were based on research that targeted low-temperature performance, binder modification, and surface durability. Data synthesis was done through an analysis of material performance results related to durability and cost-effectiveness.

1.1. Fundamentals and applications of bituminous surfacing

Asphalt overlays and surface treatments are the two methods for constructing bituminous surfacing, and they offer excellent preventive measures to extend the service life of pavement infrastructure [3]. Moreover, surface treatments include sprayed seals, slurry and combination seals.

Sprayed seals are thin layers or films of bitumen binder applied to the road surface before aggregate cover, e.g., a single seal. Upon spreading and compacting the aggregate cover, the sprayed seals will create an adhesive and waterproofed protection within the newly formed layer [3].

A mixture of bitumen emulsion, aggregates (crusher dust), additives and water are the building blocks for slurry seals, while single seals with voids filled with graded slurry are known as combination seals [3, 5].

1.2. Surface treatments: A focus on chip seal and reseal types

When applied at the right time, chip seal helps extend the pavement's service life, thus improving the quality of roads. There are several types of surface treatments, and their utilisation in any project depends on the needs, scope, and budget requirements identified by the designer.

As the name suggests, single seals are chip seals constructed using a single layer or application of bituminous binder and evenly graded aggregate, while double seals are made using two applications of bitumen and evenly graded aggregate, respectively [6]. The layer thickness for a single chip seal ranges from 6 – 13 mm [7]. The second layer of aggregate in a double seal is usually half the approximate size of the first layer of aggregate [6]. Double seals are suitable for roadways with intense traffic flow, and they offer protection to the windscreen and minimise the extent of noise generated by vehicular tyres [3]. The quality of ride-on-chip seals can also be improved using slurries in the form of Cape seals.

Cape seals are vital surface treatments providing smooth and convenient surfaces for road users. The concept of utilising Cape seal as a surface treatment can be traced to the Western Cape Province of South Africa, and its construction process involves filling the aggregate voids in a chip seal with slurry or microsurfacing [3, 8]. The composition of Cape seal includes fine sand, cement, lime, bituminous binder and crusher dust [9]. The material composition of the Cape seal makes it provide smooth surfaces. The aim of using lime and cement in the slurry for Cape seal is to enhance the consistency and improve the mix's surface smoothness and bond strength. Overall, the use of lime and cement in slurry should be 1-1.5% by aggregates weight [3]. Using lime and cement to enhance the workability of slurries can prevent the emulsion separation from the aggregate [10].

Bituminous binders used as tack coats for sealing activities offer adhesion between the road surface and incoming aggregates (in the case of chip seal). Tack coats can be applied as neat, modified binders or cutback binders. However, cutbacks should be avoided when constructing seals in winter to prevent bleeding during summer [3, 11]. Regarding cost, tack coat accounts for a meagre project sum ranging between 0.1% to 0.2% [11]. Hence, the use of tack coats in sealing activities offers significant cost savings.

The molecular structure and chemical composition are the two significant factors dominating bitumen's behaviour at low temperatures [12]. Evaluation of the chemical composition of bitumen is a difficult task to perform, as proven by researchers, and according to Nizamuddin [13], bitumen contains saturates (11.9–15.8%), aromatics (39.6–53.1%), resins (22.8–34.8%), and asphaltenes (10.3–12.1%).

A study on porous asphalt samples using Thin layer chromatography-flame ionisation detector (TLC) suggests that the ageing process directly affects the chemical properties of bitumen [14]. Overall, the study mentioned that saturates' response to ageing is negligible, while the ageing process of the binder increases the resin and asphaltene content but causes a reduction in the content of aromatics. A simulation incorporating molecular dynamics to evaluate the molecular structure and performance of bitumen at low temperatures suggests that the susceptibility to failure of bitumen at low temperatures can be improved by utilising materials with more resins and aromatics in the bitumen [12]. Based on the significance of bitumen composition, it becomes necessary to understand the molecular and chemical structure of bitumen modified with additives like Sasobit® REDUX and how it can impact surface treatments at low temperatures.

Bitumen modifiers such as polymer (Elastomers and plastomers), aliphatic synthetic wax, and naturally occurring hydrocarbons are known to enhance bitumen functionality [4]. Bitumen modifiers containing aliphatic synthetic wax, obtained from the Fischer-Tropsch (F-T), are known to improve the low-temperature performance of bitumen [15]. In addition to low-temperature enhancement, Iwański and Mazurek [16] reveal that applying 2% or more synthetic wax dosages to bitumen enhances its resistance to plastic deformation. A multiple stress creep recovery (MSCR) test showcases that Fischer Tropsch-Paraffin wax at 1.5% prevents rutting of binder and turns a PG 64 to PG 70 [17]. Therefore, more study into how synthetic wax influences the performance of bitumen will guarantee their effective use in surface treatments, especially at low temperatures.

