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Effect of Agro Waste and Industrial-based Geopolymer on the Physical and Rheological Properties of Asphalt Binders

[1*]ThankGod Chukwuebuka Alexander, [2]Samuel Waweru, [3]Timothy Nyomboi

[1]Civil Engineering Department, Pan-African University, Institute for Basic Sciences, Technology and Innovation (PAUSTI), Juja, Kenya

ORCID iD: https://orcid.org/0000-0002-7465-6526

[2]Masinde Muliro University of Science and Technology, Kakamega, Kenya

[3]Civil Engineering Department, Pan-African University, Institute for Basic Sciences, Technology and Innovation (PAUSTI), Juja, Kenya

***Correspondence:** thankgod.alexander.193124@unn.edu.ng

Abstract

Geopolymers are emerging as promising sustainable additives in asphalt technology due to their excellent durability, mechanical strength, and resistance to high temperatures, and chemical degradation. This study investigates the effects of utilizing dual precursors and dual alkali solution on the physical and rheological properties of asphalt binder. The dual precursors, which included rice husk ash (RHA) and quarry dust (QD), were mixed with the dual alkali solution namely sodium hydroxide (NaOH) and sodium silicate, to produce the geopolymer used in modifying the asphalt binder. A series of laboratory tests were conducted to investigate the properties of 80/100 asphalt binder modified with varying proportions (3%, 5%, 7%, and 9%) of the RHA and QD based geopolymer. The physical properties including ductility, softening point, penetration, viscosity, and elastic recovery were systematically evaluated. Furthermore, rheological tests were performed to assess the rutting resistance of the geopolymer-modified binders. The results demonstrated that the incorporation of RHA and QD based geopolymer significantly enhanced both the physical and rheological performance of the asphalt binder compared to the unmodified binder. In conclusion, the use of RHA and QD based geopolymer as a binder modifier shows promising potential for improving asphalt binder properties and enhancing its suitability for pavement applications.

Keywords: Asphalt binder; geopolymer; binder modification; storage stability; rheology; flexible pavement

1. Introduction

Bituminous pavements, commonly used in road and construction industries, often encounter significant challenges due to increasing traffic volumes and extreme weather conditions. These pavements are susceptible to various forms of distress, such as rutting, moisture damage, fatigue cracking and thermal cracking [1, 2, 3]. The continuous occurrence of these issues, often exacerbated by inadequate design and maintenance, leads to the progressive degradation of the pavement, which in turn increases life-cycle costs and poses safety risks to road users [4]. Given the crucial role bituminous pavements play in a nation's economic development, governments worldwide allocate significant resources to improve road infrastructure. In countries with severe weather and heavy traffic, substantial investments are made annually to maintain deteriorating pavements. Although asphalt binder is the most commonly used pavement material, it faces significant financial and environmental concerns. For instance, the production of asphalt binder is energy-intensive and contributes to CO_2 emissions. In the context of global efforts to reduce greenhouse gas (GHG) emissions by 50 to 80% by 2050, substantial action is required to limit global temperature rise to below 2°C. Ma et al. [5] underscores the importance of reducing GHG emissions during the production of raw materials and the asphalt concrete mixing process. As a result, minimizing the use of asphalt binder and cutting down energy consumption during hot mix asphalt production could yield both economic and environmental advantages.

Notably, the performance of bituminous binders plays a crucial role in determining the overall quality of asphalt pavements [6]. As economic activities continue to expand, traffic volumes have surged, resulting in an increase in daily axle loads. Conventional petroleum asphalt binders are no longer sufficient to meet the evolving demands of modern pavements. This has led to widespread use of modified asphalt binders with improved properties for pavement construction. Despite their advantages, these binders present certain challenges. One significant drawback is their high cost [7, 8]. The prices of binders modified with materials such as SBS [9, 10] and nanomaterials [11, 12] are relatively expensive. Although waste rubber powder offers a more cost-effective alternative for binder modification [13], it suffers from limitations like poor storage stability [14, 15], requiring immediate use after preparation. Composite-modified asphalt binders have also been extensively researched [16, 17], offering significant performance improvements but at the cost of higher expenses and complex production processes. Therefore, there is a pressing need for a modified asphalt binder that not only delivers excellent performance but is also cost-effective and environmentally sustainable.

To address this need, recent advancements have shifted focus toward improving the rheological properties of asphalt through the incorporation of by-products and waste materials. The widespread availability of materials such as blast furnace slag, quarry dust, rice husk ash, fly ash, and red mud has sparked interest in their potential applications. Notably, geopolymers have emerged as particularly promising materials in this context, effectively reducing waste and utilizing by-products. When used as asphalt modifiers, geopolymers have been shown to enhance the rheological behaviour of asphalt binders, improving rutting resistance and mitigating pavement deterioration. Moreover, geopolymers contribute to reducing CO_2 emissions by decreasing the demand for asphalt binder production, making them a highly attractive option both economically and environmentally for asphalt pavement construction.

