

Performance of conventional properties of coal bottom ash, waste cooking oil, and zycotherm-sp2 binders

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KEYWORDS	ABSTRACT
Conventional Properties Coal Bottom Ash Waste Cooking Oil ZycoTherm-SP2 Binders	This study presents the performance of Waste Cooking Oil (WCO), Coal Bottom Ash (CBA), and ZycoTherm-SP2 (ZT-SP2) as binder modifiers for Warm Mix Asphalt (WMA). The production of high-quality products depends on a reliable and well-regulated environment, with the control of mixing and compaction temperatures remaining a critical concern. This study aims to characterize the conventional properties of the bitumen binders by incorporating CBA, WCO, and ZT-SP2 in a controlled laboratory. The study's main contribution is the integration of a new warm mix chemical additive (ZT-SP2) into the binder mixtures, which lowers the mixing and compaction temperatures by 30°C and 30 – 40°C °C, respectively. CBA, WCO, and ZT-SP2-modified binders were produced and characterized in the laboratory setup. The modifiers' optimum contents were discovered to be 5%, 4%, and 0.1%, respectively, and these optimum contents enhanced the bitumen's conventional properties. The viscosity of the modified binder, 0.62 Pa·s at 135°C, guarantees adequate workability according to Superpave requirements; however, it may affect rutting resistance, necessitating additional modification for high-temperature or high-load applications.

1. Introduction

Bitumen is one of the materials most frequently used to produce asphalt mixtures. WCO and CBA are waste elements that require advanced management practices, particularly in the pavement construction sector. These substances have typically been intentionally or unintentionally released into the environment, upsetting land, marine life, and people. Comprehensive studies described CBA as a filler material [1], a sustainable material [2], fine aggregates in concrete [3], supplementary material [4], biowaste

[5], and a mechanical stabilizer [6]. Moreover, some researchers have described WCO as an unsusceptible asphalt material [7], a promising material for bio-lubricants [8], bio-asphalt as a substitute for bitumen binder [9], and a rejuvenator [10]. ZT-SP2 is a new warm mix additive capable of reducing the mixing temperature by 30°C, increasing the compaction temperature between 30°C and 40°C, and allowing further compaction below the minimum standard [11].

Due to increasing pollution from human activity, the globe is contaminated with harmful compounds

from several sources. The WCO and CBA are two noticeable pollutants left behind by human activity. Han et al. [13] reported that consumerism and the growing amount of waste being disposed of are the main causes of the unsatisfactory annual growth in waste generation worldwide. Consequently, there may be environmental damage if this waste is disposed of directly into the environment. In addition to being economically advantageous, using these wastes to construct pavements sustainably could result in considerable gains in foreign exchange earnings and a reduction in environmental damage [14-17]. The majority of waste products are hazardous, destructive, explosive, chemically reactive, and transmissible, and they are often disposed of in landfills, endangering public health and the environment [15].

For WMA modification, the combination of CBA, WCO, and ZT-SP2 provides a sustainable, economical, and performance-enhancing solution [16]. ZT-SP2 ensures moisture resistance and long-term durability [11], WCO enhances workability and flexibility [10], and CBA strengthens the mixture [2]. The synergy among these modifiers addresses the primary failure mechanisms in asphalt pavements, namely rutting, fatigue cracking, and moisture damage, making them appropriate for both conventional and high-performance applications, as demonstrated by a comparative literature review and performance benchmarking.

The use of CBA and WCO in bitumen modification can aid in the reduction of waste materials [18]. According to Babangida et al. [20] and Thakur & Han [21], Carbon-neutral materials (CNMs) are utilized in the construction of green pavements, which are designed to minimize excess carbon emissions released by moving vehicles. The WMA technologies can be used to eliminate the environmental problems related to high production and compaction temperatures when using waste materials [22,-24]. The warm mix additives were used by several researchers to decrease the mixing and compaction temperatures [23,25]. The superior properties of CBA and WCO-modified bitumen, which enhanced the binders' resistance to fatigue and rutting, are credited with the strong adhesion.

CBA is a useful substance that may be used in a variety of construction and civil engineering applications to enhance material qualities due to its accessibility, cost-effectiveness, and sustainability. WMA, which contains WCO, has drawn attention as a

justifiable way to recycle waste resources and improve the performance of the asphalt mixture. WCO has the potential to be a sustainable modifier or rejuvenator that changes the characteristics of bitumen binder [16]. Other wastes, such as steel fibers [27], hemp fibers [28], sewage sludge [29], and waste ceramic [30], can be incorporated into concrete and asphalt pavements for long-term durability. However, depending on its treatment and integration, it can have a variety of effects on the structural behaviour of WMA [16]. WCO has several uses that support the economy, sustainability, and ecological preservation, especially in the manufacturing of biodiesel, industrial applications, and the construction industry [31]. ZT-SP2 (an organ silane-based chemical) is added to WMA to improve its performance characteristics [11]. The addition effectively reduces moisture susceptibility, such as stripping, since it is designed to promote bonding between the aggregates and the bitumen binder, especially when moisture is present [11]. Additionally, ZT-SP2 allows for a reduction in manufacturing compaction temperatures, a major benefit of WMA. As a result, CBA, WCO, and ZT-SP2 are used in this study. This study is designed to characterize the conventional properties of bitumen binders by incorporating CBA, WCO, and ZT-SP2 in a controlled laboratory setting.

2. Waste Materials and Additives

This section provides a review of the chemical and physical properties of CBA, the chemical and physical properties of WCO, and the chemical and physical properties of ZT-SP2.

2.1 Coal Bottom Ash (CBA)

One of the by-products of burning coal in power plants is CBA. CBA is one of the wastes produced during the burning of coal in a furnace [4,32]. Hamada et al. [3] found that there is a significant variation in the effect of concrete properties containing CBA. According to Mohammed et al. [33], using CBA waste as a replacement material is one of the most effective ways to reduce the rising costs in the construction sector. The researchers also found that recycling this material is an effective strategy to reduce uncertainties about its disposal. According to Muthusamy et al. [34], Mohammed et al. [33], and Izzati et al. [35], the application of CBA in the asphalt mix during production is rising as asphalt concrete technology continues to advance. The researchers also revealed that the high mixing temperature and resistance to fire

are reduced when CBA is incorporated into the asphalt mixtures. Some of the technical justifications for using CBA include waste use and ecological benefits; affordable material; lightweight aggregates for cement concrete mixtures; improved insulation qualities; enhanced workability in cement concrete mixtures; improved drainage properties; cement replacement in concrete; base and subbase material in pavement construction; mixing ingredient; sustainable supplementary material; resistance to frost in cold weathers; pozzolanic activity; and decrease in consumption of natural resources [3, 36, 37, 38, 39]. Table 1 presents the recent review's conclusions on CBA in asphalt mixtures.

