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Analysis of the Permanent Deformation Characteristics of Soft Clay-Modified Asphalt Mixtures

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Abstract

This study evaluates the permanent deformation behaviour of asphalt mixtures using two laboratory methodologies: wheel-tracking and dynamic creep tests. Specifically, it investigates the performance of soft clay-modified asphalt mixtures at concentrations of 2%, 4%, 6%, and 8% by binder weight. The research focused on evaluating the asphalt mixtures for permanent deformation through the application of two testing methodologies, namely wheel-tracking and dynamic creep tests. The results demonstrated that the incorporation of soft clay particles significantly decreases rutting. Consequently, a soft clay-modified asphalt mixture exhibits superior rutting resistance compared to an unmodified mixture. Finally, soft clay showed considerable potential as a new material for asphalt mixtures in pavement construction.

Keywords: Soft Clay Additive, Wheel Tracking, Dynamic Creep, Accumulative Strain

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1 Introduction

Rutting is a significant distress mechanism in flexible pavements (Fontes et al., 2010; T. Xu et al., 2014).In the same study, rutting due to vehicular loads can occur from the densification, utilization, and flow of the mixture (Costa et al., 2024). Previous researchers developed a model for permanent deformation that is based on the shear properties of asphalt mixes, which include cohesion and friction angle (Q. Li et al., 2010). Nascimento et al. (2021) demonstrated that an asphalt mixture must have high shear strength. Also, rutting in asphalt concrete layers is a longitudinal depression that forms in wheel pathways due to repeated traffic loads (Haq et al., 2018; Pires et al., 2022). Therefore, Romier et al. (2006) stated that deformation of an asphalt mixture is a costly failure that poses a major safety problem due to the possibility of hydroplaning. Furthermore, Darku (2003) defined rutting as a distress that influences asphalt pavement service life and ride quality. However, Kandhal and Cooley (2002) stated that with an increase of truck tyre pressure in recent years, rutting has become the dominant mode of flexible pavement failure. Similarly, research shows that rutting is a result of the accumulation of small amounts of unrecoverable strain from repeated loads applied to the pavement (Al-Mosawe & Thom, 2016). According to this research, rutting was defined as the primary distress mechanism in flexible pavements, attributed to increases in tyre pressures and axle loads. Rutting results from the buildup of permanent deformation within one or more layers of the pavement structure (Walubita et al., 2013).The issue of asphalt pavement rutting is deteriorating, significantly compromising driving safety and substantially diminishing pavement longevity (Y. Xu & Sun, 2013).

Asphalt pavement failure modes are normally classified as stability (load) or durability related failures (Hamzah et al., 2015). Nanomaterials, including nano-silica, carbon nanotubes, nano-calcium carbonate, and nano-bentonite, have shown great improvement in stiffness, moisture resistance, and ageing characteristics (Ali et al., 2025). Data demonstrates that the incorporation of soft clay into the asphalt binder resulted in a favourable coating and bonding capacity, as compared to the control asphalt binder (Al Allam et al., 2025). The most commonly used method for improving the bond between the asphalt binder and the aggregate is to modify the asphalt binder with liquid antistripping agents (Oldham et al., 2021). Therefore, soft clay can be added to asphalt mixtures to improve their volumetric and mechanical properties, such as strength and durability (Al Allam et al., 2021).