1.1 Geopolymers and their application in modifying asphalt binders

In recent years, geopolymers have emerged as a significant advancement in road construction particularly in the reduction of the optimum binder content, enhancing the stability and bond between asphalt binder and aggregates, and improving the density of asphalt mixture through a process known as geopolymerization. Geopolymers, characterized as amorphous three-dimensional inorganic aluminosilicate materials, share similarities with organic polymers derived from oil. However, geopolymers distinguish themselves by being non-flammable, inorganic, and highly stable at room temperature. Importantly, their ability to undergo rapid polycondensation at room temperature has garnered global attention and promoted their application in flexible pavement construction. A noteworthy advantage of geopolymers is their rapid setting at room temperature, eliminating the need for external heat sources during the geopolymerization process. This feature contributes to a reduction in carbon emissions, a common concern associated with the manufacture of asphalt binder. The innovative use of waste materials in road construction has been effectively addressed through the adoption of geopolymer-modified binders, introducing a novel approach. The concept of geopolymer, credited to Davidovits, was initially presented in 1978 [18].

Geopolymerization is a chemical process involving the reaction of an alkali solution with a silica (SiO_2) and alumina (Al_2O_3) rich material to produce an amorphous to semi-crystalline aluminosilicate polymer. The material rich in silica and alumina, referred to as a precursor, plays a crucial role in this process [18]. The geopolymerization process consists of three key steps: the dissolution of Si and Al from the precursor into the alkali solution, the coagulation (agglomeration) of the dissolved ingredients, and the polycondensation of these ingredients. These steps culminate in the formation of an aluminosilicate structure with a 3D network.

Geopolymers utilize aluminosilicates from solid waste sources such as slag, fly ash, metakaolin, waste marble dust, blast furnace slag, making them cost-effective and environmentally friendly solutions for waste disposal. Interestingly, these solid wastes have been employed in diverse studies by researchers to geopolymerize asphalt binders, effectively improving their mechanical properties, durability, high-temperature resistance, freeze-thaw cycle resistance, and resistance to chemical corrosion [19, 20, 21]. These precursors, often cost-effective, have demonstrated promising results when utilized with the appropriate alkali solution molarity [22, 23].

Geopolymers exhibits superior mechanical properties, robust durability, high-temperature resistance, freeze-thaw cycle resistance, and resistance to chemical corrosion [19, 20, 21], making them widely employed in cement concrete. Interestingly, while there has been increasing use of geopolymers in asphalt pavements [22, 23, 24], their effectiveness as an asphalt modifier remains inadequately explored as there has been little research on this topic.

One of the recent studies on the rheological properties of geopolymer-modified asphalt binder, specifically using fly ash as geopolymers was conducted by Bujang et al. [25]. The study assessed the impact of fly ash geopolymer additive on the rheological properties of unaged and short-term aged asphalt binders. Utilizing asphalt binder 80/100 and 60/70 penetration grade, mixtures with 0%, 3%, 5%, 7%, 9%, and 11% fly ash geopolymer by weight of asphalt binder were prepared. The results of the study revealed that the addition of fly ash geopolymer (FAG) significantly increased stiffness (G*) and decreased the phase angle (δ) in both unaged and short-term aged modified asphalt binders compared to the control asphalt binder. In a similar study, Hamid et al. [26] studied the rheological properties of geopolymer-modified asphalt binder, using fly ash as the precursor. The study revealed significant effects on the rheological properties of the asphalt binder, including improved temperature susceptibility, shear modulus, and rutting factor when incorporating 3%, 6%, and 9% geopolymer binder. In another study, Hamid et al. [27] explored the effects of geopolymer curing on asphalt binder rheological properties, revealing that curing time impacts complex shear modulus, temperature, and viscosity. Mixtures with higher geopolymer content exhibited increased resistance to permanent deformation.

Sidek et al. [28], in a related study utilized granite aggregate and asphalt binder grade 60/70, incorporating fly ash geopolymer at concentrations of 3%, 5%, 7%, 9%, and 11% of the total binder. The results of the study indicated a notable enhancement in the resilient modulus of the asphalt mixture with fly ash geopolymer additives, showing approximately a 30% improvement compared to the controlled sample. In a similar study, Ibrahim et al. [29] studied the viability of geopolymer modification on asphalt physical properties and storage stability, noting decreased penetration and ductility values and improved softening point and viscosity. The geopolymer-modified asphalt concrete demonstrated higher resistance to rutting due to elevated softening points compared to base asphalt.

The provided literature above shows the persistent efforts of researchers to address the challenges associated with using base asphalt binders. As discussed in the above literature, the use of geopolymer-modified asphalt binders has shown promising results in enhancing the rheological properties, including complex shear modulus, viscosity, and high-temperature performance. The reviewed literature indicates that only a limited number of researchers have explored the feasibility of using dual precursors and dual alkaline solutions to improve the properties of base asphalt binders. The rationale behind using dual precursors and dual alkali solutions for the geopolymerization of asphalt binders is to achieve improved properties while reducing the financial costs associated with flexible pavement construction.

