Performance Classification of Asphalt Binder Reinforced with Waste Polycarbonate Particles for Sustainable Pavement Applications

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ABSTRACT

The use of polymers to modify asphalt binders has become increasingly popular as a way to enhance the longevity and sustainability of road pavements. This research examines how adding waste polycarbonate (PC) particles affects the performance grading of asphalt binder, focusing on its ability to improve mechanical and rheological properties for road applications. Waste polycarbonate, recognized for its toughness and heat resistance, was mixed into the asphalt binder at different concentrations to study its impact on critical performance measures such as penetration deepness, softening point, ductility and viscousity; to analyze the distribution and bonding of polycarbonate within the asphalt matrix.

Findings reveal that polycarbonate modification boosts the binder's heat resistance, stiffness, and elasticity, leading to better resistance to rutting and enhanced durability in high-temperature environments. However, too much polycarbonate increased stiffness, which could reduce flexibility in cold conditions. The study identifies an optimal polycarbonate content to balance high-temperature steadiness with low-temperature crack endurance and resistance. These results highlight the potential of waste polycarbonate materials as eco-friendly asphalt modifiers, supporting circular economy practices and the creation of advanced pavement materials.

INTRODUCTION

The pursuit of longer-lasting and more sustainable road infrastructure has driven notable progress in modifying asphalt binders. While conventional asphalt binders are commonly used, they have inherent weaknesses, including rutting in high temperatures, thermal cracking in cold weather, and moisture-related damage. To improve their durability and performance, researchers have investigated various polymer-based reinforcements, with recycled thermoplastics emerging as a particularly promising option due to their economic and environmental benefits.

Polycarbonate (PC), a high-performance engineering thermoplastic, offers excellent mechanical strength, thermal stability, and resistance to environmental wear. With the growing problem of plastic waste worldwide, repurposing waste polycarbonate for asphalt modification presents a dual advantage—enhancing binder performance while supporting sustainable waste management. However, key questions remain regarding polycarbonate's interaction with asphalt, optimal usage levels, and long-term impact on pavement durability, necessitating further research.

This study evaluates the performance of asphalt binder reinforced with polycarbonate particles, focusing on rheological, thermal, and structural properties. By conducting a thorough analysis, the research aims to identify the best incorporation method and measure the extent to which polycarbonate enhances asphalt's engineering characteristics. The results will offer important insights into the viability of polycarbonate-modified asphalt as an economical and eco-friendly solution for modern road construction, contributing to more resilient and sustainable transportation systems.

MATERIALS AND METHODS

Penetration Test

The penetration test assesses the consistency and hardness of bituminous materials, playing a crucial role in quality control for road construction and maintenance.

The objective of this test was to measure the penetration value of modified bitumen using a penetrometer, following ASTM D5 standards. This test determines bitumen hardness, which is vital for material characterization in road construction, roofing, and civil engineering applications.

Bitumen samples were conditioned to the specified test temperature until thermal equilibrium was achieved. Contaminant-free samples were heated to no more than 75°C. The penetrometer (GEWISS GW44207) was calibrated, and the needle met ASTM D5 specifications. A water bath maintained the test temperature (25°C), and a thermometer monitored the water temperature.

The prepared sample was placed in a container, and the penetrometer needle was gently placed on its surface. A 100g load was applied for 5 seconds, and the penetration depth (in mm) was recorded to the nearest 0.1 mm. This process was repeated at three different locations, and the mean penetration value was calculated. In this experiment, the higher penetration depth values indicated softer bitumen, while lower values suggested rigid bitumen.

A Penetrometer

Softening Point Test

The softening-point test for asphalts indicates the temperature upon which the material begins to soften, which is crucial for assessing its quality in road construction and other uses. The test follows the ASTM D36/D36M standard, employing a ring-and-ball apparatus (ELE464825/01).

To begin, the ring-and-ball setup was cleaned to remove any leftover bitumen residue and positioned on a stand. A beaker beneath it was filled with distilled water. A thin bitumen disk (3-4 mm thick) was prepared, cooled, and then placed on the ball before being secured to the apparatus.