Table 1

An overview of the recent conclusions on CBA in asphalt mixtures

Review findings	Reference
The concrete paving block mixtures containing CBA had the highest compressive strength of 25.05 MPa.	Silva et al. [40]
CBA size particle (150 μm) at a 0.25 liquid-to-binder ratio was used to achieve a compressive strength of 61.0 MPa.	Mousa [36]
When compared to regular concrete, the activated alkali slag and CBA-modified mixture show the greatest improvement in mechanical strength measurements.	Reddy & Harihanandh [41]
The ground CBA-mixed cement's workability, flexural strength, and compressive strength were significantly affected by the absorption time and angular velocity.	Cheah et al. [42]
Concrete can have its conventional and mechanical properties enhanced by adding CBA to appropriate compositions at a replacement ratio of up to 30%.	Al et al. [37]
Concrete's mechanical and operational properties are reduced when CBA is used.	Tamanna et al. [4]

The major oxides in CBA are silicon oxide (SiO_2), followed by Magnesium Oxide (MgO), Iron Oxide (Fe_2O_3), Aluminum Oxide (Al_2O_3), and Calcium Oxide (CaO). According to Ju et al. [41], the primary crystalline configurations in CBA are Mullite ($3\text{SiO}_2 \cdot 2\text{SiO}_2$) and Silicon Inorganic Phosphate ($\text{Si}_3(\text{PO}_4)_4$). Therefore, CBA is hydrophilic due to its high content of Si [44] and SiO_2 [45]. Zhou et al. [46] suggest that the chemical compositions of CBA may be the most attractive feature due to their numerous high-value applications. More than 70% by weight of SiO_2 , Al_2O_3 , and Fe_2O_3 -rich solid products are

described by the category F, whereas less than or equal to 30% by weight of CaO composites are described by the category C [46]. Table 2 presents the chemical properties of CBA.

Table 1

Chemical properties of CBA

Country	Weight of CBA (%)				Reference
	SiO_2	Al_2O_3	Fe_2O_3	LOI	
China	59.9	22.9	7.9	4.0	Dong et al. [47]
India	45.4	18.1	19.9	-	Kirthika et al. [49]
Sri Lanka	44.7	23.8	4.2	15.2	Dassanayake & Nanayakkara [50]
Brazil	57.0	24.0	8.0	5.0	Antunes Boca Santa et al. [51]
USA	58.7	20.1	6.2	0.8	Oruji et al. [52]
Cyprus	55.1	28.1	8.3	3.9	Aydin [53]
Niger	62.3	27.2	3.6	-	Baite et al. [54]
Australia	54.0	25.0	4.0	2.0	Xie & Ozbakkaloglu [55]
Thailand	46.0	22.3	10.6	4.0	Onprom et al. [56]
Hong Kong	52.1	18.3	12.0	4.1	Zhang & Poon [57]

According to Rashidi and Yusup [58], CBA's particle size distribution ranges from 0.075 mm to 20 mm, which is almost similar to fine aggregates. The physical appearance of CBA varies from grey to blackish [46]. The CBA's physical properties are fineness modulus, specific gravity, specific surface area, and water absorption. According to Zhou et al. [46], the fineness modulus provides a source to select anticipated amounts for concrete mix design. The researchers also reported that the fineness modulus of CBA falls between 1.4 and 5.6, a range that corresponds to conventional fine aggregate. According to Gooi et al. [59] and Guan et al. [60], CBA can be milled to increase the fineness modulus and fulfill the usage standard limit. CBA has a lower specific gravity (range from 2.55 g/cm^3 to 2.75 g/cm^3) than regular ordinary coarse aggregates, which helps reduce the mass of the finished CBA-based products [61]. The higher specific surface area of CBA increases the generation of calcium-silicate-hydrate cream or calcium-aluminate-silicate-hydrate in the concrete mixture [46, 59, 62]. The amount of water absorbed under certain circumstances is determined by measuring water absorption, which reveals a material's level of absorbency [63]. The value of the CBA's loss of ignition level affects the water

absorption value, which varies greatly. Table 3 shows the physical properties of CBA.

Table 2

Physical properties of CBA

Country	SG	FM	WA (%)	SSA (m ² kg ⁻¹)	Reference
India	1.9	2.4	8.1	600.0	Kirthika et al. [48]
Malaysia	2.6	2.9	1.0	316.0	Ibrahim et al. [64]
Sri Lanka	2.7	-	-	809.0	Hansika [65]
USA	2.8	-	-	859 - 1102	Oruji et al. [52]
Malaysia	1.9	3.4	11.6	-	Rafieizonooz et al. [66]
South Korea	1.9	5.6	4.1	-	Ahn et al. [67]
Niger	2.2	2.7	20.2	-	Baite et al. [54]
Hong Kong	2.2	3.3	11.2	-	Zhang & Poon [57]
Thailand	2.1	2.1	6.8	-	Onprom et al. [56]

Legend: SG is the specific gravity; FM is the fineness modulus; WA is the water absorption; and SSA is the specific surface area.

2.2 Waste Cooking Oil (WCO)

WCO is a remnant that has been used for many years, containing 40% to 60% cooking oil [68]. WCO is recommended as a bitumen modifier that enhances untreated asphalt and restores its conventional properties, per Yel-Shorbag et al. [69]. There are several practical, financial, and environmental advantages of using WCO, particularly in construction projects. Through reprocessing, it lowers mixing temperatures, increases workability, and benefits the ecosystem [7]. In addition, other advantages of using WCO include the reduction of waste and ecological benefits; improved resistance to aging; production of biodiesel and bio-jet; affordability, production of bio-asphalt mixtures; industrial and lubricants materials; animal feeds; source of renewable energy; soil improvement; decrease in carbon footprint; and protection of water resources [7, 9, 20, 70]. The efficacy of WCO as a modifier in asphalt, biodiesel, or specific industrial uses is influenced by several different qualities [71]. The way it relates to other resources is significantly influenced by its chemical and physical properties [71].