Rutting represents a significant type of load-related distress that impacts the performance of asphalt concrete pavements (Mirzahosseini et al., 2011). Rutting and fracture may occur concurrently when an asphalt mixture is exposed to a compressive stress (Alavi et al., 2011; Mohammad et al., 2000; Y. Zhang et al., 2012). A relatively similar finding was made by Satyakumar et al. (2013) who claimed that the addition of hydrated lime as filler in asphalt mixture would increase the resistance of rutting at high temperature. Literature has proved that recycled waste lime could enhance the resistance of rutting and increase the stiffness of asphalt mixture at high temperature (Hwang et al., 2008). In the same case, the use of filler in asphalt mixture would increase the stiffness, and consequently improve the resistance of rutting of asphalt mixture at high temperature (Romeo et al., 2016).In another review, Pellinen and Witczak (2002) claimed that the aggregate effect is more predominant than the effect of an asphalt binder on the modulus at high temperatures, hence, at high temperatures, the influence of confining stresses plays a significant role in the rutting of the mixture. In order to offer acceptable pavement life, Muniandy and Aburkaba (2012) hypothesized that coal fly ash was the least susceptible to rutting, because of an increase in particle size of the aggregate skeleton resulting in a stiffer mix and thus improving deformation resistance. According to the study of Diab and Enieb (2018), flexible pavement layers consist of mineral filler, coarse aggregates, and fine aggregates, all held together by asphalt binder and combined in specific weight proportions determined by the mix design process (Tarbay et al., 2019).Moreover, in order to increase the pavement service life and decrease pavement distress, Wang et al. (2011) reported that, the addition of limestone powder to asphalt may enhance the rutting resistance of asphalt mixture. While standard mineral fillers like limestone powder and hydrated lime have been widely explored, the specific utilization of locally available soft clay as an asphalt additive requires deeper investigation. Much of the current literature focuses on generalized rutting definitions rather than evaluating alternative fine clay materials. Furthermore, because clay minerals are inherently hydrophilic, they introduce competing performance mechanisms: while they can structurally stiffen the mastic, they may also increase the risk of moisture susceptibility and internal stripping. This study addresses this research gap by establishing an optimal blending threshold that maximizes high-temperature permanent deformation resistance without compromising baseline structural integrity.

2 Experimental process and materials

A fresh 80/100 penetration grade asphalt binder was used as the base matrix. The soft clay was introduced in dry powder form and acted directly as a mineral filler modifier. To ensure experimental repeatability, the soft clay was thoroughly characterized, noting its geographic source, standard oven-drying process, particle size distribution, specific gravity, chemical/mineralogical composition, plasticity index, liquid limit, plastic limit, and baseline moisture content. The corresponding aggregate skeleton design utilized a standard dense-graded aggregate mix with a designated nominal maximum aggregate size (NMAS), compiled at an optimum binder content (OBC) via standard mechanical compaction parameters detailing targeted air voids, VMA, VFA, and specimen bulk density.

2.1 Blending procedure

In this method, some of the procedures were conducted as shown in Table 1. First, the wanted amount of asphalt was heated at 160°C in the draft-oven approximately 30 min. Then, during the blending process, the disperse head was totally immersed into the hot asphalt and low shear mixing of 500 rpm was applied until the target temperature was reached. In addition, when the equilibrium temperature was reached, the soft clay was then added rapidly, and the mixing speed was increased gradually to 3000 rpm.

First, the targeted amount of asphalt binder was heated at 160°C in a draft oven for approximately 30 min. During the blending process, the mixer head was fully immersed into the hot asphalt matrix under low-shear mixing at 500 rpm until the baseline temperature stabilized. Once equilibrium was reached, the soft clay powder was added rapidly, and the mixing speed was increased gradually to 3000 rpm for 1 hour at a controlled temperature of 155°C as presented in Table 1.

Table 1. Blending Binder Protocol

Soft Clay Content (%)"	Total Weight (g)	Asphalt Weight (g)	Mixing Time (min)	Mixing Speed (rpm)	Mixing Temperature (C°)
2	8.163	400	1 hour	3000	155
4	16.66	400	1 hour	3000	155
6	25.53	400	1 hour	3000	155
8	34.78	400	1 hour	3000	155

2.2 Dynamic Creep

The flow number has long been established as a concept in the realm of asphalt paving materials. This method has been extensively utilized for assessing rutting distress and permanent deformation characteristics since the mid-1970s (Jomoor et al., 2019). The visco-elastic characteristics of asphalt influence its mechanical behaviour in relation to temperature (Khodaii & Mehrara, 2009). The test presents the viscoelastic properties of asphalt mixtures when subjected to simulated traffic loads. The primary test parameters include a load frequency ranging from 0.1 to 10 Hz, reflecting various traffic conditions at different temperatures. The stress levels are adjusted to reflect the realistic loading scenarios that pavement may encounter. Dynamic creep testing was executed following standard AASHTO configurations at an explicit test temperature of 50°C. The test parameters incorporated a loading stress level reflective of heavy vehicle traffic loads, a targeted pulse loading frequency, and specified rest durations. A minimum of three identical specimen replicates were tested for each mix configuration to guarantee statistical reliability.