The ring was positioned over the bitumen sample, and the entire assembly was submerged in the water bath. The water was heated increasingly at the rate of 5°C per minute while being gently stirred to maintain uniform heat distribution. As the temperature rose, the bitumen softened until the ball descended 25.4 mm through the sample, marking the softening point—the stage where the bitumen turns into a soft, viscous fluid. The temperatures at which softening and ball drop occurred were recorded for analysis.

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Ductility Test

Assessing the ductility of bitumen is crucial to determine its capacity to stretch and deform under tensile stress without cracking, typically following the ASTM D113 standard. For the test, a bitumen sample was prepared by heating it to 75–100°C to achieve a workable consistency. The heated bitumen was then poured into a mold to form a briquette-shaped sample, which was placed on a base plate and secured. The mold was submerged in a water bath (Techie TE-10A) maintained at 25°C ± 0.1°C, with the water level covering the specimen to a depth of approximately 20 mm. The sample was left to cool and solidify in the water.

Once cooled, the mold (measuring 10 ± 0.1 mm in diameter and 30 ± 0.13 mm in length) was taken out of the water bath, and the briquette was carefully removed. The specimen was then attached to a pulling device, ensuring proper alignment with its longitudinal axis. The testing machine (MATEST B755AC0003) was activated, applying a constant pulling speed of 50 mm/min until the briquette fractured. The ductility value was determined by measuring the elongation before rupture, calculated as the difference between the final stretched length and the original length. Multiple tests were conducted to ensure result accuracy and consistency. The ductility was recorded in millimeters at the point of breakage.

A Softening Point Tester

A Ductilometer

Viscousity Test

The viscosity test for bitumen plays a crucial role in the construction and asphalt sectors, helping evaluate the flow characteristics and workability of bituminous materials. The test was conducted using a Rotational Viscometer (MATEST S.P.A. B087) following the ISO 3219:2015 standard. Before testing, the bitumen sample was heated to 60°C after confirming its homogeneity, representativeness, and absence of contaminants. The viscometer was then prepared by attaching the suitable spindle and performing the necessary calibration. Next, the heated bitumen was poured into the sample container, and the spindle was immersed fully into the material. The viscometer was activated, and the time (in seconds) required for the spindle to complete 60 revolutions within the bitumen was recorded.

Typical Rotational Viscometer

RESULTS AND DISCUSSION

Penetration Test

Table 1 displays the penetration depths of various bituminous samples tested with different modifiers: Car Bumper (CB), Compact Disc (CD), and Dispenser Water Bottles (DWB). The modifiers were added in proportions of 0%, 5%, 10%, and 15%, with both fine and coarse particle sizes. The results indicate that the lowest penetration depth (50.00 mm) occurred with 15% fine CB particles, while the highest (106.67 mm) was recorded for 5% coarse CD particles. In comparison, the control sample had a penetration depth of 149.33 mm.

For CB, penetration decreased with increasing fine particle content (5%–15%) but increased with coarse particle content. CD and DWB followed similar trends, showing varying penetration depths that reflect their suitability for asphalt production. Generally, lower penetration values indicate better-performing modifiers. Penetration tests are essential in construction and quality control, as they assess bitumen consistency and hardness—key factors in material performance. These tests help determine the softening point, aiding in selecting the right bitumen grade for different climates (softer for cold regions, harder for hot ones). Additionally, penetration values predict aging resistance, with harder bitumen being more durable (Chen and Sun. 2003; Dong and Sun 2006)

The tests also ensure on-site quality compliance, verifying that bitumen meets project specifications for roads, roofing, and other applications. Furthermore, penetration results guide material selection—softer bitumen for waterproofing and harder types for pavements—while also hinting at bitumen’s adhesive properties. A specific penetration value can enhance bitumen's adhesion to aggregates in asphalt mixes, which is crucial for pavement performance. This measurement also helps evaluate bitumen's viscoelastic behavior, key to understanding how it deforms and flows under stress. Such data is essential for designing durable bituminous materials that can endure traffic loads and environmental conditions. These penetration tests significantly influence the selection, performance, and quality control of bitumen in various applications, offering insights into its consistency, temperature sensitivity, and durability. This aids engineers and researchers in making informed decisions about material formulation and usage (Rasmussen et al. 2002; Li, 2013)

