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Microstructural Analysis and Performance Implications of Asphalt Binder Reinforced with Waste Polycarbonate Particles

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Abstract
The incorporation of polymeric materials into asphalt binders has emerged as a promising strategy for enhancing pavement durability and sustainability. This study investigates the microstructural characteristics of asphalt binder reinforced with waste polycarbonate (PC) particles, focusing on its morphological attributes and performance implications. Waste polycarbonate, a highperformance thermoplastic known for its superior mechanical strength and thermal stability, was introduced into asphalt binder at varying concentrations. The modified binders were analyzed using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) to evaluate particle dispersion, interfacial bonding, and potential chemical interactions between the polymer and binder matrix.
The results revealed that polycarbonate modification significantly influenced the microstructure of the asphalt binder, enhancing phase distribution and interfacial adhesion. Improved dispersion of polycarbonate particles contributed to increased binder stiffness and thermal stability, which are critical for mitigating rutting and deformation at elevated temperatures. However, excessive polycarbonate content led to phase separation, highlighting the need for dosage optimization. These morphological insights provide a deeper understanding of the role of waste polycarbonate in asphalt modification and its potential to enhance pavement performance. The findings support the integration of recycled polymers in road construction, aligning with sustainable development goals and promoting eco-friendly infrastructure solutions.

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I. Introduction:

The structural integrity and longevity of asphalt pavements are largely dependent on the properties of the asphalt binder. However, conventional binders are often susceptible to various forms of degradation, including rutting, fatigue cracking, and moisture-induced stripping, leading to premature pavement failure. To enhance the performance and durability of asphalt binders, researchers have increasingly explored the incorporation of polymeric modifiers. Among these, waste polycarbonate (PC) has garnered attention due to its excellent thermal stability, mechanical strength, and potential for sustainable reuse in road construction.

While extensive research has been conducted on the rheological and mechanical enhancements offered by polymer-modified asphalt, a critical gap remains in understanding the microstructural interactions between asphalt binder and polycarbonate reinforcement. Morphological analysis provides essential insights into the dispersion of polycarbonate particles within the binder matrix, interfacial bonding characteristics, and structural modifications that influence overall performance. Advanced imaging techniques such as Scanning Electron Microscopy (SEM) enable a detailed examination of phase distribution, polymer-binder compatibility, and potential improvements in structural integrity.

This study investigates the microstructural characteristics of asphalt binder reinforced with selected waste polycarbonate particles, focusing on the dispersion patterns, surface morphology, and binder-polymer interactions. By correlating these morphological attributes with performance related properties, the research aims to establish a fundamental understanding of how polycarbonate reinforcement influences binder behavior. The findings will contribute to the development of innovative, high-performance, and sustainable asphalt formulations, supporting the integration of recycled materials into modern pavement engineering.

II. Material and Method

The Scanning electron microscopy (SEM) procedures was conducted according to ASTM E1508:

III. Results and Discussion

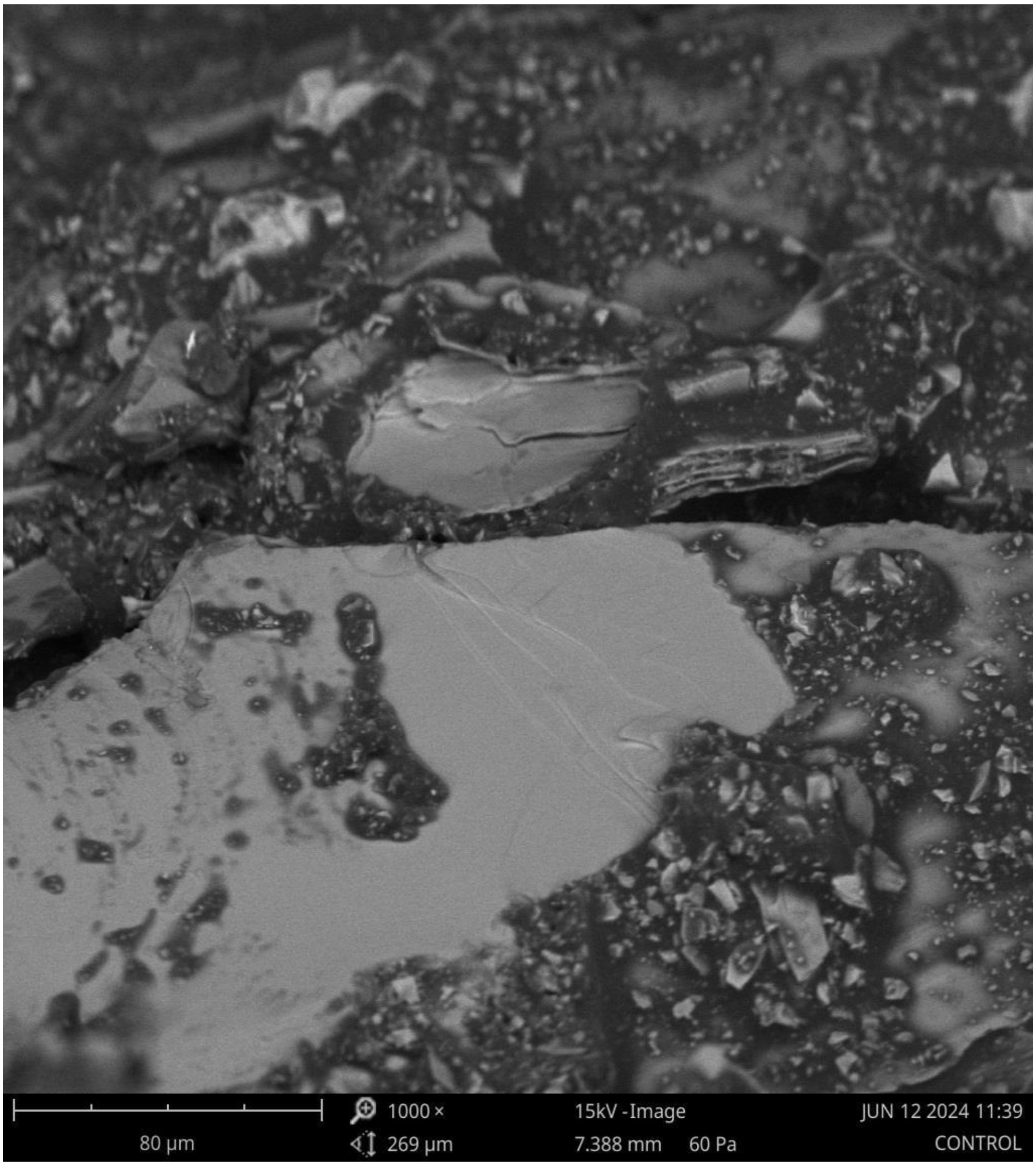

Figure 3a: SEM image for Sample with 0% modifier (CONTROL)