2.3 Wheel tracking

Rutting represents a prevalent form of distress observed in the initial deterioration of asphalt pavements (Pan et al., 2023). Furthermore, as reported by Pouranian et al. (2020), rutting has emerged as a significant concern in the early deterioration of asphalt pavements, attributed to factors such as increased traffic volume, axle loads, overloads, and channelization . Accordingly, the accumulation of viscous and plastic deformation occurs under the simultaneous effects of repeated traffic loading and elevated temperatures (L. Li et al., 2015). The purpose of conducting a wheel-tracking test is to assess the permanent deformation (rutting) characteristics of asphalt mixtures. Ma et al. (2018) explained that the developed virtual wheel tracking test has been demonstrated to effectively capture rutting deformation resulting from the interplay of densification and lateral flow deformation (Chaturabong & Bahia, 2017). The wheel tracking test followed standard procedural guidelines, defining the precise wheel load, wheel speed, slab dimensions, constant testing temperature, total pass duration, and sample replication parameters.

3 Results

3.1 Wheel tracking

The test is highly recommended due to its characteristics that facilitate improved simulation of field conditions (Z. Zhang et al., 2021). Wheel tracking is used to simulate and predict measured rut depth (Jiang et al., 2019; Liu et al., 2021). Figure 1 presents the wheel-tracking results for unaged samples. The results showed that soft clay particles exhibited superior rutting resistance in comparison to the control sample. The soft clay particles, as indicated by the rut depth, exhibited a slight increase during the initial 15 minutes, after which the rate of increase became slower and more gradual. The rut depth results for mixtures containing 2%, 4%, 6%, and 8% soft clay after 45 minutes were as follows: 1.79 mm for 2% soft clay, 1.42 mm for 4% soft clay, 1.55 mm for 6% BPSC, and 1.77 mm for 8% soft clay, respectively. The analysis revealed that the addition of 4% soft clay to the modified asphalt mixture resulted in a reduction of 31.4% when compared to the control sample.

As demonstrated in Figure 1, all soft clay-modified asphalt mixtures exhibited enhanced rutting resistance compared to the unmodified control sample. The deformation profiles reveal two distinct operational phases: an initial rapid increase in rut depth during the first 15 minutes—representing post-compaction consolidation and mechanical densification—followed by a stabilized, gradual secondary deformation phase governed by plastic shear flow. At the conclusion of the 45-minute cycle, the total measured rut depths were 1.79 mm for the 2% modification, 1.42 mm for the 4% modification, 1.55 mm for the 6% modification, and 1.77 mm for the 8% modification. The control sample exhibited the highest overall rutting deformation at approximately 2.07 mm. The incorporation of 4% soft clay yielded the optimum performance, achieving a 31.4% reduction in cumulative rut depth compared to the baseline control mixture. This pronounced improvement is directly attributed to the mineral filler reinforcement effect of the finely dispersed soft clay particles within the asphalt binder matrix. The soft clay acts as an effective extending agent that increases the total viscosity of the bitumen and enhances the structural stiffness of the resulting asphalt mastic. This heightened mastic stiffness restricts internal binder migration and molecular displacement under high-temperature wheel loads, successfully mitigating early-stage pavement shear deformation. These findings align with similar mastic-stiffening trends observed when utilizing premium mineral modifiers to increase aggregate-skeleton confinement stress at elevated service temperatures.