Gas chromatography-mass spectrometry is one of the standard techniques frequently used to identify the chemical composition of WCO. The gasification technique, solvent separation technique, hydro-treatment technique, transesterification reaction technique, and membrane technique are some of the other techniques that have recently been used to evaluate waste oil treatment and recovery [72, 73, 74].

According to Jacobson et al. [75] and Kim et al. [76], oxidation, polymerization, and valorization reactions yield a higher WCO saponification number and viscosity than unused oil. Table 4 shows the chemical compositions of WCO.

Table 3

Chemical compositions of WCO

Type of FFA	Carbon chain	Sharma et al. [77]	Forout et al. [78]	Chhetri et al. [79]
Myristic acid	C14:0	0.99	0.77	0.90
Palmitic Acid	C16:0	28.65	31.88	20.40
Palmitoleic acid	C16:1	0.97	-	4.60
Stearic acid	C18:0	2.55	6.45	4.80
Oleic Acid	C18:1	24.69	41.04	52.90
Linoleic acid	C18:2	40.88	17.98	13.50
Linolenic acid	C18:3	1.27	0.43	0.80
Others	-	-	1.45	1.10

Temperature and cooking time are two factors that affect the physical properties of WCO [80]. Sun et al. [81] discovered that pavement creep decreases with increasing WCO compositions. Yel-Shorbag et al. [69] found that the asphalt blend's fatigue resistance is increased by the repeated addition of WCO. For the operation and compaction of asphalt pavements, the WMA contemporary technologies primarily reduce the viscosity of the binders [82, 83, 84]. The rheological qualities of binders and the physical and durability features of WMA mixes can be affected differently by contemporary technologies [22][85]. Table 5 presents the physical properties of WCO.

Table 4

Physical properties of WCO

Property	Unit	Wt. of WCO	Standard Method
Density at 15°C	g/cm ³	0.9252	-
Viscosity at 40°C	mm ² /sec	47.444	ASTM D445
Viscosity at 100°C	mm ² /sec	10.645	ASTM D445
Viscosity index	-	223.000	-
Flash point	°C	-	ASTM D92
Pour point	°C	-3.000	ASTM D97
Colour	-	-	-
TAN	-	9.130	-
Carbon residue	%	0.390	-
Refractive index at 20°C	-	-	-

2.3 ZycoTherm-SP2l (ZT-SP2)

ZT-SP2 is an innovative warm mix additive that is mainly used to improve performance in asphalt mixes [11]. ZTSP2 is a great option for high-performance asphalt utilization since it enhances resistance to moisture damage. Supplementary advantages are workability and handling, improved bonding (adhesion), improved pavement durability, better performance with RAP, lower mixing and compaction temperature, resistance to deformation and rutting, promoting cost-effectiveness, ecological sustainability, reduced fatigue cracking; compatibility with WMA; compatibility with reused materials; prolonged paving period; and harsh climate durability, and possible challenges [11]. To completely reap these advantages, it's crucial to make sure that the design mix and content are appropriate.

For ZT-SP2 to work in asphalt applications, its chemical composition is essential to comprehend. ZT-SP2's capacity to produce covalent connections with aggregates' inorganic surfaces is one of its primary chemical properties [11]. Characteristically, silicates, oxides, and aluminates—aggregates with hydroxyl categories (-OH) on their surfaces—are found in asphalt mixtures [11]. By forming steady siloxane bonds (Si-O-Si) with these -OH categories, ZT-SP2's silanol categories improve bonding between aggregates and asphalt binders [11]. When it comes to extremely polar aggregates, including those that contain silica, limestone, or supplementary raw materials with a silicate source, ZT-SP2 is very useful [11]. Compared to the physical adherence observed in conventional asphalt mixtures, the chemical link that is formed between the asphalt binder and aggregate is harder [11].

The physical properties of ZT-SP2, namely, its stability, comfort of handling, and capacity to WMA at lower temperatures, are crucial to its performance in WMA [11]. When ZT-SP2 is at room temperature, it is normally a liquid. This is useful because, in comparison to solid chemical stabilizers, liquids are simpler to measure, blend, and distribute evenly in asphalt mixes [11]. The liquid form of ZT-SP2 varies in appearance from clear to somewhat cloudy, contingent upon its particular composition [11]. Its transparency or clarity indicates its cleanliness and the absence of large solid elements that could obstruct blending [11]. Reduced viscosity improves the bonding between the asphalt binder and aggregates by enabling the warm mix additive (ZT-SP2) to flow and cover particles of aggregate more successfully [11]. Because of its low viscosity, ZT-SP2 may be extensively blended with the bitumen binder without demanding a significant energy involvement, which

contributes to one of the key objectives of WMA approaches: lowering production temperatures [11]. The chemical and physical properties of ZT-SP2 are provided in Table 6. The summary of the advanced rheological parameters for asphalt binder assessment is presented in Table 7.

Table 5

Chemical and physical properties of ZT-SP2 [11]

Property	Unit	Findings
Freezing point	$^{\circ}\text{C}$	$< - 8$
Melting point	$^{\circ}\text{C}$	$< - 8$
Boiling point	$^{\circ}\text{C}$	> 200
Colour	-	Pale Yellow to brownish yellow
Odour	-	Mildly fragrant
Flash point	$^{\circ}\text{C}$	> 75 and > 250 (2% by weight of bitumen (closed-cup technique))
Viscosity	CPS	< 500 CPS (at $30 \pm 2^{\circ}\text{C}$)
Density	g/cm^3	$1.00 \pm 0.01 @ 30 \pm 2^{\circ}\text{C}$
Density of relative vapor	g/cm^3	(Air = 1) > 1 (calculated)
Oxidizing characteristics	-	Not oxidizing
Explosive characteristics	-	Not explosive
Solubility in water	-	Water-soluble
Physical state	-	Liquid

Table 7

Summary of the advanced rheological parameters for asphalt binder assessment

Parameter	Test Type	Represents	Ideal Value
$G^* \cdot \sin \delta$	DSR (PAV-aged)	Fatigue resistance	≤ 5000 kPa
Fatigue Life (Nf)	Linear Amplitude Sweep	Repeated load durability	High
Non-recoverable compliance	Multiple Stress Creep Recovery	Rutting susceptibility	Low
% Recovery (R)	Multiple Stress Creep Recovery	Elastic recovery	High
Aging Index	DSR (RTFO/PAV)	Aging susceptibility	Low
ΔT_c	BBR	Low-temp cracking	Close to 0 or positive

3. Research Methodology

The research comprises preliminary research, production, and characterization of modified bitumen. The materials were prepared based on the standard

requirements for pavement works. Fig. 1 shows the research methodology flow chart.