2. Overview of advancements in bitumen modification to address traditional limitations.

2.1. Sasobit® Fischer Tropsch additives: development and impact in bitumen.

Wax is an organic compound that is solid at room temperature and melts at an increasing temperature, and it includes paraffin and microcrystalline wax [18]. A group of n-alkanes containing little to zero branches in their structural composition are known as Paraffin wax (carbon atoms range between C20–C40), while the end product from the fractional distillation of crude oil containing essentially naphthenes and iso-paraffins is called the micro-crystalline wax [18].

The performance of wax-modified bituminous binders is heavily governed by the structural properties of the wax, particularly by the carbon chain length, which influences rutting resistance and flow behaviour. Understanding carbon chain length is essential to ensure the wax complies with existing specifications. In this regard, Reynhardt [19] provides the expression for estimating the average linear carbon chain length of a given wax based on the ratio of CH_2 and CH_3, which is equal to (m – 1)/2 as expressed in Eqs. (2). This evaluation of the carbon chain length in wax can be made possible through the use of nuclear magnetic resonance (NMR). While NMR can, in principle, provide a rapid estimate of the chain length, the smaller peaks are often not resolved, and since there is minimal branching in paraffin waxes, the branching effects can be safely ignored.

$$\frac{1}{2N}\sum_i(m_i-2) = \frac{1}{2N}\sum_i m_i - 1 \quad (1)$$

$$= \frac{1}{2}\underline{m} - 1$$

$$= \frac{I_{CH2}}{I_{CH3}}$$

Given that:

N = Total number of chains in a sample, $\underline{m}$ = average chain length, while I_{CH2} and I_{CH3} = Intensities for CH2 (methylenes) and CH3 (methyl) groups.

Therefore,

$$\underline{m} = 2\left(\frac{I_{CH2}}{I_{CH3}} + 1\right) \tag{2}$$

Examples of wax materials used as flow improvers in bitumen include ‘‘FT-paraffin, montane wax, oxidised polyethylene wax, thermoplastic resins and fatty acid amide’’ [20]. The molecular weights for each of these petroleum waxes vary significantly, with paraffin wax having the highest molecular weight owing to its long hydrocarbon chains compared to the other waxes [20]. Waxes with long carbon chains are known to provide enhanced binder performance, such as rutting resistance, compared to those with shorter carbon chain lengths [21]. Thus, the reason for the wide application of paraffin wax as a flow improver in bituminous binders.

One of the latest products by Sasol is Sasobit® REDUX. Sasobit® REDUX is not another form of petroleum wax; instead, it is a modified application of the popular Sasobit® technology, a commercial wax that catalytically depolymerises Fischer-Tropsch (F-T wax) synthetic wax ('Sasobit') along with other hydrocarbons [22].

FT-paraffin is the final product of the Fischer-Trospch process, and its major constituents are hydrocarbons with carbon atoms ranging from 40 to 100 [20]. Specifically, the carbon atoms present in Sasobit® range from 40 to 115 in chain length [23]. F-T synthesis is a standard practice that helps keep off sulphur and ensures little aromatics in the wax [24]. F-T synthesis, especially in the Shell Middle Distillate Synthesis (SMDS) process, produces high-purity hydrocarbons as waxes and fuels. The products have no sulfur and only trace amounts of aromatics. This is because synthesis gas is catalytically converted and then followed by the hydro-processing step (s), leading to cleaner fuel that meets the most stringent environmental specifications [25].

The F-T process gives rise to the production of paraffin or olefin chains, as expressed in Eqs. (3) – (4) below. The reaction in Eqs. (3) is purely exothermic (heat is released), in which about -150 kJ is given out for every mole of carbon monoxide (CO) that reacts with hydrogen in the system. The H_20, a co-product of the F-T process, interacts with CO to produce CO_2 and H_2, as further illustrated in Eqs. (5) [26].

$$n\,CO + (2n + 1)\,H_2 \rightarrow C_nH_{2n+2} + n\,H_2O \tag{3}$$

$$n\,CO + 2n\,H_2 \rightarrow C_nH_{2n} + n\,H_2O \tag{4}$$

$$CO + H_20 \leftrightarrow CO_2 + H_2 \tag{5}$$

The most crucial distinction of the Sasobit® technology is that it removes the high viscosity effect of the binder at high temperatures by rupturing its crystalline structure and building up a new crystalline structure inside the bitumen [27]. In this way, brittleness and rutting at high temperatures are also resisted by Sasobit® modified bitumen. When directly comparing it to the parent product Sasobit®, it can be explained that at 115 °C, Sasobit® dissolves in the bitumen. Correspondingly, 85 °C is the temperature at which Sasobit® REDUX mainly dissolves in bitumen [28]. For this reason, Sasobit® has been extensively used in warm mix asphalt (WMA).