2. Objectives

Interestingly, this study focuses on the improvement of the properties of asphalt binder through geopolymerization, employing dual precursors, namely an agro-waste (rice husk ash (RHA)) and an industrial by-product (quarry dust (QD)) to improve the properties of asphalt binder. These precursors were combined with dual alkali solution namely, sodium silicate and NaOH. It is noteworthy that previous research on geopolymer-modified asphalt binder has often focused on the use of industrial by-product, neglecting the agricultural by-product such as rice husk. The study evaluates the effects of the dual precursor-alkali solution mixture on the physical performance, elastic recovery performance, viscosity and storage stability of the base asphalt binder. Additionally, the rheological properties was also conducted to investigate the rutting resistance of the geopolymer modified asphalt binder. Quarry dust (QD), a waste obtained from the quarry industry is known to have fine particles and high density. The fine particles of QD are able to fill voids of materials thus impacting a high density to the material [30]. In addition, rice husk ash (RHA) is a potential pozzolanic material which is rich in silica and alumina, which are important constituents in the geopolymerization process [31]. The above serves as the reasoning for selecting these two sustainable waste materials for the geopolymerization of asphalt binder.

3. Materials and Methods

3.1 Materials

3.1.1 Asphalt binder

The asphalt binder is also known as bitumen. In this study, the conventional 80/100 penetration grade asphalt binder was used to produce the modified asphalt binder. This particular binder was selected owing to its widespread application in high-temperature regions, where it must resist heat-induced softening and deformation. The binder was sourced from PG Holdings Limited, a bitumen company located at Eastern Bypass in Nairobi, Kenya. The properties of the asphalt binder were evaluated through various tests, including ductility, penetration, softening point, dynamic viscosity, specific gravity and elastic recovery using the American Society for Testing and Materials (ASTM) specifications. The physical characteristics of the binder are presented in Table 1.

Table 1: Physical properties of 80/100 asphalt binder

Test	Test Standard	Result	Specification (As per ASTM)
Penetration @ 25°C	ASTM D5	86	80 - 100
Softening Point (°C)	ASTM D 2398	45	40
Ductility @ 25°C (cm)	ASTM D113	116	>100
Dynamic viscosity (cP @ 135°C)	ASTM D7042	335.5	100 - 3000cP
Specific gravity (g/cm3)	ASTM D70	1.01	1.01-1.06
Elastic recovery	ASTM D6084	13	60% - 70%

3.1.2 Quarry dust

The quarry dust used in this study was sourced from Mlolongo, Machakos County, Kenya. Quarry dust (QD) is a by-product of the quarry industry and is widely regarded as a significant environmental issue in areas where it is found in large quantities. As a result of the evident environmental challenges posed by QD, researchers across various disciplines, particularly in the pavement and construction industry, have consistently developed methods to repurpose QD in order to mitigate or eliminate its harmful effects on the environment [32, 33, 34]. Table 2 shows the physical and chemical constituent of the quarry dust used in this study. The chemical constituent reveals that the quarry dust contains a high silica content (66.269%) and a moderate amount of alumina (12.637%), along with other compounds. Figure 1 presents a depiction of the quarry dust.

Table 2: Physical and chemical constituent of QD

Test	Result
Colour	Dark grey
Physical state	Powder
Size (mm)	0.075mm
Specific gravity (g/cm3)	2.07
Si2O2 (%)	66.269
Al2O3 (%)	12.637
CaO (%)	2.697
Cl (%)	1.104
K2O (%)	8.168
Ti (%)	1.493
Fe (%)	6.173
Others	1.459

Figure 1: Quarry dust

3.1.3 Rice husk ash

The rice husk used to produce the rice husk ash (RHA) was sourced from Juja market, Kiambu County, Kenya. RHA is produced from rice husk, a by-product often considered waste in rice milling industries [35]. Therefore, similar to quarry dust, it is essential to repurpose RHA into meaningful applications. RHA can be produced through two main methods: uncontrolled and controlled methods [36, 37]. Table 3 shows the physical and chemical constituent of the RHA, with the detailed production process discussed in the next section. A quick view of Table 3 reveals that the RHA contains a high silica content (93.194%) among other components. According to ASTM C618-012, the RHA can be classified as a class N pozzolan. Figure 2 presents a depiction of the rice husk ash.

Table 3: Physical and chemical constituent of RHA

Test	Result
Colour	Whitish grey
Physical state	Powder
Size (mm)	0.075mm
Specific gravity (g/cm3)	2.13
Si_2O_2 (%)	93.194
Al_2O_3 (%)	1.268
CaO (%)	1.427
P_2O_5(%)	1.061
K_2O (%)	1.128
Cl (%)	0.839
Fe (%)	0.698
Tn (%)	0.171
Mn (%)	0.147
Others	0.067
Loss on ignition	1.94

Figure 2: Rice husk ash

3.1.4 Alkaline activator

Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were utilized as the alkaline activator (AA) in this study, and it was purchased from Euro Industrial Chemicals Limited located in Industrial area, Nairobi, Kenya. NaOH was dissolved in distilled water to produce 8 Molar (8M) NaOH solution. NaOH and Na_2SiO_3 were selected as the activator from among several well-established alternatives due to its high reactivity and its capacity to improve the properties of the base asphalt binder when used together [38, 39, 40, 41]. Table 4 and 5 shows the physical and chemical constituent of NaOH and sodium silicate used in this study.