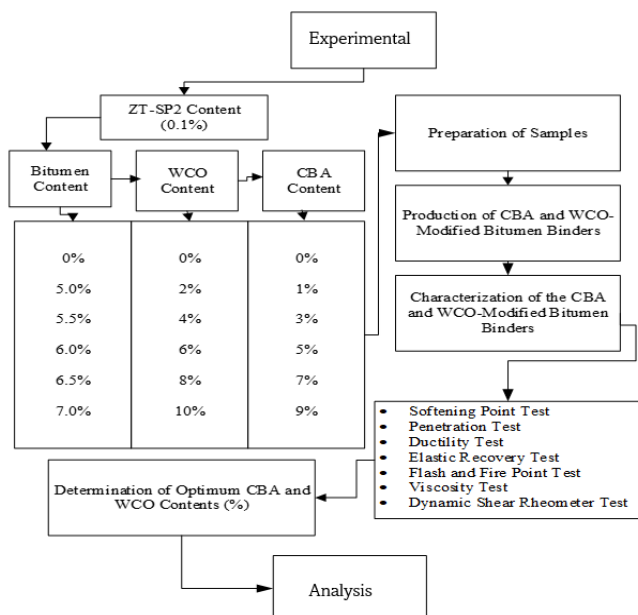


Fig. 1. Methodology flow chart

Materials were selected based on their affordability and accessibility. The materials used in this study were bitumen 60/70, aggregates, CBA, WCO, and ZT-SP2. These materials were prepared according to the JKR [94] standard requirements for pavement works. The mixing procedures and right proportions have been established by prior research and experimental techniques to ensure consistency in asphalt mixtures. The samples were prepared according to the hypothesis, and the results of the laboratory testing helped ascertain the right proportion of mixtures for subsequent tests. According to the intended mix design, the constituent materials, binder, aggregates, and modifiers (CBA, WCO, and ZT-SP2) were proportionately combined to produce a total of 1500 g of the asphalt mixture. To provide a consistent and representative sample for laboratory testing and analysis, each component was weighed and added by its assigned % by mass. A standardized laboratory mixing procedure was used to guarantee uniformity and reproducibility in the asphalt mixture. By applicable regulations and best laboratory practices, the protocol took into consideration important factors such as material conditioning, combining temperature, equipment specifications, and blending duration.

3.1 Materials Preparation

Aggregates were oven-dried at $105 \pm 5^\circ\text{C}$ for 24 hours to eliminate moisture and then preheated to the mixing temperature ($155 - 160^\circ\text{C}$). Bitumen was heated to 145°C to ensure sufficient fluidity. WCO was filtered, preheated to approximately $120 - 130^\circ\text{C}$, and added to the binder to act as a rejuvenator. CBA

was oven-dried and sieved to pass through a $75 \mu\text{m}$ sieve, serving as a filler. ZT-SP2, a silane-based anti-stripping agent, was used as received and integrated into the binder before blending with aggregates.

3.2 Mixing Apparatus

A laboratory-scale mechanical mixer was used for aggregate-binder blending at low speeds. A high-shear mixer was used for mixing WCO and ZT-SP2 into the binder to ensure uniform dispersion. Additional apparatus such as a hotplate with controlled heating, an oven, precision weighing balances ($\pm 0.01 \text{ g}$), and thermocouples for temperature monitoring.

3.3 Mixing Technique

ZT-SP2 was added at 0.1% by weight of binder and blended for an additional 5 minutes under the same temperature and speed conditions to produce a 1500 g WMA specimen. The binder was first blended with WCO and CBA at 145°C using a high-shear mixer operating at 1000 – 1500 rpm for 10 to 15 minutes. Pre-heated aggregates were placed into the blending bowl, and the modified bitumen was poured over the aggregates. The aggregate-binder blend was then mixed using a mechanical mixer for 2 to 4 minutes at a speed of approximately 100 – 150 rpm to ensure uniform coating. The fully blended mixture was immediately poured into a preheated container for compaction for subsequent laboratory testing.

3.4 Controlled Environments

Blending Temperature: Maintained at 145°C for both bitumen and aggregate incorporation. **Blending Duration:** 2 – 4 min for final mixture; 15 – 20 min total for bitumen preparation. **Blending Speeds:** 1000 – 1500 rpm for modifier mixing into binder; 100 – 150 rpm for bitumen-aggregate blending. To guarantee repeatability and a reliable comparative investigation of the mechanical and rheological characteristics of the changed mixes, this procedure was meticulously adhered to for every sample.

A ZT-SP2 was blended with the bitumen 60/70 to produce a ZT-SP2-modified binder sample. This sample and CBA contents (1%, 3%, 5%, 7%, and 9%) were mixed thoroughly at 145°C to produce the CBA-Modified Warm Mix Binder (CBAMWMB) samples. The CBA content that produces the best performance was selected as the optimum CBA content. These samples were then characterized to determine their basic properties. After the characterization of CBAMWMB samples, the production of the WCO-modified samples was made. Similarly, the WCO

contents (2%, 4%, 6%, 8%, and 10%) and ZT-SP2-modified binder were blended carefully at 145 °C to produce the WCO-Modified Warm Mix Binder (WCOMWMB) samples. The WCO content that produces the best performance was selected as the optimum WCO content. The WCOMWMB samples were then characterized to determine their fundamental properties. After the characterization of WCOMWMB samples, the control (virgin) samples were produced. The virgin samples were prepared at 145°C and 160°C to produce the Virgin Warm Mix Binder (VWMB) and Virgin Hot Mix Binder (VHMB) samples, respectively, without adding any modifier (0% modifier). These samples' important properties were determined, and the averages of these samples were used for comparison purposes. Fig. 2 shows the blending procedures of modified samples. The binder tests conducted include softening point, penetration, ductility, elastic recovery, flash and fire point, viscosity, and DSR. All these tests were conducted according to their ASTM standard requirements. Fig. 3 shows the binder tests conducted in this study.