Unlike hot mix asphalt (HMA), which is produced above 140 °C, WMA ensures pavement construction at a lower temperature between 100 to 140 °C, while half-WMA is produced at 70 to 100 °C [29]. Sasobit® REDUX supports Half-WMA, and its use results in energy efficiency, as noted by Edwards and Isacsson [20]. Another key benefit of Sasobit® in WMA is the rapid return of traffic to the road, which is essential in ensuring the timely curing of tack coat for surface treatment construction in cold climates.

At the cooling phase, some variations have been observed in the properties of bitumen modified with Sasobit® products. For instance, the congealing point (at 0°C) and penetration (at 25°C) [dmm] for Sasobit® REDUX are in the range of 72 - 83 and 16 – 30 compared to the Sasobit® having 100 - 110 and 0 – 2 for congealing point and penetration, respectively [28, 30]. These enhanced properties of Sasobit® REDUX are vital in preventing cracks in surface treatments; e.g., chip seals should be thoroughly studied.

Unlike Sasobit®, which crystalises at about 90°C, causing increments in the stiffness of the bitumen due to the creation of crystal lattices-like structure in the binder, Sasobit® REDUX has a negligible impact on the stiffness of the binder, and it crystallises from 60°C, thus providing an anti-ageing effect on the binder and preventing it from cracking [28, 30]. These enhancements with Sasobit® REDUX should be investigated to understand their impact on the chip seal's flexibility and crack control in cold weather.

Crystallisation of waxes in bitumen is an essential area of interest among researchers. Wax in bitumen can affect the properties of bitumen in the pavement, causing it to crack at low temperatures [20]. Therefore, one can suggest that more wax in bitumen translates into higher stiffness in the binder, thus justifying the need to establish the optimum wax content in bitumen to achieve the best performance.

Sasol [30] recommended that the average dosage for Sasobit® REDUX should be between 1 – 1.4 % by weight to the bitumen, and for Sasobit®, it is 1.5% by weight of the bitumen [17]. Previous reviews on Sasobit® by Edwards and Isacsson [20] discussed that incorporating more than 4% Sasobit® into bitumen will result in stiffness and cracking in bitumen at low temperatures, concluding that 3% is the maximum dosage for Sasobit®. It is evident that increased binder stiffness is undesirable for surface treatments. In addressing these concerns, Sasol [30] highlighted that Sasobit® F-T wax indeed contributes to the stiffness in bitumen but has a negligible effect on the performance of binders at cold temperatures, resonating with the views of the promoters of wax in bitumen that the technology does not propagate cracking, fatigue and adhesion failures in pavement [20]. A study by Sharma [31] reveals that the resistance to rutting potential in bituminous mixes is closely related to the zero-shear viscosity; therefore, further studies could examine the stiffness of binders modified with Sasobit® REDUX using the zero-shear viscosity process.

Overall, Sasobit® REDUX has more robust improvements and better performance at low temperatures than Sasobit®. The benefit of Sasobit® REDUX in minimising cracks should be expanded to pavement surfacing, including chip seals in cold regions where temperature fluctuations often result in crack formation in the pavement structure. It should be noted that several previous studies on Sasobit® have mainly focused on its application in WMA, but research into its applications in chip seal construction has gained limited momentum.

2.2. An overview of nanotechnology application in pavement construction

Nanotechnology has a long history embedded in the ancient Greek word. The prefix ''nannos'' originates from the Greek word, which refers to a short man or Dwarf [32]. In scientific terms, nano is a unit representing one-billionth (0.000 000 001) of the base unit, while the scale in which nanotechnology is expressed is known as the nanoscale, which implies that the material has at least one of its dimensions less than 100 manometers [32, 33].

Nanotechnology has gained significant attention in many disciplines, including physics, ''chemistry and electrical engineering'' thus justifying the need to advance this innovation in the pavement industry, an essential branch of civil engineering [34].

New problems demand new solutions. The increasing wheel loads, the escalating population of road users across many modern cities and the impact of the unforgiven climate change on pavement infrastructure make conventional road construction material unreliable. It is evident that an innovative approach to enhance and extend the service life of pavement infrastructure is crucial, and nanotechnology is among the options that fill these gaps perfectly.

From the deep subgrade structure to the topmost asphalt layer of pavement structure, several investigations have shown the robustness of using various nanotechnology products to enhance pavement performance [33, 35-38]. Examples of nanomaterials that have been successfully used as bitumen modifiers for asphalt include nanosilica, nano-hydrated lime, graphite nanoplatelets, carbon nanotubes and nano clay [11].

The improvements brought by nanotechnology in pavement technology, mainly as modifiers for bitumen, are massive, ranging from a hydrophobic effect to enhanced engineering properties such as resistance to rutting and temperature fluctuation, improved durability, and flexibility of road material [33, 36, 39, 40].

Since surface treatments such as chip and Cape seals offer a cost-effective means to enhance the service life of roadways, incorporating Sasobit® REDUX in tack coats and nanomaterial such as nano silane technology in Cape seals can contribute to a more resilient seal in cold regions.