Table 4: Physical and chemical constituent of NaOH

Symbol	Test Parameter	Unit	Value	Standard	Specification
Colour	White				
NaOH	Assay [as NaOH]	% w/w	99.10	IS-252:2013	Min. 99.00
Na_2CO_3	Sodium Carbonate [as Na_2CO_3]	% w/w	0.50	IS-252:2013	Max. 0.60
NaCl	Chloride [as NaCl]	% w/w	0.0132	IS-252:2013	Max. 0.02
Na_2SO_4	Sulphate [as SO_4]	% w/w	0.0025	IS-252:2013	Max. 0.01
Fe	Iron [as Fe]	ppm	9.20	IS-252:2013	Max. 10.00
Ni	Nickel [as Ni]	ppm	1.50	IS-252:2013	Max. 3.00
$NaClO_3$	Chlorate & Perchlorate [as $NaClO_3$]	ppm	<1.00	IS-252:2013	Max. 1.00
	Matter insoluble in water	% w/w	<0.05	IS-252:2013	Max. 0.05

Table 5: Physical and chemical constituent of Na_2SiO_3

Symbol	Value
Specific gravity @ 20°C	1.530
% Na_2O	13.76
% SiO_2	28.90
Total Solids	42.66
Na_2O:SiO_2 Ratio	1:2.10

3.2 Methods

3.2.1 Rice husk ash production

The production of rice husk ash (RHA) involves two primary techniques outlined in literature namely, the controlled and the uncontrolled techniques. In this study, the controlled technique was employed. The uncontrolled technique, which involves open-field combustion of rice husk, is widely known by researchers to increase the carbon content in RHA, thereby reducing its pozzolanic potential. Conversely, the controlled technique is designed to increase the amorphous silica percentage in RHA. In this study, RHA was produced in a carefully monitored furnace with a heating temperature of 650oC. This temperature which was maintained for 2 hours, was chosen based on recommendations from previous studies indicating that temperature between 500 and 700oC enhance the amorphous silica content, thereby improving pozzolanic activity [36, 37, 42]. After the combustion of the rice husk, the resulting ash, known as RHA, was collected and left to cool for 24 hours in a container. Once cooled, the RHA was ground and passed through a BS 200 test sieve before being used in the experimental program of this study.

3.2.2 Geopolymer preparation

As previously mentioned, geopolymers are synthesized using aluminosilicate materials that contain high amounts of Al2O3 and SiO2 activated by a strong alkaline solution. It is important to note that the combination of NaOH and Na_2SiO_3 produces geopolymer with excellent mechanical properties [43]. First, the alkaline solution was prepared by mixing sodium hydroxide (8M) and sodium silicate solution in a ratio of 100:50% by mass respectively. Thereafter, the alkaline solution was combined with the two precursors (RHA and QD) at a liquid-to-solid ratio of 0.3 and stirred for 6 minutes. The resulting slurry was poured into 20 mm plastic cube molds. The samples were cured at room temperature (25°C) for 24 hours, followed by additional curing in an oven at 60°C for another 24 hours. Finally, all samples were ground into a powder and particles larger than 0.15mm in diameter were removed by sieving. The microstructure of the geopolymer was examined using the desktop scanning electron microscope. Figure 3 illustrates the micromorphology of the geopolymer at 750x magnification, revealing a structure with compact gel formations.

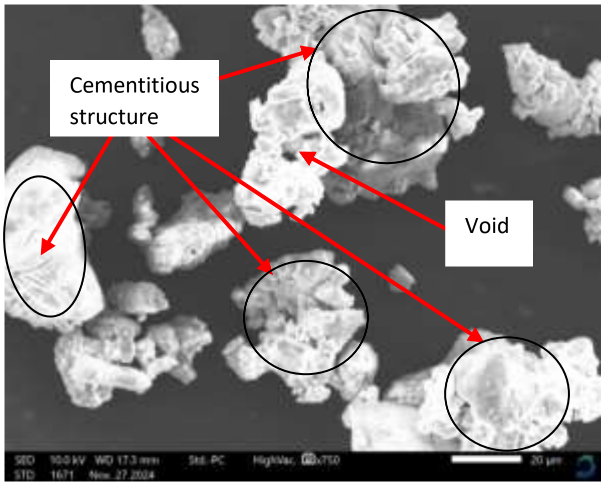


Figure 3: Scanning electron micrograph at 750x magnification

3.2.3 Preparation of geopolymer-modified asphalt binder

The geopolymer-modified asphalt binders were prepared through the wet-mixing technique. The geopolymer-modified asphalt binder was prepared using a base asphalt binder of 80/100 penetration grade, with the entire preparation process conducted at a constant temperature of 160 °C. The synthesized geopolymer was gradually introduced into the flowing base asphalt and manually stirred using a glass rod. This mixture was then subjected to high-shear mixing at 4000 rpm for 1 hour. The shear mixer used in the process had an adjustable rotational speed ranging from 200 to 11000 rpm. Upon completion of the shearing process, the blend was allowed to remain static at 160 °C to stabilize. Air bubbles were subsequently removed to yield the final geopolymer-modified asphalt binder. The geopolymer was incorporated into the base asphalt binder at concentrations of 3%, 5%, 7%, and 9% by weight. Figure 4 presents the materials and equipment utilized in the modification process.