Table 1: Results of Penetration Test

Modifier Type	Control (mm)	5% Fine (mm)	10% Fine (mm)	15% Fine (mm)	5% Coarse (mm)	10% Coarse (mm)	15% Coarse (mm)
CB	149.33±5	57.00±2	53.50±	50.00±	90.33±	95.17±	100.00±
CD	149.33±5	106.67±5	102.00±	97.33±	77.33±	68.83±	60.33±
DWB	149.33±5	92.00±1.7	91.83±	91.67±	98.00±	101.33±	104.67±

Modifiers are often added to bitumen to enhance its properties. These additives can alter bitumen’s penetration value—a measure of hardness—so their selection and dosage must be carefully considered. For instance: Polymer-modified bitumen typically has lower penetration, increasing stiffness and deformation resistance; Crumb rubber modifiers often raise penetration, improving flexibility; Hydrated lime may slightly increase penetration, enhancing workability. Fibers can have mixed effects, depending on type and quantity; Anti-stripping agents mainly improve aggregate adhesion, with minimal impact on penetration. Nano-sized modifiers vary in effect, sometimes increasing workability or stiffness. The impact of modifiers depends on their type, formulation, and dosage. Engineers optimize these factors through testing to achieve desired performance for specific projects (Rasmussen et al. 2002)

Softening Point

Table 2 displays the softening temperatures of modified samples. The highest softening point (100°C) was observed in 15% coarse CB and DWB samples, while the lowest (46.67°C) was seen in 5% fine CD samples. All modified samples (CB, CD, DWB) showed increased softening points with higher dosages (5%–15%) and larger particle sizes, outperforming the control sample (42.33°C).

The softening point indicates when bitumen softens and becomes prone to deformation. Higher softening points improve high-temperature stability, reducing rutting in hot climates, while lower softening points enhance flexibility in cold regions, preventing cracks. This property is vital for selecting the right bitumen grade based on climate conditions. In asphalt pavements, a higher softening point resists rutting under heavy traffic, whereas a lower softening point prevents cracking in cold weather. Proper softening point selection ensures strong aggregate adhesion and cohesion, enhancing pavement durability. Additionally, bitumen with a lower softening point withstands freeze-thaw cycles better, minimizing damage in colder climates (Christensen and Anderson,1992)

Results of Softening Point Test

Modifier Type	Control (ºC)	5% Fine (ºC)	10% Fine (ºC)	15% Fine (ºC)	5% Coarse (ºC)	10% Coarse (ºC)	15% Coarse (ºC)
CB	42.33±	63.67±	79.83±	96.00±	61.33±	80.67±	100.00±
CD	42.33±	46.67±	54.83±	63.00±	49.00±	54.67±	60.33±
DWB	42.33±	48.67±	54.33±	60.00±	61.67±	80.83±	100.00±

The softening point also influences the temperatures at which bitumen can be efficiently handled and used in construction. Bitumen with a lower softening point can be mixed and laid at lower temperatures, which can be advantageous in terms of energy consumption and emissions reduction during construction (Christensen and Bonaquist 2015). The choice of bitumen with an appropriate softening point is crucial for the long-term durability of pavements. It helps prevent issues such as rutting, cracking, and premature pavement failure, ultimately reducing maintenance and repair costs. Therefore, softening point of bitumen plays a significant role in determining its suitability for specific applications and environmental conditions. Engineers and asphalt mix designers carefully consider the softening point when selecting bitumen grades to ensure that the resulting asphalt mixture will perform optimally over its intended service life. Different regions and projects may require bitumen with varying softening point specifications to achieve the desired performance characteristics (Christensen et al.,2003)