Silane mainly contains silicon and hydrogen atoms, enabling it to form durable bonds or adhesion with bituminous binders and inorganic materials such as soil or aggregate [41, 42]. Furthermore, water is required to bring about hydrolysis, which is a chemical reaction whereby organofunctional silanes result in the formation of silanol. Once the emulsion breaks and water is expelled (from the silanol), the newly formed structure is known as the siloxane structure [41]. The formation of the siloxane structure is the reason for the ‘‘hydrophobic effect’’, otherwise known as the water-repellent surface of pavement materials improved with nano silane-modified binder [43]. The benefits of nano silane in terms of strength and hydrophobic effect should be extensively explored and expanded to Cape seal construction.

Like Sasobit® REDUX, nanomaterials have gained little attention in constructing surface treatments in cold weather. However, their use in pavement sublayers and overlays is widely investigated [44, 45].

Amid scarce resources, some benefits of utilising nanomaterials to enhance the performance of bitumen for pavement construction are given in Table 2. Although these benefits are not directly linked to surface seal construction, the study's outcome could be applied to advance surface treatments in cold weather with nanomaterials.

Table 1: Impact of some selected nanomaterials on pavement materials.

Nanomaterial	Impact	Reference
Nano-SiO2	It provides resistance to rutting and increases the complex modulus ǀG*ǀ and stiffness in bitumen, and it improves resistance to moisture damage in asphalt mixtures.	[46]
Nano TiO2	It enhances the rheological properties of the binder and offers protection against ageing and permanent deformation in bitumen.	[47]
Carbon nanotubes (CNTs)	It improves the mechanical and rheological characteristics of asphalt concrete but has a significant cost implication.	[48, 49]
Nano clay	Extend fatigue life, enhance softening and penetration point and increase tensile strength in asphalt mixtures.	[50]
Nano iron oxide (Fe2O3)	It enhances the physical properties of asphalt binder, and the recommended dosage for nano Fe2O3 ranges between 1% to 3%	[51]
Nano calcium carbonate (CaCO3)	It provides an anti-ageing effect in bitumen at low temperatures, prevents moisture damage, extends fatigue life, and improves rutting potential in asphalt samples.	[52, 53]

3. The significance of modified binders on chip seal performance in cold weather

Based on these limitations in the use of Sasobit® REDUX and nanomaterial in constructing chip seals, this review examines a broad spectrum of other modification methods to ensure the construction of seals in cold weather. The findings from these studies are crucial and could serve as the launch pad for investigating seal construction with Sasobit® REDUX and nanomaterial.

A previous study by Galooyak [46] shows improved performance of asphalt mixtures with nano-SiO_2 and Sasobit®. The benefits of nano-SiO2 and Sasobit® can be examined in terms of their potential to advance the construction of durable chips and Cape seals.

Slow curing of the binder used in the construction of chip seals often results in the failure of adhesion in cold weather [3]. An anionic emulsion is suitable for prime coating and surfacing dressing where quick curing of binder is a top priority

[54]. This will be beneficial for constructing chip seals in cold weather to mitigate adhesion failures in chip seals. Leveraging on this insight, Jordaan et al. [55] evaluated the susceptibility to punching failure, aggregate loss, and bleeding on a chip seal modified with Sasobit-M® as a tack coat and a Cape seal modified with anionic nano silane bitumen emulsions using the third-scale model mobile loading simulator (MMLS3). The study indicated that these modifications enabled the construction of the seals at low temperatures. The modification improved the performance of the seals tested below 20 ^{0}C. Future studies could examine how these modifiers interact with aggregates of different types to ensure that the most compatible aggregates are selected. Also, a careful comparison of these modifiers with traditional materials in terms of long-term performance for surface treatments should be investigated. Finally, a guideline for safely using these materials in constructing chip seals should be well-established.

Slurries seals made with reclaimed asphalt pavement (RAP) are cost-effective compared to virgin aggregates; however, slurries containing RAP take longer to cure [5]. Future studies should examine the potential of incorporating anionic nano silane to formulate slurries seals with RAP to minimise the continuous utilisation of virgin aggregates.

An investigation on the effect of polymer-modified bitumen emulsion on chip seal performance using MMLS3 discovered that the modification improved the resistance to bleeding and rutting potential in the chip seal [56]. The analysis also indicates that the modification is cost-effective and that the chip seal's service life can be extended by 2 years relative to an unmodified bitumen emulsion. Similar studies on nanomaterials and Sasobit® REDUX should be investigated to understand their long-term impact on chip seals.

In another study on how SBR and branched carboxylated X-SBR affect the properties of chip seal in cold weather, Abedini et al. [57] concluded that SBR-modified binder significantly prevented aggregate loss in chip seal at -20ºC compared to X-SBR when subjected to Vialit test. Vialit test is a typical experiment for examining the bond characteristics between the binder and aggregate [58]. The enhancement in the rheological properties of the binder due to the impact of SBR is the reason for the improvement in the chip seal in cold weather. The study recommended avoiding the latter (X-SBR) in constructing chip seals in cold regions [57]. The insight from this study can be employed to examine the bond structure of chip seals modified with Sasobit® REDUX using the vialite test.