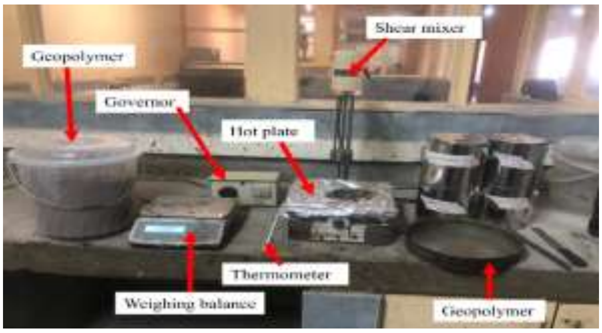


Figure 4: Material and equipment setup

3.3 Evaluation of geopolymer-modified asphalt binder

3.3.1 Physical characterisation

The main physical properties of the asphalt binder were evaluated through standard tests, including penetration [44], dynamic viscosity [45], softening point [46], ductility [47], and elastic recovery [48]. The results of these tests were compared to the specifications outlined in the Kenyan RDMIII.

3.3.2 Rheological properties evaluation

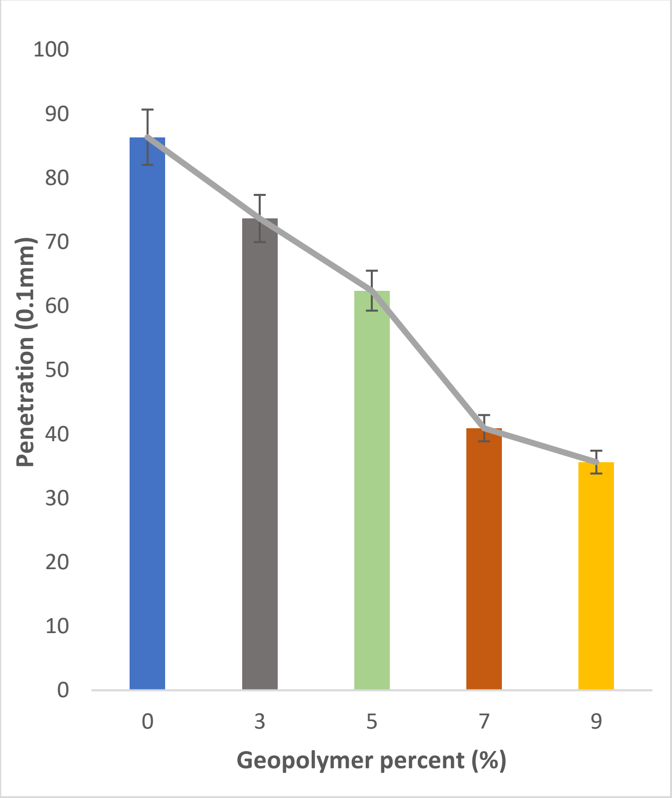
To assess the rutting resistance of unmodified and modified asphalt binders, a Dynamic Shear Rheometer (DSR) test was employed, following the procedure outlined in [49]. This test evaluates the shear stress response and the linear viscoelastic characteristics of asphalt under oscillatory shear conditions using parallel plates. The rutting resistance test utilized a 25 mm parallel plate geometry with a 1 mm gap. Prior to testing, the samples underwent short-term aging through the Rolling Thin Film Oven (RTFO) method [50] to replicate the effects of mixing and transportation during pavement construction. The primary objective of the test was to determine the rutting resistance parameter, expressed as G*/sinδ. This parameter is derived from the complex shear modulus (G*), which represents binder stiffness, and the phase angle (δ), which indicates the elastic response of the material. All measurements were conducted at a constant frequency of 10 rad/s across multiple temperatures: 64°C, 70°C, 76°C, 82°C, and 88°C.

3.3.3 Storage stability of the geopolymer-modified asphalt binder

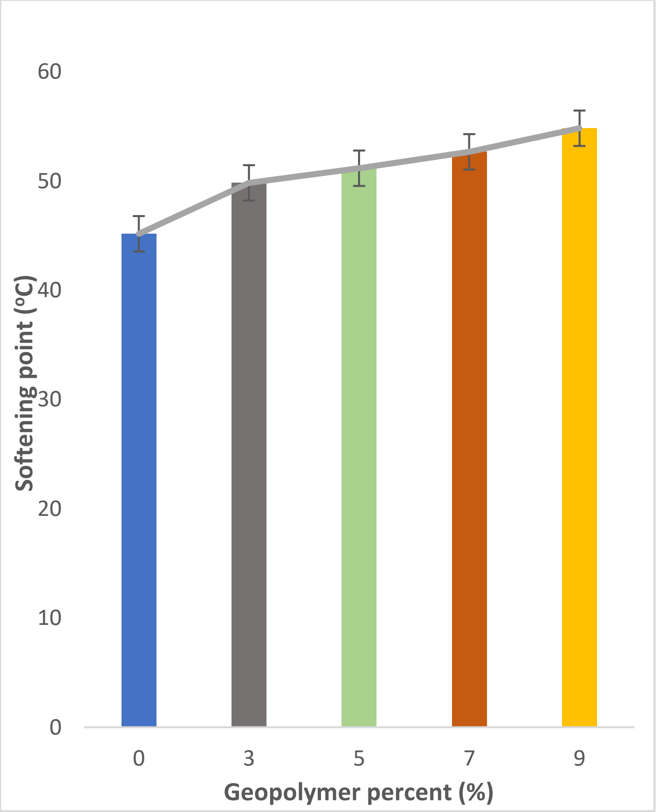
The storage stability test, as outlined in [51], was conducted to assess the tendency of the asphalt binders to undergo phase separation during prolonged exposure to elevated temperatures. In this procedure, the modified binders were first heated and poured into aluminum tubes, which were subsequently placed in an oven maintained at 163℃ for 48 hours. Following thermal conditioning, the tubes were cooled in a freezer at 10℃ for 4 hours. After cooling, each tube was segmented into top, middle and bottom sections. The softening points of the top and bottom segments were measured, and the difference between these values (SPdiff) was used as an indicator of storage stability.