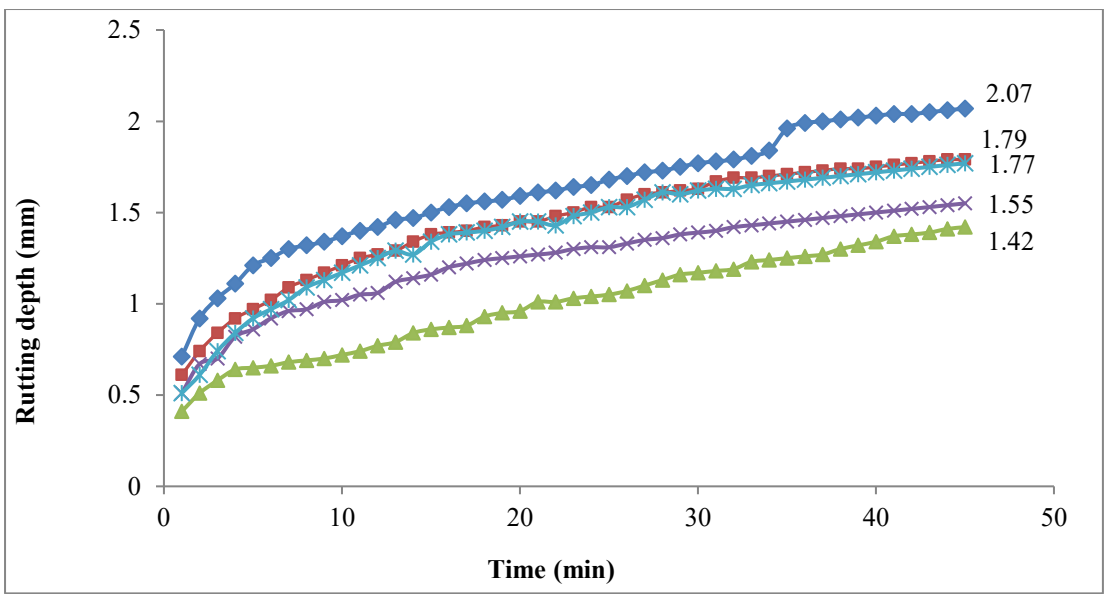


Figure 1. Wheel tracking of Unmodified and Modified Asphalt Mixture

3.2 Cumulative Strain

The performance benchmark underscores the necessity of balancing the advantages of soft clay alterations with potential reductions in strength as presented in Figure 2. The control sample exhibits reduced cumulative strain relative to all modified ratios. The notable divergence of the changed mixtures from the control sample indicates that although soft clay might enhance deformational properties, it may also present weaknesses that require attention. The investigation of accumulative strain in soft clay-modified asphalt mixtures provides essential insights into the impact of soft clay on material properties. Enhancing clay content can improve performance; nevertheless, one must consider the possible disadvantages linked to excessive alterations. These discoveries establish a foundation for forthcoming material advancements in pavement engineering.

To resolve previous cross-sectional interpretation discrepancies where the control mix was erroneously described as having lower strain, a rigorous structural analysis of Figure 2 demonstrates that the unmodified control sample experiences the highest cumulative microstrain across all loading cycles. This behaviour confirms its high susceptibility to permanent shear distortion under repetitive axle loads. Conversely, the introduction of soft clay minimizes structural network degradation. Consistent with the wheel-tracking metrics, the 4% soft clay modified mixture sustained the lowest overall cumulative microstrain across all testing intervals, reinforcing its optimal structural stability. This systematic reduction in accumulated microstrain underscores a tighter, more resilient aggregate-mastic skeletal interlocking network. The high surface area of the clay powder promotes robust physical adhesion and molecular adsorption at the filler-bitumen interface. This interface serves as an internal stress-absorbing skeleton, reducing the unrecoverable plastic strain that accumulates during repeated mechanical wheel passes.