A performance assessment of chip seal samples using a three-point bending beam test showed that conventional rubber chip seal has lower fatigue life than rubber chip seal with fibre reinforcement [59]. The concept from this study could also be applied to evaluating the fatigue life of chip seals enhanced with other modifications, such as chip seals made with Sasobit® REDUX.

An in-depth study to investigate how modifications in bitumen, along with the choice of aggregate types, affect the performance of chip seals revealed the following. Across eight different tests, CRS-2L-modified emulsions delivered significantly better results than the traditional B100/150 penetration hot binders. Limestone aggregates clearly outperformed basalt in preventing failures, highlighting a significant area for further research [60]. This study opens opportunities to examine how Sasobit® REDUX could potentially improve the performance of chip seals, particularly in boosting their durability, adhesiveness and effectiveness.

In a similar study, Rahman et al. [61] investigated the effect of crumb rubber-modified bitumen on the durability of chip seals and observed that the modification greatly enhanced the longevity of chip seals as compared to the conventional bitumen. Hence, having such positive effects, it becomes logical to investigate if Sasobit® REDUX modified bitumen can have such long-term equivalent effects on chip seals.

At this point, it is worth mentioning that a thorough assessment of construction materials in terms of properties and characteristics is needed to ensure their use in surface treatments. A general requirement for material selection when constructing a chip and Cape seal in cold weather is provided in Table 1, while Fig. 1 provides basic requirements and stages for designing a chip and Cape seal.

Table 2: Key considerations and material characteristics for chip seal construction in cold weather

S/N	Findings	References
1	Sealing of fifty-four pavement surfaces during winter in the coldest parts of South Africa recommends 14/Grit, 14/5, 20/7, Cape seals, Grit seals, sand seals, slurry, and microsurfacing for surface treatment in winter	[3]
2	Hot binders with 0% solvents may be applied if the pavement surface temperature is 25ºC and rising. For emulsions, it should be 10ºC and rising	[3]
3	Bitumen emulsion is effective in constructing chip seals, and they offer similar performance as chip seals made with hot asphalt.	[62]

Note:
- 14/Grit - single seal consisting of 14 mm aggregate and fine sand,
- 14/5 – double seals comprising 14 mm aggregate (first layer) and 5 mm aggregate (second layer)
- 20/7 - double seals comprising 20 mm aggregate (first layer) and 7 mm aggregate (second layer)

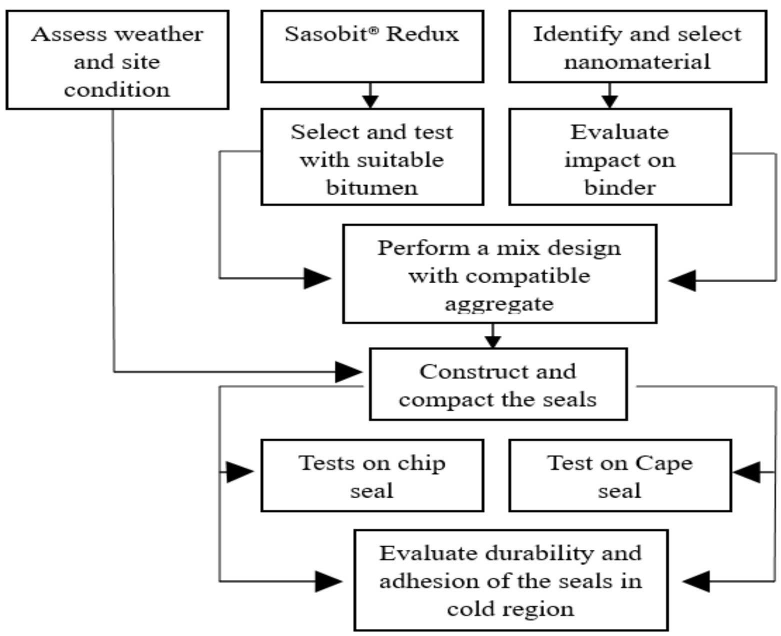

Fig. 1: Workflow for binder evaluation and seal design in cold weather conditions

4. Conclusion

This study explored the potential of Sasobit® REDUX and nanomaterials in enhancing chip and cape seals in cold regions, addressing challenges such as cracking, aggregate stripping, and freeze-thaw damage. Incorporating 1–1.4% Sasobit® REDUX by weight of bitumen significantly improved bitumen's low-temperature performance, while anionic nano silane imparted superior binder-aggregate adhesion and hydrophobic properties and successfully replaced the use of lime and cement in slurries for Cape seal. Aggregate selection was found to be critical for durability. In the case of single-chip seals, the required layer thickness ranged from 6 mm to 13 mm, whereas for double-chip seals, a second application was beneficial with aggregates of about half the size of the first layer, which enhanced interlock and reduced imperfections. Limestone aggregates were superior to basalt in adhesion and freeze-thaw cycle resistance; hence, longevity was promised. The effectiveness of binders in chip seals is temperature-dependent. Solvent-free hot binders should be used only when the pavement temperature is 25°C and rising, while emulsions should not be used at temperatures below 10°C and rising. These innovative materials and aggregate techniques offer economically viable and environmentally friendly alternatives towards maintaining roads in cold regions, hence prolonging the service life and improving the durability of the surface treatment. Further research should be directed toward validating these results on a broader scale field application.