4. Results

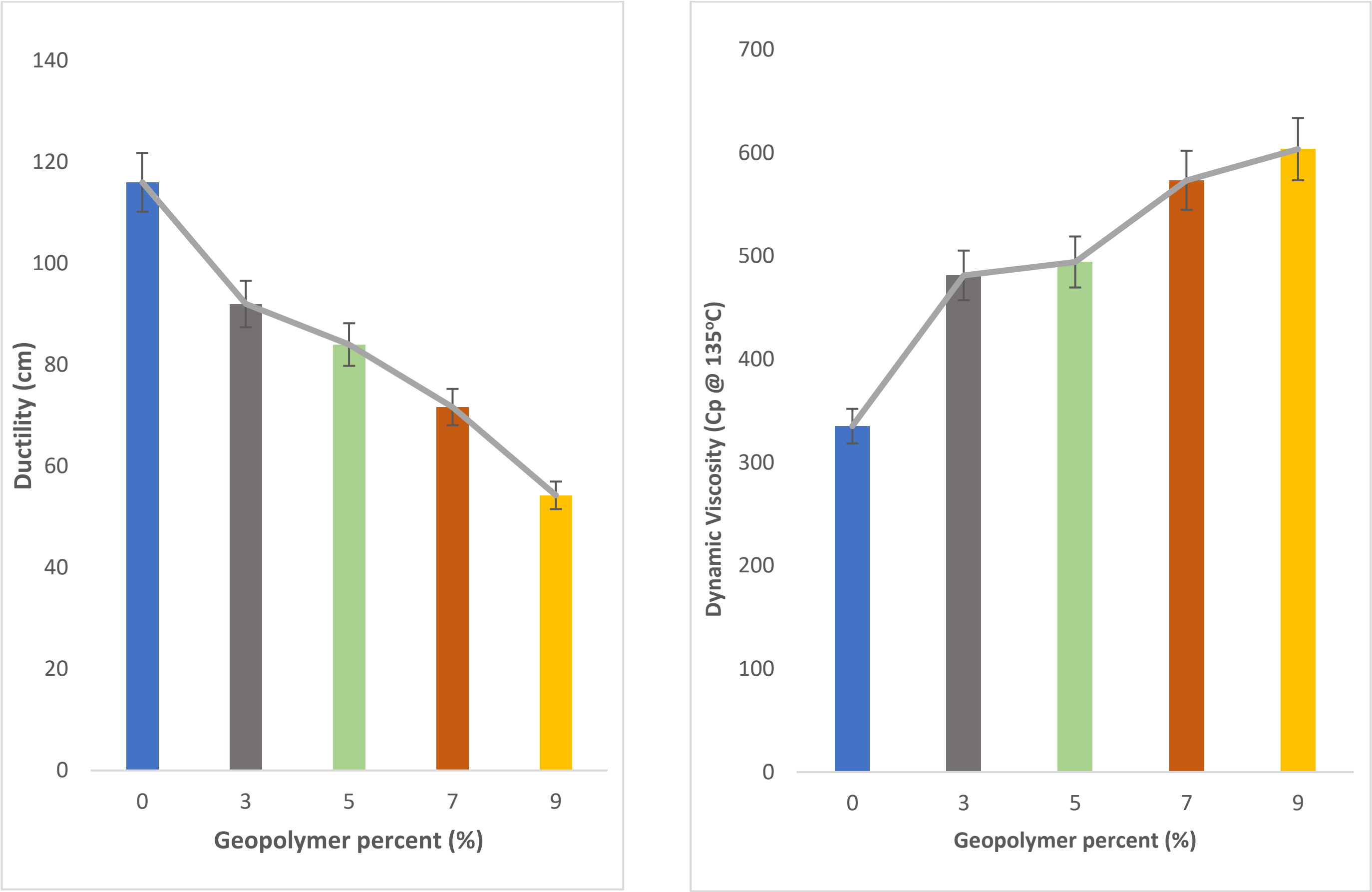
4.1 Physical Properties of Asphalt Binders



(a)