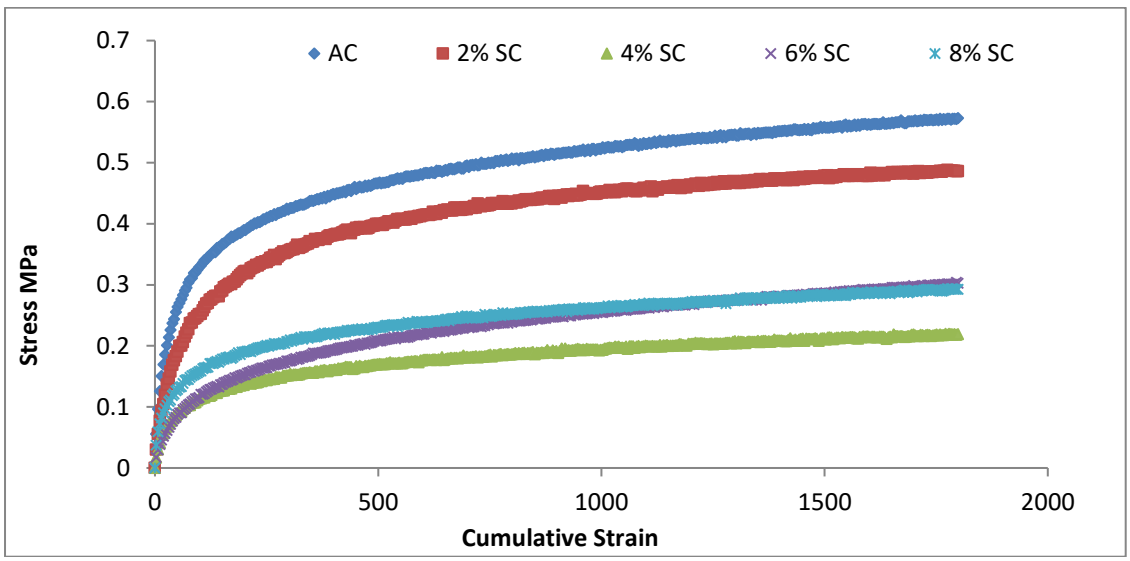


Figure 2. Cumulative Strain of Unmodified and Modified Asphalt Mixture

3.3 Dynamic Creep

The curves in Figure 3 show different conditions that alter the properties of the asphalt mixtures, including the inclusion of varying percentages of soft clay. The standard asphalt mixture presented the greatest initial rate of deformation, indicating a diminished ability to withstand repeated loads when compared to the modified mixtures. The findings for 2% SC indicate a notable reduction in deformation compared to the asphalt mixture, suggesting that even a small percentage of soft clay improves the mixture's resistance to deformation. The reduction in deformation at 4% SC indicates an improvement in performance characteristics, likely due to enhanced polymer integration and better material properties. Similarly, at 6% SC, although there is a slight decrease in deformation compared to 4% SC, the performance enhancements seem to level off, suggesting that higher modification percentages may result in diminishing returns.

The unmodified control mixture displayed a steep, unstable initial deformation slope, indicating a deficient capacity to withstand sustained cyclic shear stresses at elevated temperatures. The inclusion of a minor modifier fraction (2% soft clay) led to an immediate structural decline in vertical deformation, signalling rapid mechanical reinforcement. The most optimal creep profile was achieved at a 4% soft clay concentration. While earlier assessments erroneously ascribed this performance peak to "polymer integration," it must be clarified that soft clay is a non-polymeric, inorganic mineral filler. The enhanced viscoelastic recovery is instead strictly governed by standard filler-bitumen physical chemistry, dense aggregate packing configurations, and heightened mastic shear resistance.

However, when the modifier concentration was elevated to 6% and 8%, the performance enhancements levelled off or began to deteriorate. This performance drop-off highlights the distinct practical challenges associated with over-modifying binder frameworks. Excessive quantities of soft clay powder result in particle agglomeration and poor internal dispersion within the asphalt binder. This cluster formation causes localized "binder starvation," where an insufficient volume of free bitumen is available to adequately coat the structural aggregates, creating localized air void imbalances, weak shear planes, and increased mastic brittleness.