References

[1] Sabita, *Bituminous Binders for Road Construction and Maintenance. Manual 2*, 5th ed. 2012, Howard Place, South Africa: Sabita. ISBN 978-1-874968-61-0

[2] S. Shuler, E. Lord, A. Epps-Martin, and D. Hoyt, *Manual for emulsion-based chip seals for pavement preservation*, TRB Report No. NCHRP 680, 2011.

[3] Sabita, *Manual 40/TRH3: Design and Construction of Surface Treatments. 3rd ed. 2021.* Southern African Bitumen Association, Cape Town, South Africa *ISBN 978-1-874968-77-1.*

[4] TG1, *The use of modified bituminous binders in road construction.* 2020: Technical Guideline 1, 5th ed, 2021. Sabita. Howard place, South Africa. ISBN 978-1-874968-74-0

[5] M. Saghafi, N. Tabatabaee, and S. Nazarian, *Performance evaluation of slurry seals containing reclaimed asphalt pavement.* Transportation Research Record, 2019. **2673**(1): p. 358-368.

[6] D. D. Gransberg and D. M. James, *Chip seal best practices*. Vol. 342. 2005: Transportation Research Board.

[7] J. Mahoney, M. Rutherford, and R. Hicks, *Guidelines for spring highway use restrictions*. 1987. FHWA-TS-87-209; Turner-Fairbank Highway Research Center: McLean, VA, USA,

[8] M. Solaimanian and T. W. Kennedy, *Evaluation of the cape seal process as a pavement rehabilitation alternative (No. FHWA/TX-99/1788-S).* 1998, University of Texas at Austin. Center for Transportation Research.

[9] G. Van Zyl and H. Fourie, *Key aspects of good performing Cape seals*. in *Proceedings of the 11th Conference on Asphalt Pavements for Southern Africa (CAPSA 2015), Sun City, South Africa*. 2015. pp. 16-19.

[10] TRH3, *Design and Construction of Surfacing Seals*. Version 1.5 ed. 2007: South African National Roads Agency Ltd.

[11] S. Chen, Z. You, N. P. Sharifi, H. Yao, and F. Gong, *Material selections in asphalt pavement for wet-freeze climate zones: A review.* Construction and Building Materials, 2019. **201**: p. 510-525.

[12] S. Liu, X. Qi, and L. Shan, Shan, *Effect of molecular structure on low-temperature properties of bitumen based on molecular dynamics.* Construction and Building Materials, 2022. **319**: p. 126029.

[13] S. Nizamuddin, Y. J. Boom, and F. Giustozzi, *Sustainable polymers from recycled waste plastics and their virgin counterparts as bitumen modifiers: A comprehensive review.* Polymers, 2021. **13**(19): p. 3242.

[14] U. Isacsson and H. Zeng, *Relationships between bitumen chemistry and low temperature behaviour of asphalt.* Construction and building materials, 1997. **11**(2): p. 83-91.

[15] M. Iwański and G. Mazurek, *Rheological characteristics of synthetic wax-modified asphalt binders.* Polimery, 2012. **57**(9): p. 661-664.

[16] M. Iwański and G. Mazurek, *Optimization of the synthetic wax content on example of bitumen 35/50.* Procedia Engineering, 11th International Conference on Modern Building Materials, Structure and Techniques, MBMST, Vilnius, Lithuania, ELSEVIER. *Procedia Engineering*, 2013. **57**: p. 414-423.

[17] I. M. U. Din and M. S. Mir, *Experimental investigation of low viscosity grade binder modified with Fischer Tropsch-Paraffin wax.* International Journal of Pavement Research and Technology, 2020. **14**: p. 129-137.

[18] H. Soenen, J. Besamusca, H. R. Fischer, L. D. Poulikakos, J. P. Planche, P. K. Das, N. Kringos, J. R. Grenfell, X. Lu, and E. Chailleux, *Laboratory investigation of bitumen based on round robin DSC and AFM tests.* Materials and structures, 2014. **47**: p. 1205-1220.

[19] E. Reynhardt, *NMR investigation of Fischer-Tropsch waxes. II. Hard wax.* Journal of Physics D: Applied Physics, 1985. **18**(6): p. 1185.

[20] Y. Edwards and U. Isacsson, *Wax in bitumen: part 1—classifications and general aspects.* Road materials and pavement design, 2005. **6**(3): p. 281-309.