However, modifiers are additives or materials that can be incorporated into bitumen to alter its properties and improve its performance for specific applications. These modifiers can have various effects on the softening point of bitumen, depending on their nature and purpose. Adding polymers to bitumen, like S.B.R. (styrene-butadiene rubber) or S.B.S (styrene-butadiene-styrene), can reduce the softening point. Polymer-modified bitumen (PMB) has enhanced flexibility and elasticity at higher temperatures due to the lower softening point. This is especially beneficial for improving resistance to rutting and cracking in hot climates. The addition of crumb rubber derived from recycled tires can also reduce the softening point of bitumen. This type of modified bitumen, often referred to as rubberized bitumen or crumb rubber asphalt, has improved elasticity and resistance to temperature-related deformations. Rejuvenators are additives used to restore aged and stiff bitumen to its original properties. These additives can reduce the softening point of aged bitumen, making it more flexible and workable. Rejuvenation is commonly used for recycling old asphalt pavement materials (Finn, 1990)

Modifiers offer the flexibility to customize the softening point of bitumen to meet specific project requirements. Depending on the dosage and type of modifier used, the softening point can be adjusted to achieve the desired balance of stiffness and flexibility for a particular application or environmental condition. It's important to note that the effects of modifiers on bitumen properties, including the softening point, can vary depending on the type and concentration of the modifier, as well as the base bitumen used. Engineers and pavement designers carefully consider these factors to select the appropriate modifier and optimize the modified bitumen for its intended use, taking into account the desired performance characteristics and environmental conditions. Additionally, laboratory testing and analysis are typically conducted to assess the impact of modifiers on bitumen properties and ensure that the modified bitumen meets specified performance criteria (Harnsberger, 2011)

Ductility Test

Table 3 shows the ductility properties of modified bituminous samples compared to the control samples. It is observed that samples modified with CD showed best enhancement among the results shown (96.33mm, 91.17mm, 86.00mm, 80.00mm, 81.50mm and 83.00mm), when compared with the control samples (61.67mm). Similarly, CB, CD and DWB show decreasing length of ductility from 5% -15% dosages, and particle sizes (fine and coarse).

However, the ductility of bitumen, which measures its ability to deform under tensile stress without breaking, has significant effects on its performance in various applications, especially in the construction and road industry. Bitumen with higher ductility is more resistant to cracking. This is crucial in road construction

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because it helps prevent the formation of cracks due to temperature variations and traffic loads (Ruan et al., 2003). Ductile bitumen can stretch and accommodate stress without developing cracks. Also, ductile bitumen contributes to the durability of asphalt pavements and roofing materials. It can withstand the expansion and contraction caused by temperature fluctuations over time, reducing the need for frequent repairs and replacements. Bitumen used in flexible pavement structures benefits from higher ductility. It allows the pavement to deform elastically under traffic loads and then return to its original shape, reducing permanent deformation and rutting. Ductility influences the adhesion of bitumen to aggregates in asphalt mixtures. Bitumen needs to form a strong bond with aggregates to ensure the stability and longevity of the road surface. Ductile bitumen enhances this bond, reducing the risk of aggregate stripping (Li et al, 2017). Bitumen ductility performs a critical role in determining the longevity, durability, and quality of various construction materials and infrastructure projects. The appropriate level of ductility should be selected based on the specific application and environmental conditions to ensure the desired performance characteristics (Frolov et al, 1983)

Results of Ductility Test

Modifier Type	**Control (mm)**	**5% Fine (mm)**	**10% Fine (mm)**	**15% Fine (mm)**	**5% Coarse (mm)**	**10% Coarse (mm)**	**15% Coarse (mm)**
CB	61.67±	70.00±	46.33±	22.67±	46.00±	24.50±	3.00±
CD	61.67±	96.33±	91.17±	86.00±	80.00±	81.50±	83.00±
DWB	61.67±	76.33±	60.17±	44.00±	44.00±	27.50±	11.00±

Modifiers are substances mixed into bitumen to modify its characteristics and improve its performance in different uses. For instance, elastomers like SBS (Styrene-Butadiene-Styrene) can greatly boost bitumen's ductility, making it more flexible and resistant to cracking—an essential quality for asphalt in flexible pavements. Polymer-based modifiers such as SBS and SBR (Styrene-Butadiene Rubber) enhance ductility across a wide temperature range, making them ideal for areas with extreme weather conditions. These modifications help prevent cracking in cold climates and reduce rutting in high heat (Frolov et al, 1983; Ruan et al., 2003)