The complex shear modulus (G^*) and phase angle (δ), which jointly characterize the stiffness and viscoelastic behaviour of the material, are measured by the DSR test. To evaluate the binder's resistance to irreversible deformation at elevated temperatures, the rutting resistance parameter, $G^*/\sin \delta$, was computed. AASHTO T 315 / ASTM D7175 requirements were followed in the use of a DSR to assess the high-temperature rheological performance of both conventional and modified binders.



Fig. 2. Blending procedures of modified samples

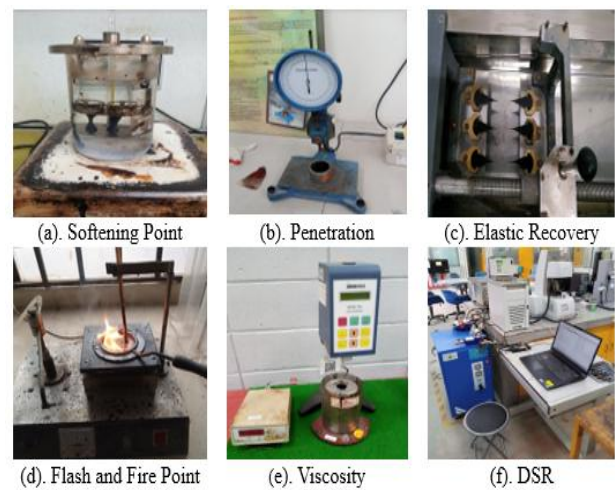


Fig. 3. Binder tests

4. Results and Discussions

This section provides analysis, interpretation, and discussion of all the modified binders' properties results. The results are extensively explained in the form of figures and tables to provide comprehensive clarification of the findings. The CBA, WCO, and ZTSP2-modified binders are investigated for their possibilities to improve the properties of conventional asphalt binders. The results of the various properties of CBA and WCO-modified samples are discussed in the subsections.

4.1 Softening Point

Fig. 4 shows the average results of the softening point for all binders. There are relatively minor differences in all the mixes' resistance to high-temperature softening. A high level of uniformity in the design mix is shown by all the mixes' comparatively small range (0.49 °C). This consistency is necessary to guarantee consistent behaviour across many consignments or construction projects utilizing this bitumen. VHMB binder is the stiffest and best suited for hot conditions or heavy-weight traffic locations where resistance to rutting is essential because it has the maximum softening point value. With the minimum softening point value, the WCOMWMB binder might be a little more flexible, but it might also be less likely to soften when heated. A high degree of consistency is suggested by the slight variations in softening point among the mixes, suggesting that the bitumen binders are dependable and well-articulated throughout a range of circumstances. In conditions where elasticity is essential, such as colder climates where asphalt must withstand expansion and contraction without cracking, the WCOMWMB binder would function better. Fini et al. [85] found that the WCO-modified binder is insignificantly stiff, has a very low softening point, and is more vulnerable to temperature fluctuations.

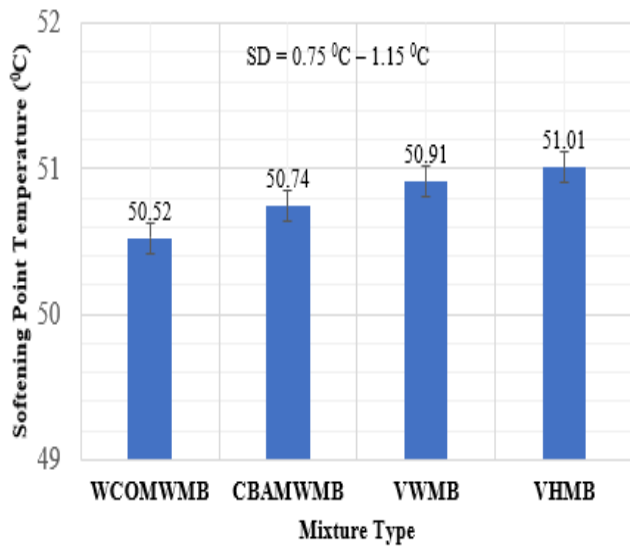


Fig. 4. Average results of the softening point for all binders

4.2 Penetration

Table 8 shows the penetration average results for all binders. Only minor variations exist in the hardness and stability of the asphalt binders throughout the four binders. VHMB binder is the softest (64 mm), offering a little more elasticity, whereas CBAMWMB binder is the toughest (62 mm), implying somewhat greater performance subjected to high temperatures or heavy-weight volumes. The consistency of the penetration findings shows that the bitumen binders in these mixes are consistently effective, guaranteeing dependable performance in a range of traffic flows and climatic situations. This may be attributed to the bitumen binder's high cohesiveness, which developed because of interactions between the binder and the modifiers. Ye et al. [88] state that when the penetration is greater than 30mm, the binder can exhibit superior resistance to fatigue cracking if it is precisely blended and compacted. Significant improvements in bitumen modification were seen by Banerji et al. [89] achieved considerable improvement when a 3% WCO was incorporated into the asphalt binder.

Table 8

Penetration average results for all binders

S/N	Mixture Type	Penetration @25°C (0.1 mm)	ASTM D5-20 Limit (0.1 mm)
1	WCOMWMB	63	60 – 70
2	CBAMWMB	62	60 – 70
3	VWMB	63	60 – 70
4	VHMB	64	60 – 70

4.3 Ductility

Table 9 presents the average findings of the binders' ductility. CBAMWMB binder (119 cm) is very elastic and can resist deformations before deforming or breaking because of its exceptional

ductility compared to VWMB and VHMB binders (118 cm). CBAMWMB binder is perfect for usage in situations requiring great flexibility, for example, cold weather or heavy-traffic capacities. Additionally, reliable performance is suggested by its homogeneity in ductility value. WCOMWMB binder has high ductility, which means that it will function effectively based on the crack resistance and flexibility, although it is somewhat less elastic compared to other binders. It may be slightly stiffer, but in the majority of situations, this change is not expected to have a major effect on the binder's performance. According to the findings of the ductility, all the mixes can be used in usages that call for flexible asphalt binders that don't deform or break easily. All of the mixes have adequate elongation qualities for bitumen applications, as evidenced by the minor increase in flexibility of CBAMWMB, VWMB, and VHMB binders over the WCOMWMB binder. The WCO and CBA were shown to have optimal contents at 4% and 5%, respectively. In line with the results of previous researchers, there were both increasing and decreasing trends in the ductility of the binder of various waste materials for bitumen modification [91, 92, 93].