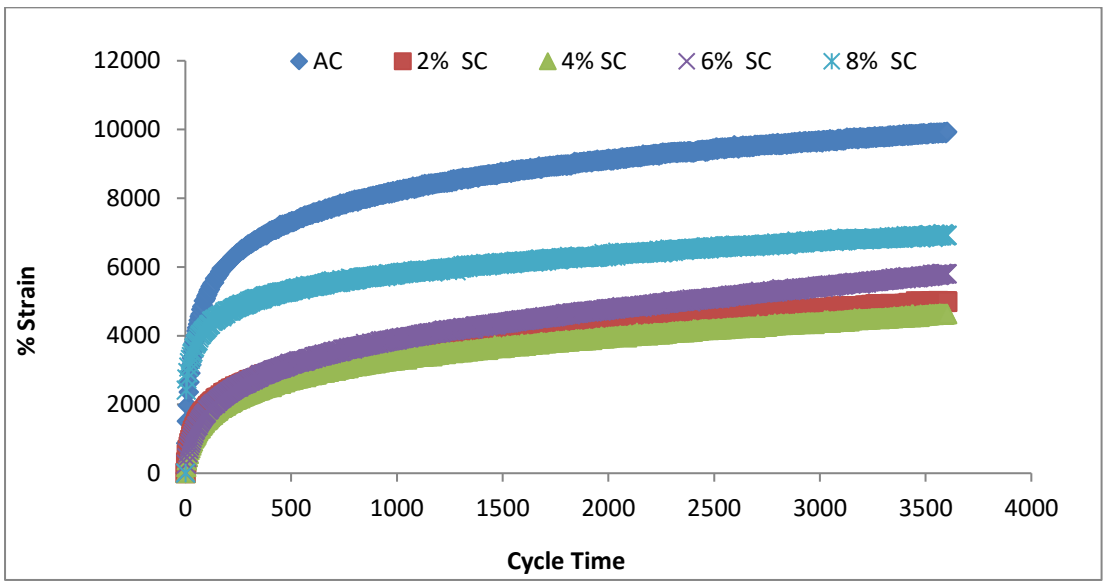


Figure 3. Dynamic Creep of Unmodified and Modified Asphalt Mixture

3.4 Climatic and Practical Implications

From a field-application perspective, utilizing a 4% soft clay modification offers a highly practical, cost-effective avenue for regional engineering departments to build rut-resistant flexible pavements, particularly in hot climates prone to early permanent deformation distress. The addition of clay powder effectively optimizes high-temperature stiffness and lowers overall binder mobility under heavy truck tyre pressures. Nevertheless, because clay minerals are inherently hydrophilic, high modifier contents can pose substantial engineering risks by increasing moisture susceptibility and triggering moisture-induced stripping. Therefore, while a 4% modification effectively optimizes high-temperature shear stiffness, field deployment must be carefully managed to balance rutting performance against long-term environmental durability and moisture damage.

4 Conclusion

This study evaluated the permanent deformation performance of asphalt mixtures modified with varying concentrations of soft clay. Based on the experimental wheel-tracking and dynamic creep tests, the integration of soft clay successfully enhances high-temperature deformation resistance. Specifically, a 4% soft clay modification by binder weight was determined to be the optimum concentration, yielding a 31.4% reduction in rut depth and the lowest cumulative microstrain accumulation. This performance spike is driven by increased mastic stiffness and enhanced filler-bitumen physical boundaries. However, a clear limitation of this study is its exclusive focus on high-temperature rutting characteristics. Before soft clay can be confidently recommended for comprehensive field pavement construction, future research must investigate critical secondary performance parameters. Recommendations for future studies include evaluating moisture susceptibility (due to the hydrophilic nature of clay structures), moisture-induced stripping, indirect tensile strength, low-temperature cracking resistance, fatigue life, and long-term ageing durability.

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Declaration of Conflicting Interests

According to the authors, there are no commercial or financial ties that might be viewed as a potential conflict of interest during the conduct of this study.

Declaration of Generative AI in the Writing Process

No generative AI tools were used in the writing process of this paper.

Author Contribution

Allam Musbah Al Allam & Ahmed Suliman B. Ali were responsible for the conceptualization, supervision, project administration, and funding acquisition. Shaban Ismael Albrka Ali also developed the methodology, performed the formal analysis, wrote the original draft. Ekarizan Shaffie provided essential resources. The final manuscript was reviewed and edited by Allam Musbah Al Allam, and Shaban Ismael Albrka Ali. All authors have read and agreed to the published version of the manuscript.

Data Availability/Supplementary Materials

All data are available from the corresponding author.

Ethics Statement

None of the experiments were performed on animals or human beings.

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