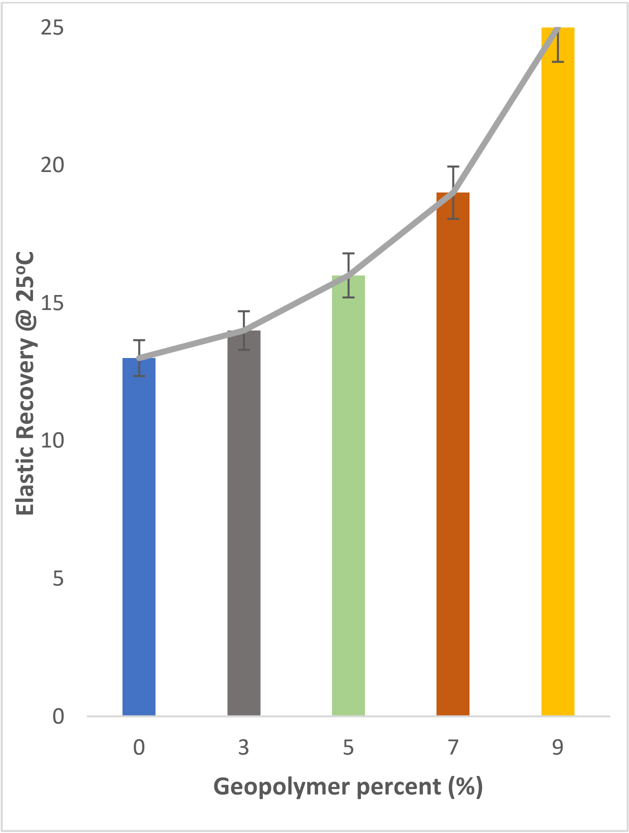


(b)



(c)

(e)



(d)

Figure 5. Physical properties of asphalt binder: a: penetration, b: softening point, c: ductility, d: elastic recovery, e: viscosity at 135 °C

4.2 Storage Stability of Asphalt Binders

Table 6: Storage Stability of Modified Bitumen

Modifier %	**Dynamic Viscosity (Cp @ 135oC)**		
	Softening point at top	Softening point at bottom	SP difference
0	45.5	46	0.5
3	48.5	49	0.5
5	50.5	51	0.5
7	49.5	50.5	1.0
9	47	48.5	1.5

4.3 Rheological Properties of Asphalt Binders

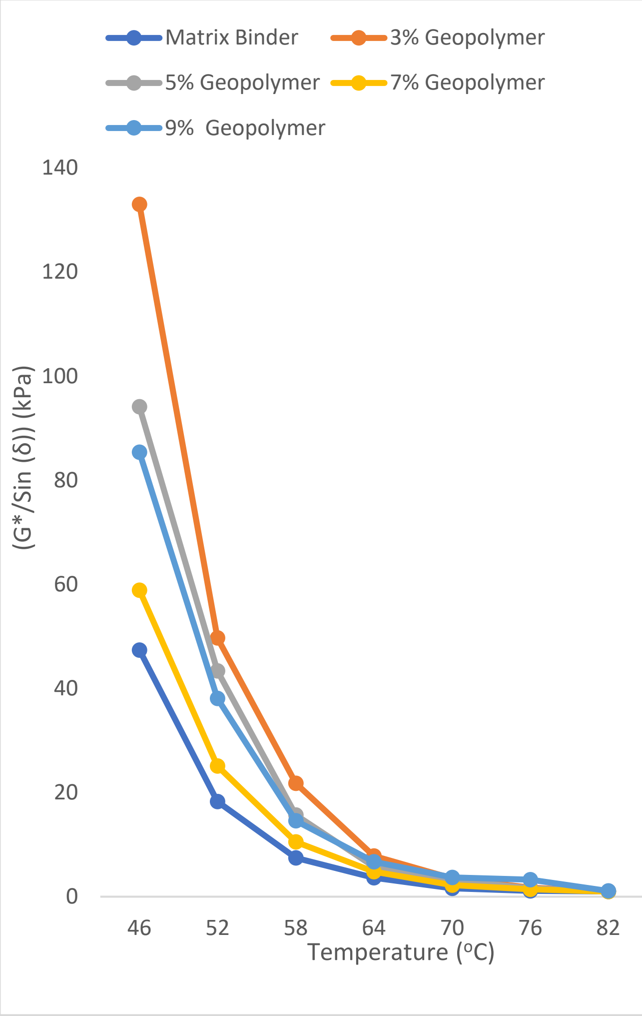


Figure 6. Rheological properties of geopolymer-modified asphalt binder

5. Discussion

5.1 Effect of geopolymer on physical properties of asphalt binders

Figure 5 illustrates the performance characteristics of the geopolymer-modified asphalt binder in terms of penetration, softening point, ductility, elastic recovery, and viscosity.

From Figure 5(a), it is evident that the penetration value of the asphalt binder progressively declines with increasing geopolymer content, indicating enhanced binder hardness. Specifically, at geopolymer dosages of 3% and 5%, the penetration value decreased by 1.3 mm and 2.4 mm respectively, relative to the control binder. Further increases to 7% and 9% resulted in noticeable increase, suggesting the effect of higher geopolymer content on binder hardness. This trend implies that the incorporation of geopolymers improves the deformation resistance of the binder. The enhanced stiffness is attributed to the inherently strong three-dimensional network structure of geopolymers, which contributes significantly to the structural integrity and hardness of the modified binder.