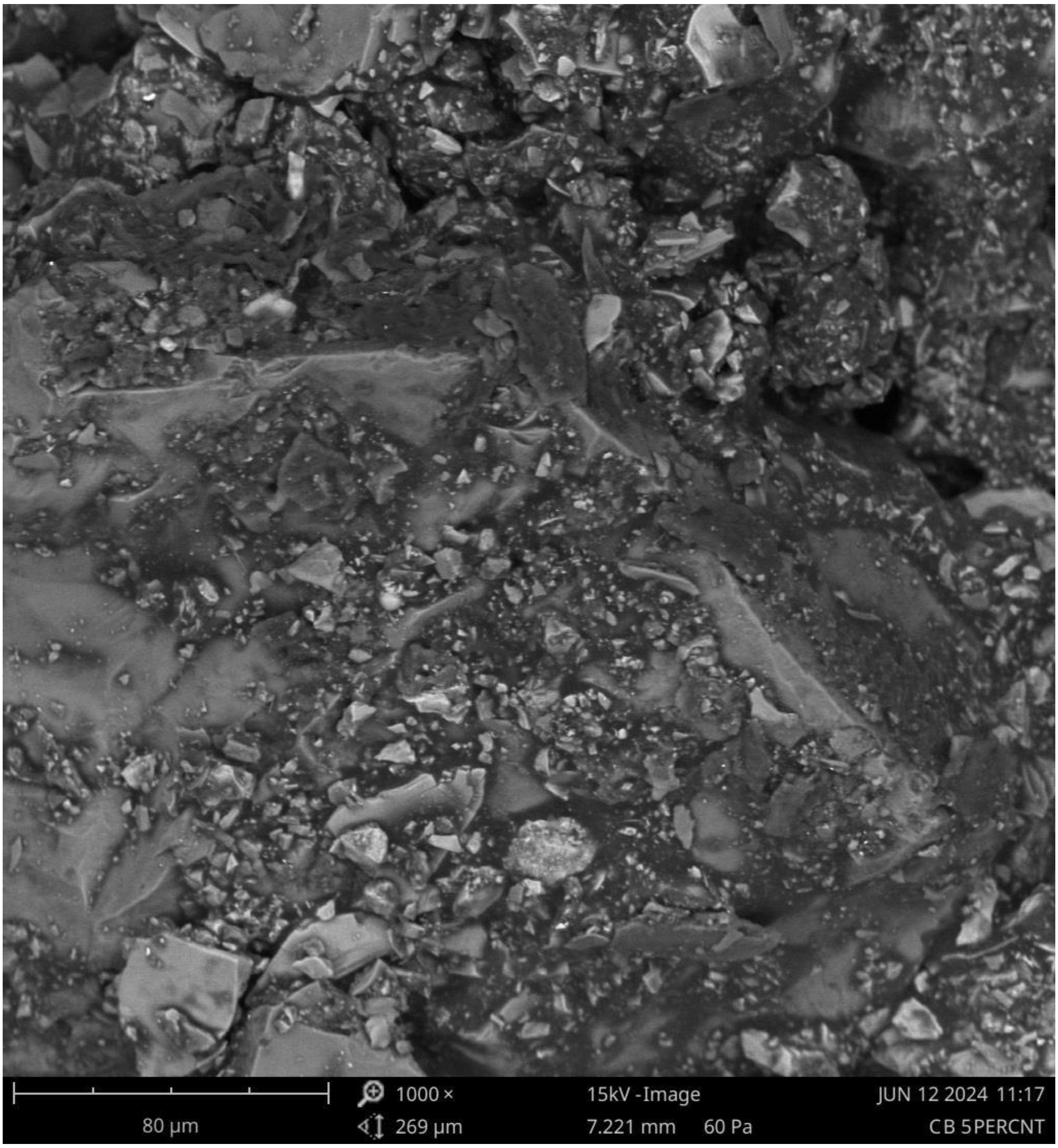

Figure 3b: SEM image for Sample with 5% CB

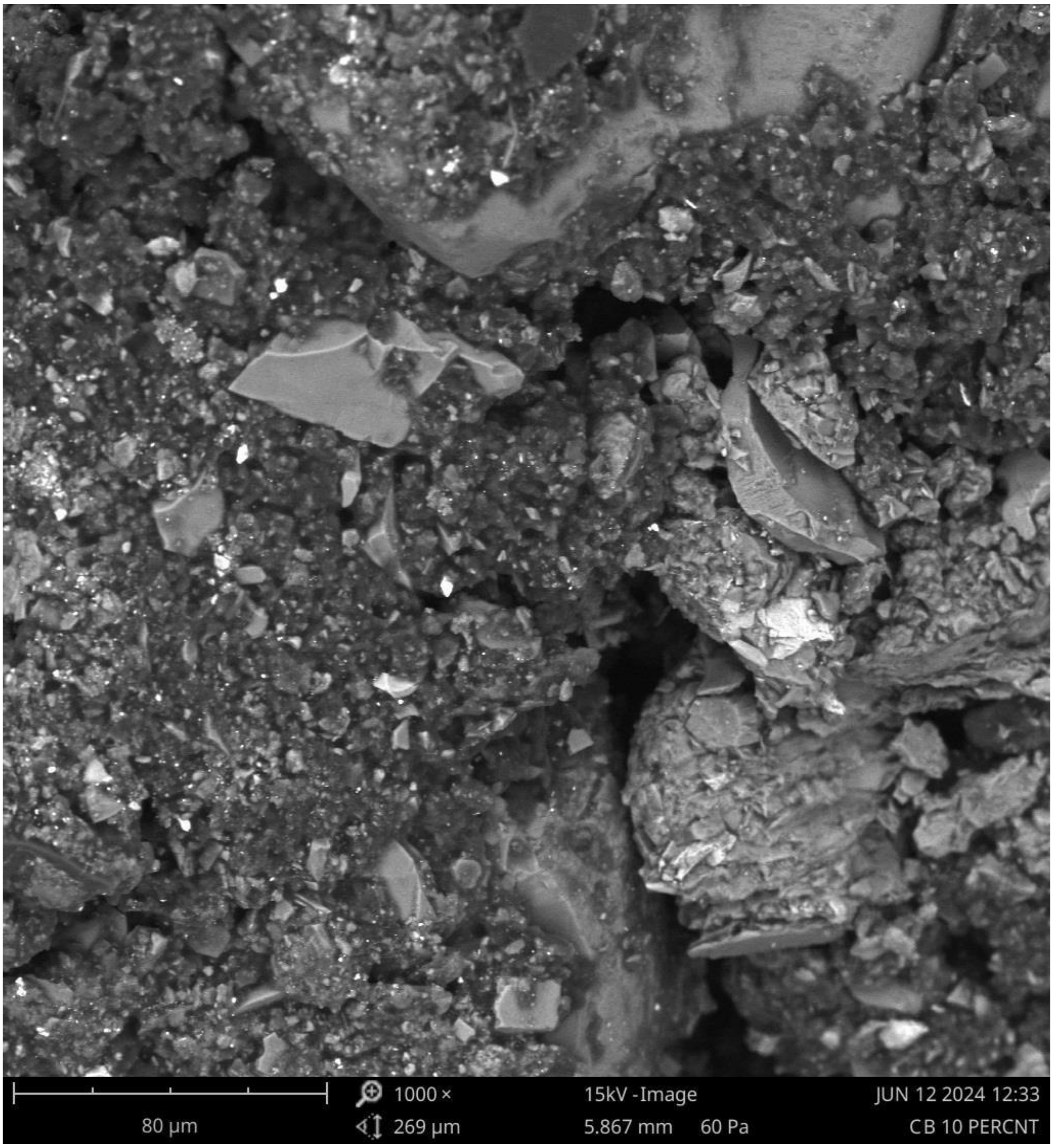

Figure 3c: SEM image for Sample with 10% CB

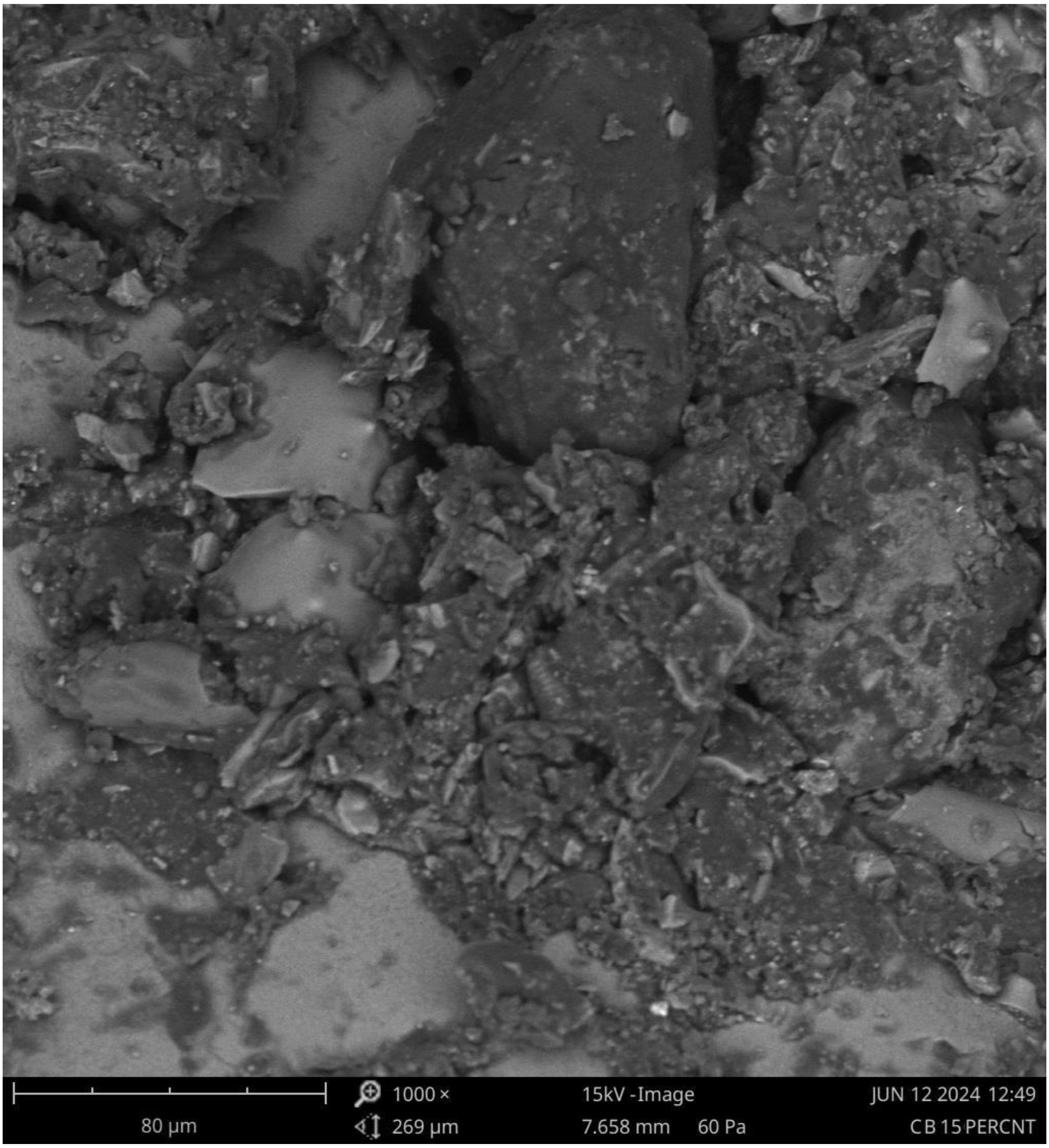

Figure 3d: SEM image for Sample with 15% CB

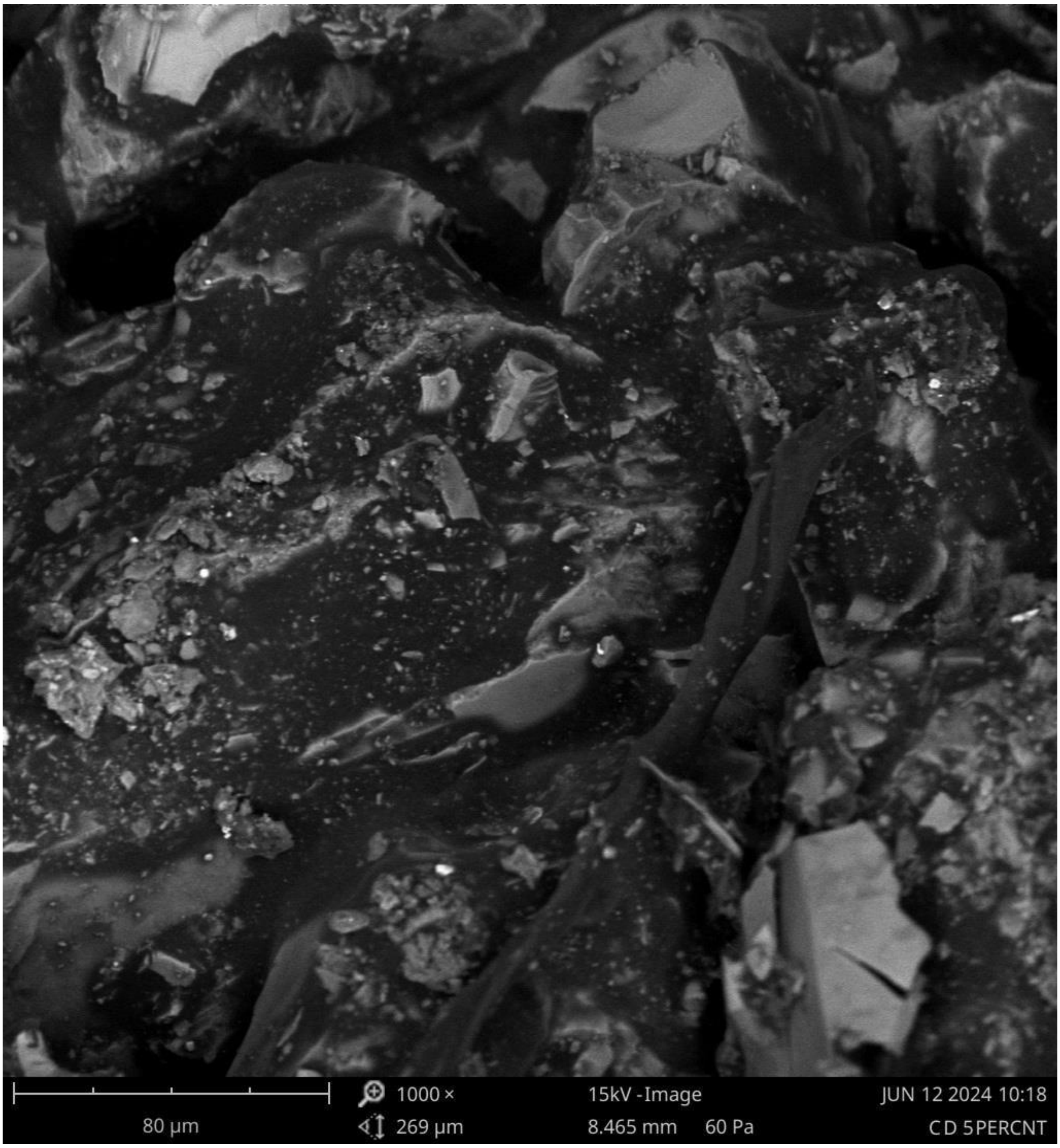

Figure 3e: SEM image for Sample with 5% CD

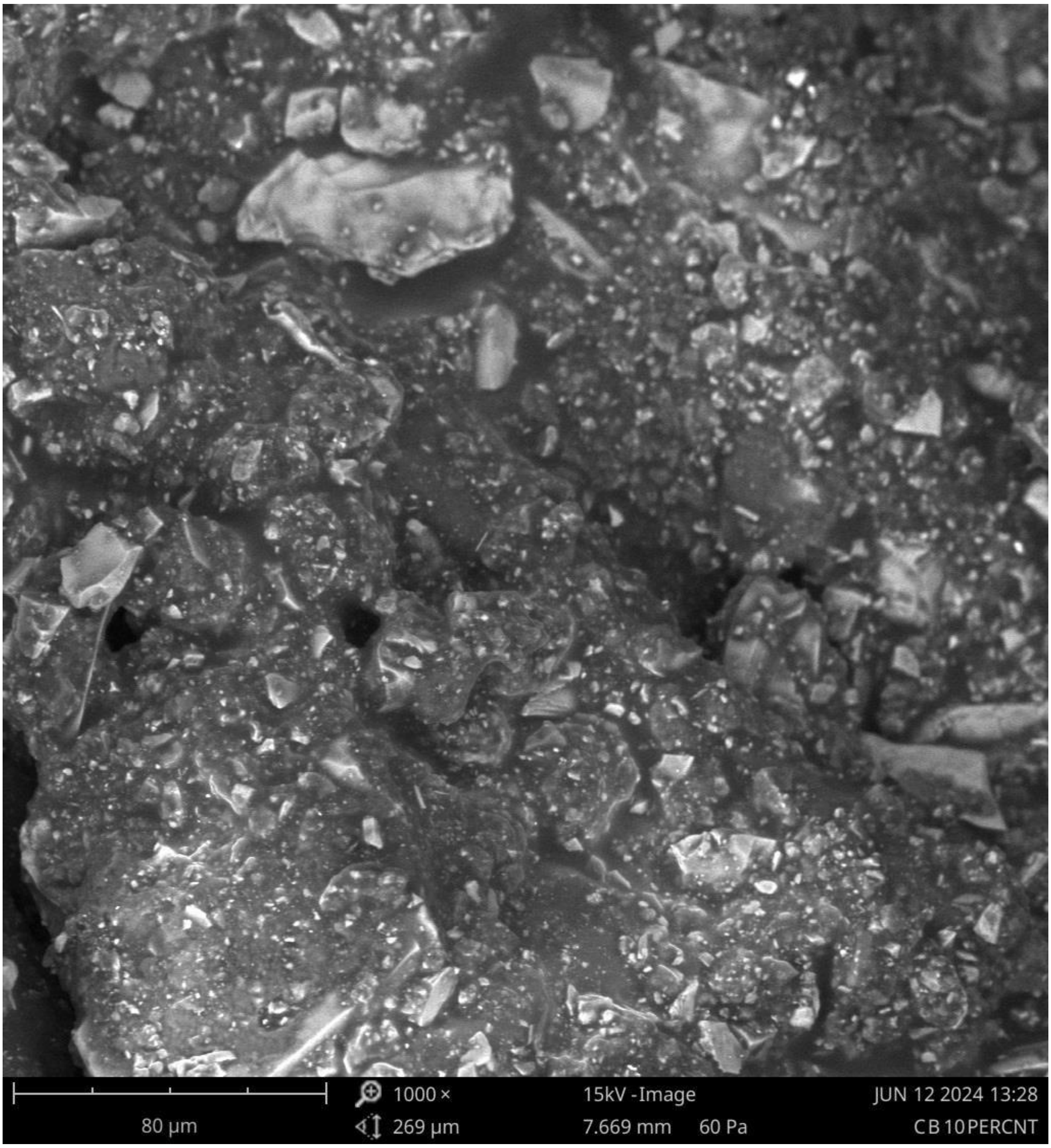

Figure 3f: SEM image for Sample with 10% CD

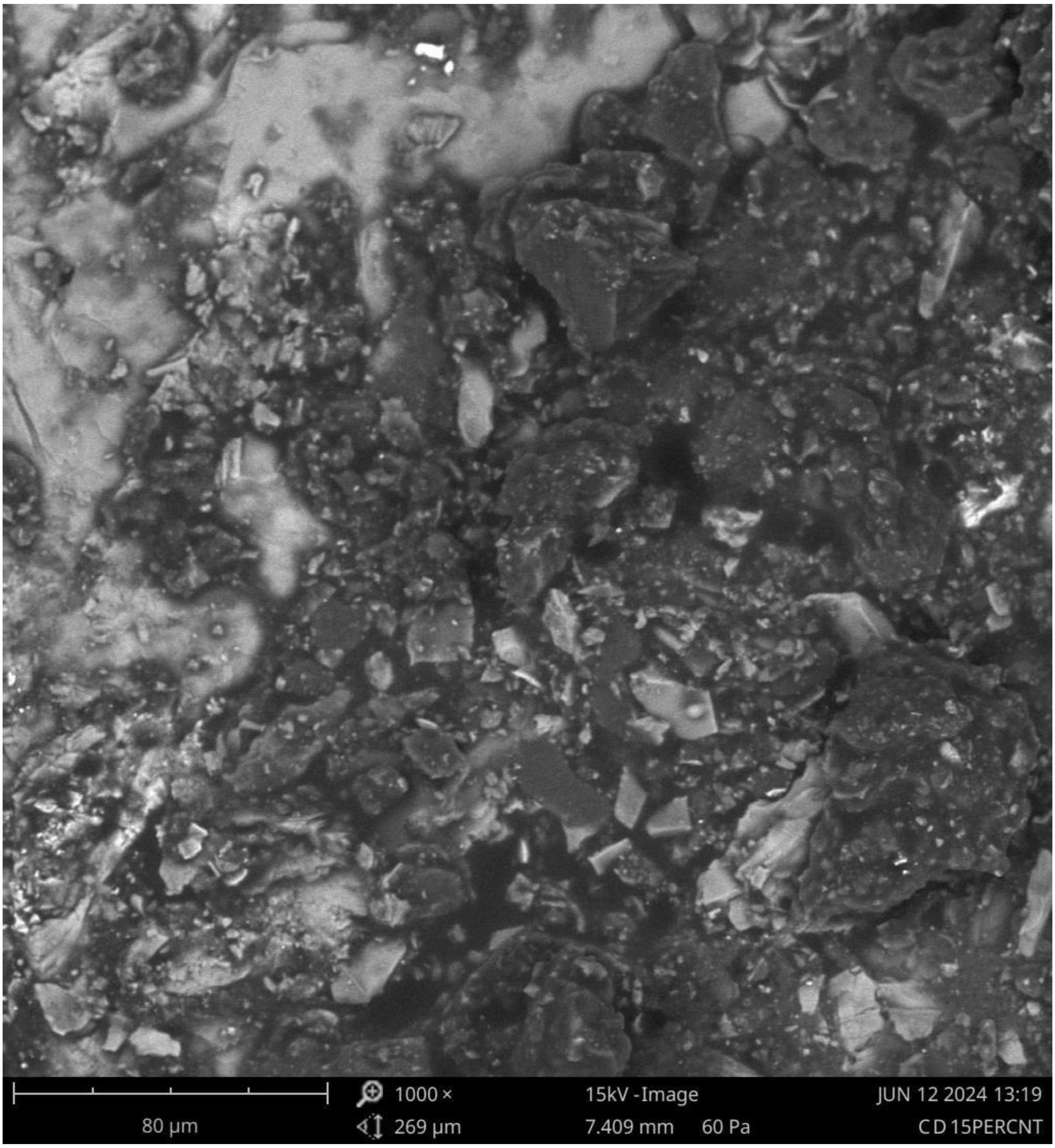