Table 9

Average results of the ductility for all binders

S/N	Mixture Type	Ductility @25°C (cm)	ASTM D113-17 (cm)
1	WCOMWMB	114	≥100
2	CBAMWMB	119	≥100
3	VWMB	118	≥100
4	VHMB	118	≥100

4.4 Elastic Recovery

The average results of the elastic recovery for all bitumen binders are depicted in Fig. 5. The elastic recovery is moderate for all WCO contents, with values between 30% and 32%. This implies that although the asphalt binders have a restricted capacity to recover from permanent deformations, they will offer some permanent deformation resistance. The WCO contents might function effectively in light-weight situations where high flexibility is not necessary, but they might not function effectively in heavy-weight situations. At 4% WCO content (32%), the modified binder has an optimum WCO content (Fig. 5(a)). Similarly, at 5% CBA content (34%), the modified binder has the maximum elastic recovery value (optimum CBA content); however, it's only a slight difference (Fig. 5(b)). Although it might perform marginally better compared to other CBA contents. The binders' minimal variations suggest that

their permanent deformation recovery capabilities will be comparable. Asphalt binders with greater elastic recovery values would be favoured for such high-behaviour applications to enhance cracking and rutting resistance than conventional binders' elastic recovery (Fig. 6). Moreover, Cao & Wang, [84] discovered a 3% WCO optimum content, which significantly improved fatigue resistance.

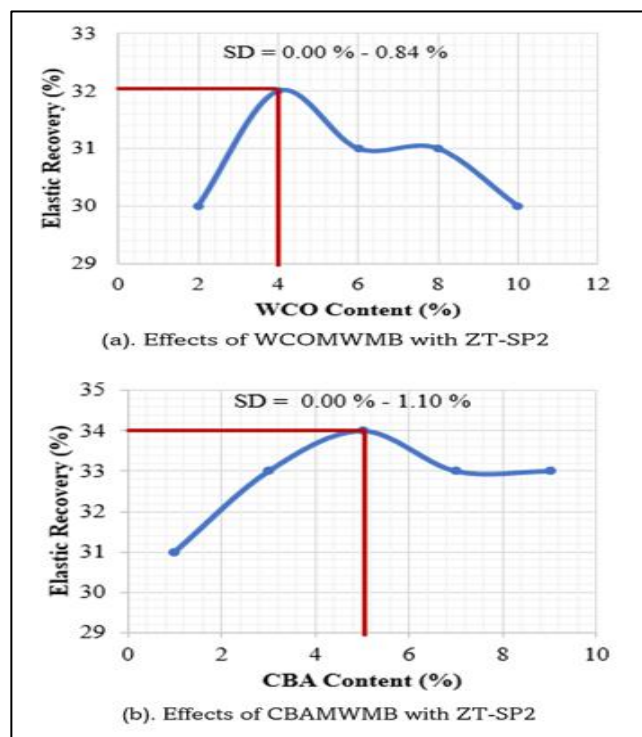


Fig. 5. Average results of the elastic recovery for the modified mixtures

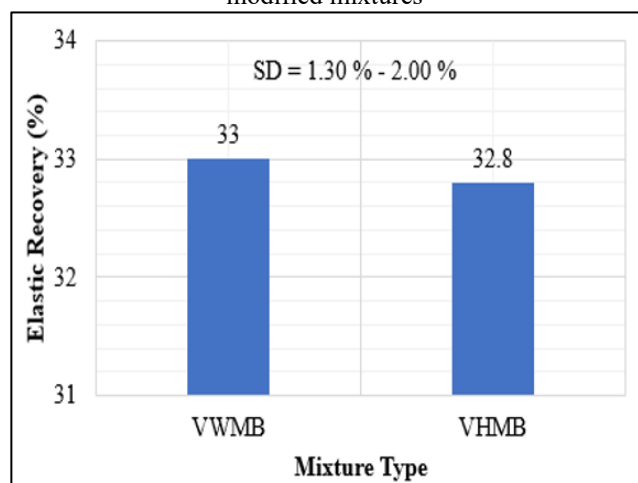


Fig. 6. Average results of the elastic recovery for virgin mixtures

4.5 Flash and Fire Point

Fig. 7(a) shows the average results of the flash point for all binders. The WCOMWMB binder (332 °C) is thought to be extremely safe for treatment and usage in typical asphalt activities, despite having the minimum flash point temperature. The CBAMWMB

binder (335 °C) has the maximum flash point temperature, which suggests a marginally greater resistance to fire. Although there is very little variation between it and the other blends, in terms of the risk of ignition, it is the safest. The VWMB and VHMB binders (334 °C) provide almost the same degree of security and resistance to ignition as the binder with the maximum flash point temperature because they have equal flash point temperatures and are only marginally inferior to the CBAMWMB binder. High flash point temperatures (between 332 °C and 335 °C) for all binders show that they are harmless to handle throughout the normal asphalt paving manufacture, conveyance, and utilization procedures. With just a few differences in volatility, the asphalt binders appear to have fairly comparable safety qualities regarding fire danger, as indicated by the small variation of values. All the findings attest to the asphalt binders' security and adherence to industry security regulations.

Fig. 7(b) shows the average results of the fire point for all binders. The minimum fire point temperatures (357 °C) are found in WCOMWMB and VWMB binders; however, there is an insignificant variation between these binders and the CBAMWMB and VHMB binders. Because of their superior resistance to prolonged burning, both are harmless for use in normal bitumen operations. The CBAMWMB binder (359 °C) exhibits the greatest resistance to maintaining combustion and has the maximum fire point temperature. This could be attributed to the addition of modifiers in the asphalt binder. But in reality, the 2 °C temperature variation is negligible and would not lead to appreciable safety gains. The VHMB binder (358 °C) has a fire point temperature that is only 1 °C less than the CBAMWMB binder, making it almost as harmless in terms of the danger of fire. All the binders have a superior resistance to withstand combustion, according to the above results, which range between 357 °C and 359 °C. This means that binders are safe for operation in normal asphalt manufacturing and paving activities. With regular discrepancies between the flash and fire point temperatures, these findings are in good agreement with the earlier published flash point findings. There are just a few discrepancies in the fire point temperatures of the blends, which suggests that their safety qualities are relatively comparable. Hence,

any bitumen offers enough fire security for management in hot conditions.