As illustrated in Figure 5(b), the softening point of the asphalt binder increased with the addition of the geopolymer. This improvement is advantageous in mitigating pavement rutting at elevated temperatures. The enhancement in thermal resistance and consistency is linked to the cementitious and thermally stable characteristics of geopolymers, which form a microgel network within the binder.

According to Figure 5(c), ductility exhibited a downward trend as the geopolymer dosage increased. This reduction reflects a rise in the stiffness and brittleness of the asphalt binder. The observed brittleness is likely due to the strong interfacial bonding between the geopolymer particles and the asphalt matrix, which may promote brittle fracture under stress.

Figure 5(d) indicates that the elastic recovery of the asphalt binder significantly improved with the addition of the geopolymer. The improvement in elasticity is a result of alterations to the viscoelastic behaviour of the binder. Geopolymers are believed to absorb lighter fractions within the asphalt, effectively increasing the proportion of the viscoelastic components and enhancing the elastic recovery performance.

In Figure 5(e), the viscosity of the asphalt binder is shown to increase with higher geopolymer content. This increase in viscosity can be associated with the enhanced molecular interactions between the geopolymer and the asphalt matrix, leading to a more cohesive and resistant binder system.

5.2 Effect of geopolymer on storage stability of asphalt binders

Table 6 presents the results of the storage stability assessment on the geopolymer-modified asphalt binder. Table 6 reveals that the matrix asphalt binder, 3% and 5% geopolymer-modified asphalt binders exhibited the smallest softening point difference, suggesting the highest storage stability. However, the incorporation of 7% and 9% geopolymers resulted in a slight increase in the softening point difference, though the change was not substantial. Overall, the modified binder displayed excellent storage stability, attributed to the stable gel-like structure formed by the geopolymer. This structure promotes uniform dispersion within the asphalt binder and prevents phase separation or sedimentation during storage.

5.3 Effect of geopolymer on rheological properties of asphalt binders

From the isochronal plot presented in Figure 6, it was evident that the addition of the different dosages of the geopolymer to the matrix asphalt binder enhanced the rutting resistance (G*/sin δ) across all tested temperatures with the 3% geopolymer-modified binder demonstrating the highest rutting factor. This clearly indicates that incorporating the geopolymer significantly enhances the resistance of the binder by increasing the G*/sin δ value. Additionally, the test temperature had a notable impact on rutting performance. As temperature increased, the rutting resistance decreased for all the mixes.

The parameters G* and δ are key indicators of asphalt binder rheological behaviour. The rutting factor (G*/sin δ) is utilized to assess the rutting resistance of asphalt binders [52, 53]. A higher value of G*/sin δ corresponds to a greater resistance of the binder to rutting deformation. The phase angle δ represents the lag between stress and strain, reflecting the viscoelastic balance of the binder [54]. At temperatures below 58 °C, G* and G*/sin δ show a steep decline with temperature. In contrast, beyond 58 °C, the rate of decline slows, and changes become minimal above 70 °C. This suggests that the temperature sensitivity of the modified binder is more pronounced at medium to low temperatures, while it exhibits stable performance in the high-temperature range. When the geopolymer content was 3% and 5%, the parameters improve significantly with 3% showing the highest increase. Beyond 5%, although improvements continue, the changes are less noticeable as can be seen from Figure 6. Thus, the optimal geopolymer dosage for enhancing binder performance is identified as 3%.

6. Conclusion

This study assessed the influence of utilizing dual precursors and dual alkali solution on the physical and rheological properties of asphalt binder. The dual precursors, which included rice husk ash (RHA) and quarry dust (QD), were mixed with the dual alkali solution namely sodium hydroxide (NaOH) and sodium silicate, to produce the geopolymer used in modifying the matrix asphalt binder. Thereafter, the physical properties such as ductility, softening point, penetration, viscosity, and elastic recovery were assessed after modifying the matrix asphalt binder with the geopolymer. The optimum mix that yielded the highest rutting resistance was obtained. Based on the experimental data from the study and the subsequent analysis performed, the following conclusion can be inferred:

1. Compared to the unmodified asphalt binder, the incorporation of geopolymers led to enhancements in hardness, consistency, stiffness, and elasticity, while also slightly increasing brittleness. The elastic recovery performance improved, indicating enhanced resistance to deformation.

2. The geopolymer-modified asphalt binder exhibited increased viscosity and demonstrated satisfactory storage stability when compared to the result of the unmodified binder.

3. The addition of geopolymer to the asphalt binder further improved rutting resistance although it was associated with a reduction in workability.

4. Compared to the specifications outlined in the Kenya Design Manual for Roads and Bridges Part III, the binder modified with 3% nanoclay exhibited the most favorable rheological performance.

5. It can be concluded that the incorporation of RHA and QD based geopolymer into asphalt binder holds significant potential as an effective additive for enhancing the performance characteristics of the binder.

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