[21] L. Desidery and M. Lanotte, *Effect of waste polyethylene and wax-based additives on bitumen performance.* Polymers, 2021. **13**(21): p. 3733.
[22] P. Caputo, A. A. Abe, V. Loise, M. Porto, P. Calandra, R. Angelico, and O. Rossi, The *role of additives in warm mix asphalt technology: An insight into their mechanisms of improving an emerging technology.* Nanomaterials, 2020. **10**(6): p. 1202.
[23] T. Yi-qiu, Z. Lei, G. Wei-qiang, and G. Meng, *Investigation of the effects of wax additive on the properties of asphalt binder.* Construction and Building Materials, 2012. **36**: p. 578-584.
[24] G. P. Van Der Laan and A. Beenackers, Beenackers, Kinetics and selectivity of the Fischer-Tropsch synthesis: A literature review. Catalysis Review, 1999. 41(3-4): p.225-318.
[25] L. Fan, K. Yoshii, S. Yan, J. Zhou, and K. Fujimoto, *Supercritical-phase process for selective synthesis of wax from syngas: Catalyst and process development.* Catalysis today, 1997. **36**(3): p. 295-304.
[26] R. Guettel, U. Kunz, and T. Turek, *Reactors for Fischer-Tropsch Synthesis.* Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology, 2008. **31**(5): p. 746-754.
[27] A. Almeida and M. Sergio, *Evaluation of the potential of Sasobit REDUX additive to lower warm-mix asphalt production temperature.* Materials, 2019. **12**(8): p. 1285.
[28] *Sasol, "Sasobit REDUX – Product information and summary of results", South Africa.* n.d.
[29] S. Capitão, L. Picado-Santos, and F. Martinho, *Pavement engineering materials: Review on the use of warm-mix asphalt.* Construction and Building Materials, 2012. **36**: p. 1016-1024.
[30] Sasol, *Sasobit REDUX Product Information, Sasol Wax Division*. n.d, Sasol: Hamburg, Germany.
[31] A. Sharma, G. R. Rongmei Naga, P. Kumar, and S. Raha, *Rheological characterization of recycled asphalt binders and correlating the zero shear viscosity to the Superpave rutting parameter.* Journal of Materials in Civil Engineering, 2022. **34**(9): p. 04022218.
[32] F. Allhoff, P. Lin, and D. Moore, *What is nanotechnology and why does it matter?: from science to ethics*. 2009: John Wiley & Sons.
[33] L. Zeng, L. Xiao, J. Zhang, and H. Fu, *The role of nanotechnology in subgrade and pavement engineering: a review.* Journal of Nanoscience and Nanotechnology, 2020. **20**(8): p. 4607-4618.
[34] M. T. Tiza, *Applications of Nanomaterials in Highway Pavements.* NanoEra, 2022. **2**(2): p. 23-29.
[35] J. Tanzadeh, F. Vahedi, P. T. Kheiry, and R. Rashid Tanzadeh, *Laboratory study on the effect of nano TiO2 on rutting performance of asphalt pavements.* Advanced materials research, 2013. **622**: p. 990-994.
[36] M. Saltan, S. Terzi, and S. Karahancer, *Examination of hot mix asphalt and binder performance modified with nano silica.* Construction and Building Materials, 2017. **156**: p. 976-984.
[37] E. S. Okem, *Stabilisation of base course materials with nanoemulsions*. 2022. (Master dissertation, Durban, University of KwaZulu-Natal)
[38] N. N. Chilukwa and M. M. H. Mostafa, *An investigation of the efficacy of nanoemulsions as alternative treatment for a marginal quality pavement material.* Road Materials and Pavement Design, 2023: p. 1-14.
[39] H. L. Zhang, M. M. Su, S. F. Zhao, Y. P. Zhang, and Z. P. Zhang, *High and low temperature properties of nano-particles/polymer modified asphalt.* Construction and Building Materials, 2016. **114**: p. 323-332.
[40] H. A. Obaid, *Characteristics of warm mixed asphalt modified by waste polymer and nano-silica.* International Journal of Pavement Research and Technology, 2021. **14**: p. 397-401.
[41] H. Ziari, P. Mirzababaei, and R. Babagoli, *Properties of bituminous mixtures modified with a nano-organosilane additive.* Petroleum Science and Technology, 2016. **34**(4): p. 386-393.
[42] R. C. L. Dryburgh, G. Jordaan, T. Modise, and M. Murphy*, The influence of the characteristics of emulsifying agents on the stabilisation of granular materials using nano-silane modified bitumen emulsions.* Pretoria, CSIR, 2019.
[43] G. J. Jordaan and W. J. V. M. Steyn, *Fundamental principles ensuring successful implementation of new-age (nano) modified emulsions (NME) for the stabilisation of naturally available materials in pavement engineering.* Applied Sciences, 2021. **11**(4): p. 1745.
[44] J. Crucho, L. Picado-Santos, J. Neves, and S. Capitão, *A review of nanomaterials' effect on mechanical performance and aging of asphalt mixtures*. *Applied Sciences, 2019, 9*(18), 3657.