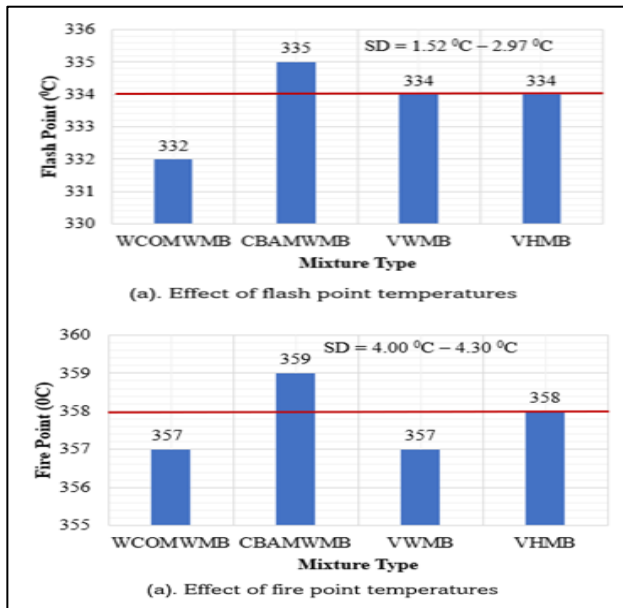


Fig. 7. Average results of the flash and fire point for all the mixtures

4.6 Viscosity

Fig. 8 presents the viscosity average results at 135 °C and 165 °C testing temperatures for the conventional and modified binders. The binders may be less appropriate for larger-temperature or advanced-load locations where resistance to rutting is crucial; however, the binders may be more unsolidified during the mixing and paving processes. At 3% and 5% CBA contents, the modified binders provide better stability between resistance to permanent deformation and paving activities (Fig. 8(a)). The modified binders work better in locations with heavy-weight traffic or extremely hot or cold climates. Its increased viscosity might necessitate more personnel during manufacturing and paving activities to maintain adequate workability. The particular application will determine which type of asphalt binder is the best; increased viscosity asphalt binders provide superior performance in difficult circumstances, while decreased viscosity asphalt binders are better suited for treatment.

At 2% and 4% WCO content (0.62 Pa.s), the modified binders are appropriate for a range of situations due to their reasonable viscosity, which balances workability and permanent deformation resistance (Fig. 8(b)). The particular requirements of the usage will determine which bitumen is the best; reduced viscosity bitumen binders are better suited for constructions where management comfort is crucial, while larger viscosity bitumen binders perform better in heavy-load situations where resistance to permanent deformation is crucial. For moderate-traffic

roads and locations where a compromise between toughness and comfort of construction is required, modified mixes containing 2% and 4% WCO contents (0.32 Pa.s) offer operation and performance stability. According to these findings, bitumen viscosity decreases with rising temperature in all cases; yet, larger viscosity mixtures maintain their better performance qualities under difficult environments, while lower viscosity mixtures provide greater functionality for effortless management and construction. The particular performance necessities and construction situations determine which bitumen is the best.

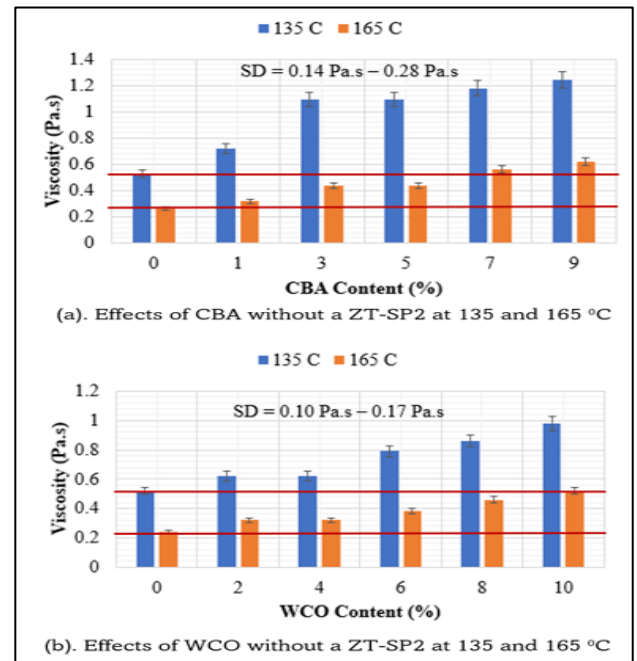


Fig. 8. Average results of the viscosity

4.7 Dynamic Shear Rheometer

The bitumen binders' resistance to rutting was determined by finding a limiting value of $G^*/\sin\delta > 1\text{kPa}$. The rutting resistance to unaged conventional and WCO-modified binders is displayed in Fig. 9(a). As anticipated, the permanent deformation resistance of the bitumen diminishes as the temperature rises. For the WCO content, up to 4% WCO content, WCO increases bitumen resistance to permanent deformation (stiffness); after that, its softening effect intensifies. In terms of optimum WCO performance, since it yields the greatest $G^*/\sin\delta$ data at all tested temperatures, a 4% WCO content is ideal for enhancing the performance at a larger temperature. These findings support earlier research showing that binder modifiers such as WCO can enhance the performance of asphalt binder; nevertheless, the benefits wear off at a certain point. With lessening results at higher contents, the result indicates that 4% WCO provides the greatest stability for improving the asphalt binder's resistance to large-temperature deformations. As anticipated, the bitumen becomes

less stiff as the temperature rises; however, CBA adjustment increases the bitumen's resistance to permanent deformation at all temperatures (see Fig. 9(b)).

For the performance at high temperatures, the stiffness and permanent deformation resistance of the bitumen are greatly enhanced by incorporating up to 5% CBA; at this content, the maximum $G^*/\sin\delta$ values are seen. For the CBA content, the CBA-modified binders continue to perform better at larger temperatures (70 °C and 76 °C), although the advantages somewhat wane as the CBA content rises over 5%. Based on this result, the optimum content for improving the bitumen's progressive-temperature performance is 5% CBA. Studies with various modifiers have shown comparable patterns. In line with the rise in $G^*/\sin\delta$ values observed with the incorporation of CBA up to 5%, Zargar et al. [12] and Kim & Han [94], for example, revealed that integrating modifiers like wastes enhances the bitumen's larger-temperature behaviour by increasing flexibility and stiffness.