Figure 3g: SEM image for Sample with 15% CD

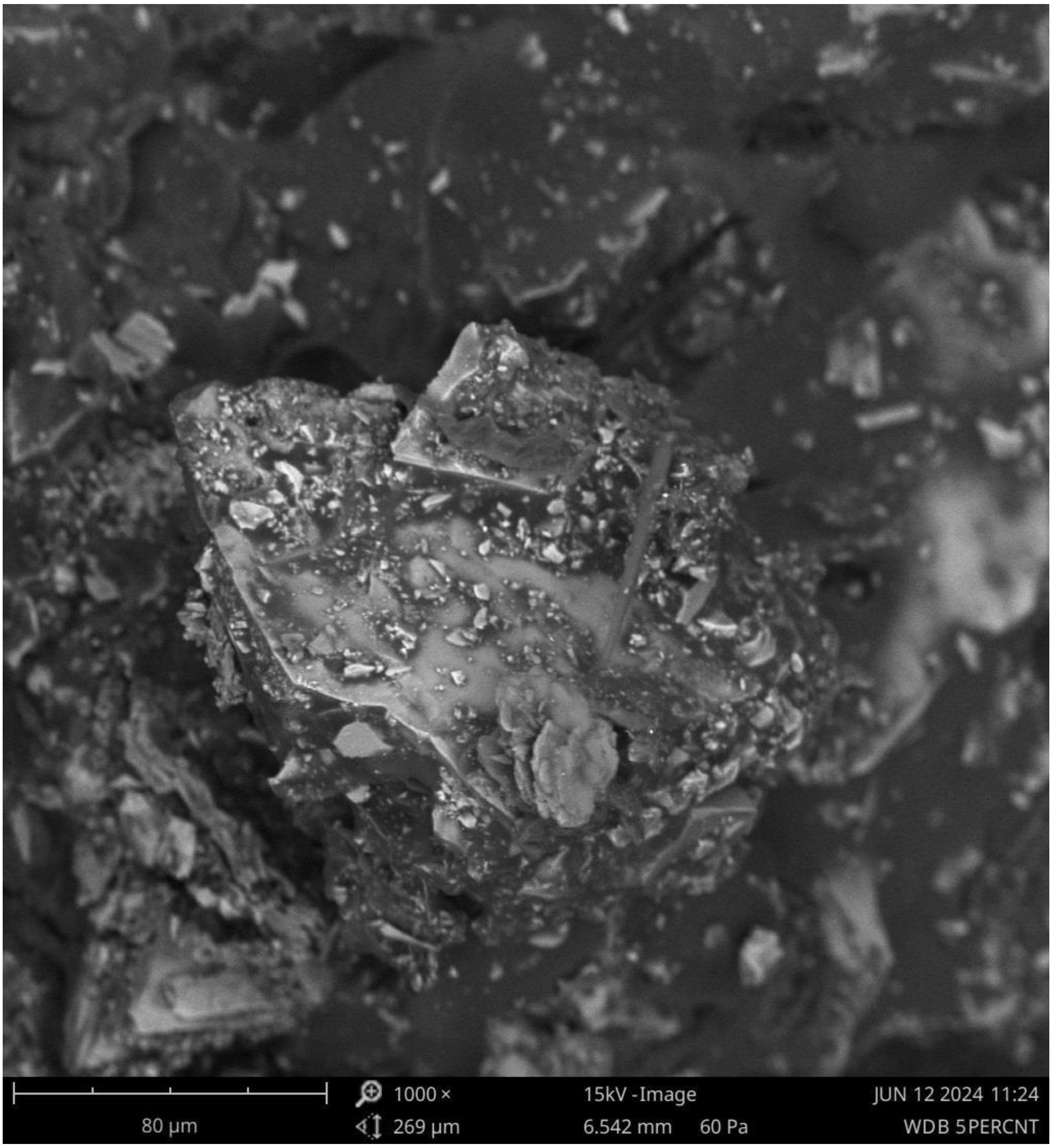

Figure 3h: SEM image for Sample with 5% WDB

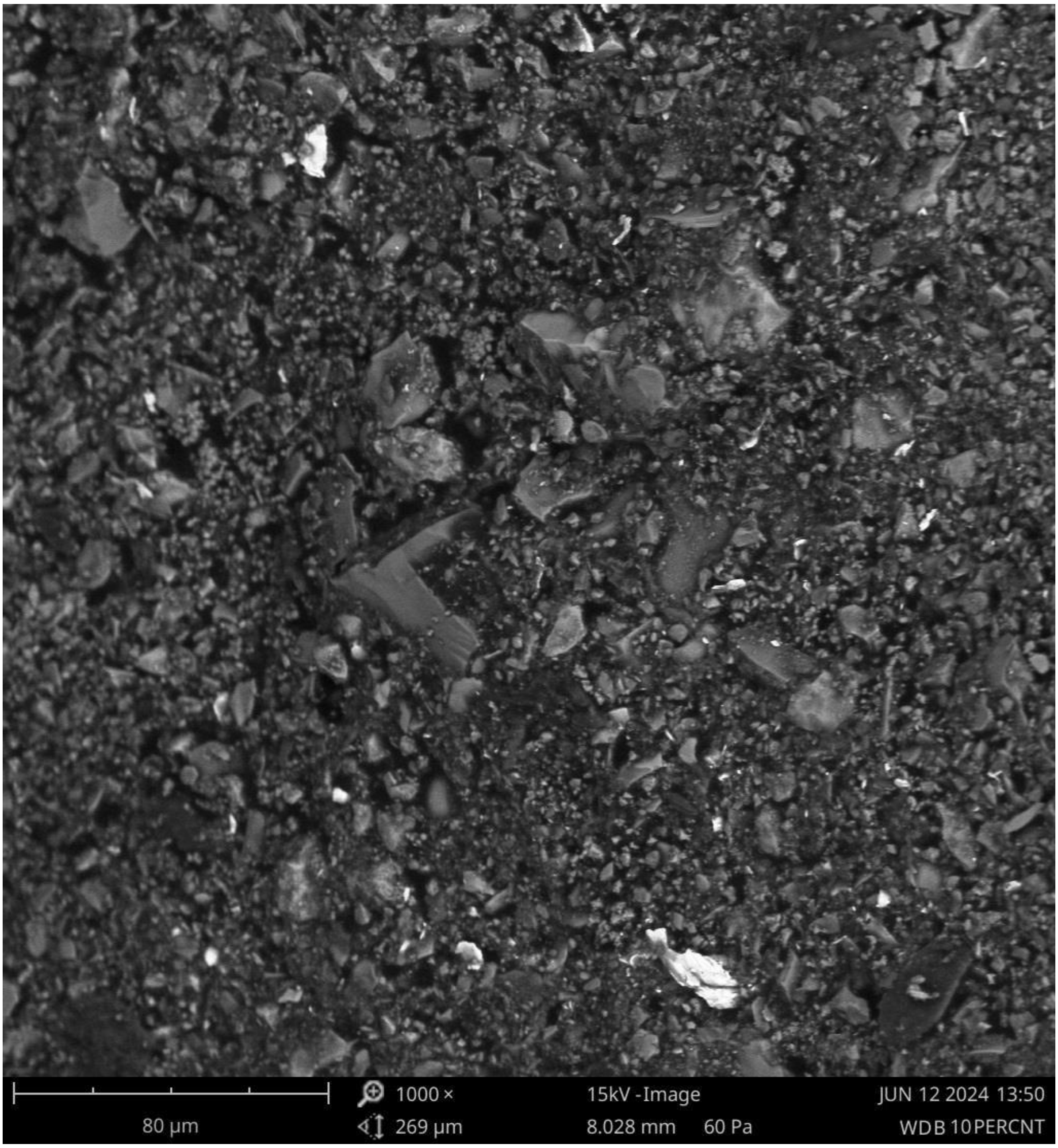

Figure 3i: SEM image for Sample with 10% WDB

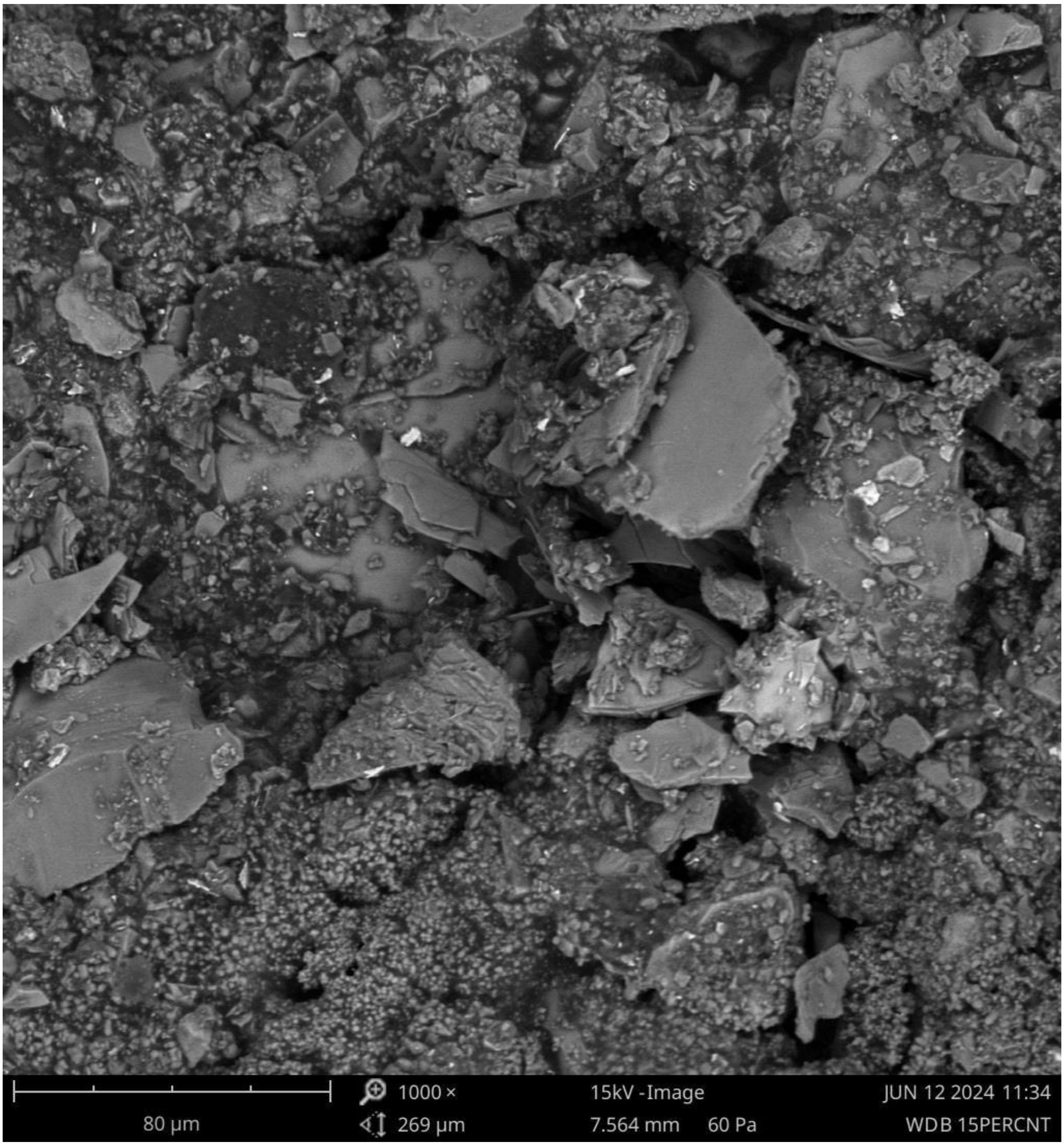

Figure 3j: SEM image for Sample with 15% WDB

Table 1: Atomic Concentration (AC) and Weight Concentration (WC) of Elements in Modified Asphalt Mixture

	CONTROL		CB						CD						DWB					
	0%		5%		10%		15%		5%		10%		15%		5%		10%		15%	