[45] G. J. Jordaan and W. J. V. Steyn, *Practical application of nanotechnology solutions in pavement engineering: Construction practices successfully implemented on roads (highways to local access roads) using marginal granular materials stabilised with new-age (nano) modified emulsions (NME). Applied Sciences, 2022, 12*(3), 1332.
[46] S. S. Galooyak, M. Palassi, A. Goli, and H. Zanjirani Farahani, *Performance evaluation of nano-silica modified bitumen.* International Journal of Transportation Engineering, 2015. **3**(1): p. 55-66.
[47] G. A. Shafabakhsh, M. Sadeghnejad, B. Ahoor, and E. Taheri, *Laboratory experiment on the effect of nano SiO2 and TiO2 on short and long-term aging behavior of bitumen.* Construction and Building Materials, 2020. **237**: p. 117640.
[48] I. Amin, S. M. El-Badawy, T. Breakah, and M. H. Ibrahim, *Laboratory evaluation of asphalt binder modified with carbon nanotubes for Egyptian climate.* Construction and Building Materials, 2016. **121**: p. 361-372.
[49] M. Barati, M. Zarei, M. Zahedi, and F. Akbarinia, *Evaluating the effect of carbon nanotubes (CNTs) and recycled glass powder (RGP) on the rheological and mechanical properties of bitumen and hot mix asphalt (HMA).* Advances in Materials and Processing Technologies, 2022. **8**(1): p. 755-773.
[50] F. Khodary, *Longer fatigue life for asphalt pavement using (SBS@ clay) nanocomposite.* International journal of current engineering and technology, 2015. **5**(2): p. 949-954.
[51] Y. He, Q. Zeng, Y. Liu, P. Liu, Y. Zeng, Z. Xu, and Q. Liu, *Evaluation of the Composite Mechanism of Nano-Fe2O3/Asphalt Based on Molecular Simulation and Experiments.* Materials, 2021. **14**(12): p. 3425.
[52] P. Das, A. Chopdar, and L. Paneru, *A review of potential use of nano-technology in pavement engineering.* Advance and Innovative Research, 2019. **148**-152
[53] A. M. Yarahmadi, G. Shafabakhsh, and A. Asakereh, *Laboratory investigation of the effect of nano Caco3 on rutting and fatigue of stone mastic asphalt mixtures.* Construction and Building Materials, 2022. **317**: p. 126127.
[54] N. Sharibaev, N. Sharibaev, S. Djuraev, and S. Sharipbaev, *Recommended bitumen emulsion for road construction: enhancing durability and sustainability.* European Journal of Emerging Technology and Discoveries, 2023. **1**(4): p. 21-23.
[55] G. J. Jordaan, W. J. V. Steyn, and A. Broekman, *Evaluation of cost-effective thin modified binder seals on Nano-Modified Emulsion (NME) stabilised base layers using Accelerated Pavement Testing (APT).* 2021.
[56] J. Lee and Y. R. Kim, *Evaluation of performance and cost-effectiveness of polymer-modified chip seals.* Transportation research record, 2010. **2150**(1): p. 79-86.
[57] M. Abedini, A. Hassani, M. R. Kaymanesh, and A. A. Yousefi, *Low-temperature adhesion performance of polymer-modified Bitumen emulsion in chip seals using different SBR latexes.* Petroleum Science and Technology, 2017. **35**(1): p. 59-65.
[58] L. You, Z. You, Q. Dai, X. Xie, S. Washko, and J. Gao, *Investigation of adhesion and interface bond strength for pavements underlying chip-seal: Effect of asphalt-aggregate combinations and freeze-thaw cycles on chip-seal.* Construction and Building Materials, 2019. **203**: p. 322-330.
[59] J. Xu, M. Zheng, X. Ding, R. Qiao, and W. Zhang, *Laboratory proportion design and performance evaluation of Fiber-Reinforced rubber asphalt chip seal based on multiple properties enhancement.* Construction and Building Materials, 2023. **403**: p. 133204.
[60] M. Karasahin, B. Aktas, A. G. Gungor, F. Orhan, and C. Gurer, *Laboratory and in situ investigation of chip seal surface condition improvement.* Journal of Performance of Constructed Facilities, 2015. **29**(2): p. 04014047.
[61] M. N. Rahman, M. T. A. Sarkar, M. A. Elseifi, C. Mayeux, S. B. Cooper III, and K. Free, *Short-term field performance and cost-effectiveness of crumb-rubber modified asphalt emulsion in chip seal applications.* Transportation Research Record, 2021. **2675**(9): p. 1049-1062.
[62] D. D. Gransberg and M. Zaman, Analysis of emulsion and hot asphalt cement chip seal performance. *Journal of Transportation Engineering*, 2005. *131*(3), pp.229-238.