The DSR results show that a balanced formulation that includes CBA/ZT-SP2 for structural reinforcement and WCO for workability can produce a binder with both good mechanical and handling properties. However, the interpretation of these rheological phenomena would remain unclear in the absence of a thorough methodology and debate, as was previously the case.

A significant drawback of the data as presented thus far is the lack of a systematic comparison between the several modified binder formulations and the base (unmodified) bitumen. Establishing a baseline for evaluating the efficacy of the modifications requires evaluating the unmodified binder's baseline characteristics, including penetration, softening point, ductility, viscosity, and rheological behaviour (e.g., $G^*/\sin\delta$, phase angle). It is challenging to measure the extent of improvement or degradation brought about by the addition of WCO, CBA, and ZT-SP2 in the absence of these reference values.

The rheological findings also show that WCO enhances binder workability and fatigue resistance by decreasing viscosity, while CBA improves rutting resistance and stiffness due to its mineral proportion. ZT-SP2 also decreases viscosity and enhances elasticity, acting as a compatibilizer. Together, these binder-modifiers produce a well-balanced binder with enhanced workability, aging resistance, stability, and performance across varying temperatures and load circumstances, provided the contents are enhanced.

The observed rheological behaviors of the CBA-WCO-ZT-SP2 modified binders align effectively with previous studies. Literature confirms the specific and combined influences of these modifiers on rutting resistance, fatigue behaviour, viscosity, and aging performance. This validation strengthens the credibility of the laboratory discoveries and supports the possibility of using such eco-friendly binder-modifiers in viable asphalt pavement applications.

Furthermore, although several WCO and CBA combinations were assessed, the results do not show statistically or practically significant differences between them. This implies that the interaction between WCO and CBA is negligible under the investigated conditions, or that the dosages may have fallen inside a performance plateau. To uncover more subtle effects and maximize the utility of these modifiers, future research should aim for a more thorough comparison with the base binder and a wider range of dosages or different test methodologies (e.g., fatigue testing, rutting simulation).

The mean of three replicates $\pm$ standard deviation is represented by all stated values. To ascertain the statistical differences between the modified blends and the conventional binder, a one-way ANOVA was performed at a 95% confidence level ($\alpha = 0.05$). The viscosity and softening point of binders modified with WCO (4%) and CBA (5%) showed statistically significant changes ($p < 0.05$).

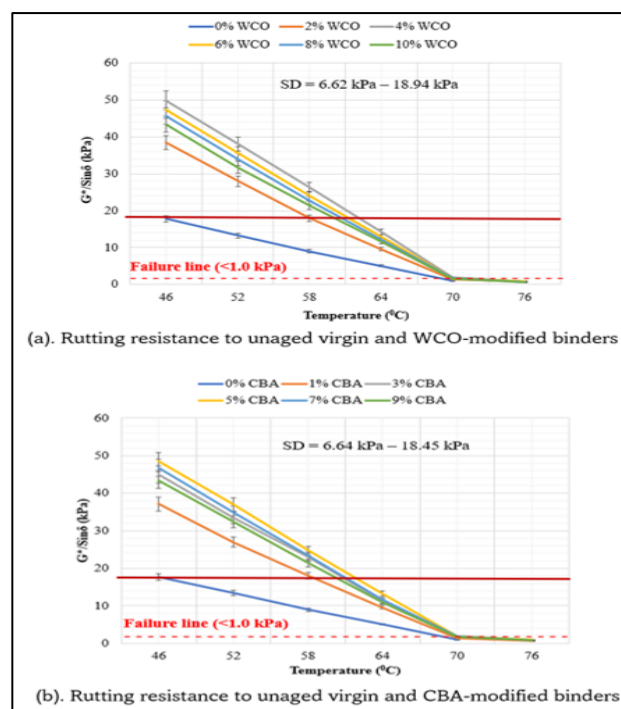


Fig. 9. Results of the DSR

5. Conclusion

The optimum contents of CBA, WCO, and ZT-SP2 improved the properties of the modified binders. The addition of these contents effectively reduces the

mixing and compaction temperatures, especially during the viscosity test. With a viscosity of 0.62 Pa·s, the modified binder is within the Superpave-recommended range, suggesting adequate workability for compaction and mixing. This implies simpler handling but possibly less resistance to rutting than the conventional binder's higher viscosity. Therefore, while the modification makes it easier to produce, it also necessitates balancing high-temperature performance.

The modified binder's resistance to rutting parameters is also notable. The optimum mixture of the binder modifiers enhanced the binders' functional performance and showed promise for environmentally friendly and reasonably priced asphalt paving solutions. Due to their improved resistance to rutting, the modified binders are well suited for application in locations with large traffic capacities and challenging environmental situations since they can retain their structural behaviour and shape even throughout extended periods of high traffic loads and high temperatures. The changes have also demonstrated the ability to increase resilience to moisture-induced deterioration, which might prolong pavement life and lessen the need for stripping. By incorporating by-products into pavement construction processes, WCO and CBA demonstrate a dedication to sustainability. Utilizing WCO improves the bitumen's ductility and elasticity while also addressing waste disposal issues and adding a renewable component. Similar to this, adding CBA, a by-product of burning coal, increases the strength and longevity of the asphalt while lowering landfill waste.

Although 0.1% ZT-SP2 is used in the study, it is unclear what the reference base is based on: the bitumen mass, binder, or the entire mix. The dosage should be indicated as 0.1% by weight of bitumen, as is customary procedure, for the sake of clarity and reproducibility. Furthermore, since no range of ZT-SP2 doses was examined or contrasted, the assertion of "optimization" is unsupported. Therefore, the word "optimized" should be avoided or explicitly described as preliminary unless such parametric research is supplied.

Future work should incorporate long-term durability testing to support real-world use. This entails assessing mechanical performance during repeated load cycles, aging resistance, and moisture-induced damage. These evaluations are essential for confirming the lifespan performance and field

usability of binders modified with WCO, CBA, and ZT-SP2.

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