Element Name	AC	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**	**AC**	**WC**
Carbon	83.88	72.41	87.78	73.20	67.65	47.64	60.95	41.14	87.53	74.48	59.76	41.36	67.99	47.03	88.63	78.37	85.00	69.31	79.85	59.84
Silicon	7.31	7.36	6.65	12.96	14.83	24.42	23.82	37.60	4.78	9.51	11.91	19.28	12.26	19.84	1.70	5.02	3.38	9.20	5.58	13.96
Aluminium	2.86	5.54	2.67	7.44	3.29	5.21	2.75	4.95	1.06	4.18	12.14	9.80	6.91	10.74	4.69	4.83	4.06	7.75	6.23	10.91
Sulfur	2.65	5.35	1.15	2.15	2.69	5.05	5.29	4.17	1.83	3.49	4.38	6.81	2.26	5.09	1.63	3.38	1.10	4.16	1.29	4.49
Nitrogen	1.74	5.02	0.77	1.71	4.01	3.30	2.19	3.32	0.85	2.35	1.70	3.84	1.32	4.24	1.33	3.14	1.58	2.89	2.32	3.91
Iron	0.49	1.98	0.41	1.60	0.95	3.10	1.07	1.86	1.85	1.84	1.59	3.67	2.19	4.04	0.52	2.12	2.96	2.82	2.16	1.89

Magnesium	0.85	1.95	0.39	0.67	1.99	2.83	1.15	1.58	0.56	1.28	1.09	3.52	2.84	2.29	0.61	1.21	0.60	1.31	0.92	1.84
Sodium	0.22	0.39	0.17	0.28	1.85	2.49	1.11	1.44	0.69	1.12	2.62	3.48	1.56	2.19	0.36	0.65	0.37	0.98	0.61	1.49