Additionally, modifiers strengthen the bond between bitumen and aggregates in asphalt, reducing stripping and improving pavement stability. They also slow down bitumen aging, preserving its flexibility and extending the lifespan of roads and roofing materials. Certain modifiers, like polymer-modified bitumen (PMB), enhance resistance to water damage, which is crucial for waterproofing applications (Li et al, 2017; Shenghua, 2018)

Engineers can customize modifiers based on project needs, adjusting for factors like traffic volume, climate, and pavement design. Modified bitumen is particularly resistant to fatigue cracking, making it a strong choice for high-traffic areas such as highways and airports. It also improves workability during construction, allowing for easier application. Moreover, modified bitumen is often more recyclable, supporting sustainable construction practices. In summary, modifiers significantly enhance bitumen's ductility and overall performance, with the selection depending on specific project goals and desired improvements (Tong, 2010; Xing et al, 2016)

Viscousity Test

Table 4 presents the viscosity test results for modified bituminous samples, indicating the time (in seconds) a spindle takes to complete 60 revolutions in heated bitumen. Compared to the control sample (45.67 Pascal-seconds), all modified samples exhibited lower viscosity. Both CB and other modifier types showed reduced viscosity across varying dosages and particle sizes, suggesting that viscosity levels depend on modifier type, particle size, and dosage (Ameri et al., 2013; Alatas and Yilmaz, 2013)

Viscosity, a key property of bitumen that measures its flow resistance, plays a crucial role in its performance, particularly in construction and road engineering. Lower viscosity bitumen is easier to process and mix with aggregates, ensuring better coating and a more uniform asphalt mixture. In contrast, high-viscosity bitumen can be difficult to handle, especially in cold conditions, often requiring extra heating and mixing (Airey, 2003). Additionally, viscosity affects bitumen’s adhesive qualities—lower viscosity enhances aggregate adhesion, improving pavement durability, while higher viscosity increases cohesion, helping withstand heavy traffic loads. High-viscosity bitumen also resists aging and environmental damage (oxidation, UV exposure, moisture), whereas low-viscosity bitumen may lead to rutting in hot climates. However, overly high viscosity can cause brittleness and cracking in cold weather. The impact of modifiers on viscosity varies based on type and dosage. Some, like crumb rubber or fibers, increase viscosity, improving deformation and rutting resistance—ideal for high-traffic conditions. Engineers tailor modifier blends to meet specific needs, considering climate, traffic, and pavement requirements to optimize performance (Airey, 1997; Airey,2002; Airey et al., 2016)

CONCLUSION

This study has demonstrated the potential of waste polycarbonate (PC) particles as an effective modifier for asphalt binder, offering significant improvements in its mechanical and rheological properties. The following are drawn as the conclusions of this work:

1. Waste polycarbonate (PC) particles improved the thermal stability, stiffness, and elasticity of the asphalt binder, leading to better resistance against rutting and deformation under high temperatures.
2. While polycarbonate modification enhanced high-temperature performance, excessive content increased stiffness, potentially affecting low-temperature flexibility. An optimal dosage was identified to balance both high- and low-temperature performance.
3. The use of recycled polycarbonate materials in asphalt binder supports circular economy principles, offering an environmentally friendly solution to plastic waste management while improving pavement durability.

Therefore, further studies should focus on long-term performance evaluations, field trials, and compatibility assessments with different asphalt grades to validate the practical application of polycarbonate-modified asphalt in road construction.

Table 4: Results of Viscousity Test

Modifier Type	Control (Pa-s)	5% Fine (Pa-s)	10% Fine (Pa-s)	15% Fine (Pa-s)	5% Coarse (Pa-s)	10% Coarse (Pa-s)	15% Coarse (Pa-s)
CB	45.67	4.01	7.23	10.46	5.83	6.73	7.62
CD	45.67	7.94	11.53	15.12	9.35	11.71	14.07
DWB	45.67±	6.87	10.36	13.86	7.92	11.01	14.11

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