Calcium	0.00	0.00	0.00	0.00	0.71	1.66	0.36	1.14	0.57	0.98	1.70	3.15	1.36	1.80	0.19	0.55	0.55	0.90	0.62	0.93
Phosphorus	0.00	0.00	0.00	0.00	0.83	1.50	0.48	1.08	0.20	0.56	1.66	2.33	0.60	1.07	0.22	0.37	0.35	0.55	0.34	0.48
Potassium	0.00	0.00	0.00	0.00	0.49	1.11	0.45	0.90	0.05	0.12	0.88	1.80	0.33	0.92	0.06	0.21	0.02	0.08	0.09	0.26
Chlorine	0.00	0.00	0.00	0.00	0.49	1.01	0.37	0.82	0.04	0.08	0.54	0.97	0.37	0.75	0.05	0.14	0.02	0.05	0.00	0.00
Titanium	0.00	0.00	0.00	0.00	0.24	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 1, which shows the atomic and weight concentration of the elements present in samples of asphalt. The scanning electron microscopy (SEM) was used to examine the microstructure and dispersion characteristics of the additive in the bitumen. Figure 7a -7j show the SEM images of asphalt modified with particles from Car bumper (CB), compact disc (CD) and Dispenser Water Bottles (DWB) at the optimum percentage of 5%, 10% and 15%, respectively. From the figures, it can be seen that all modifiers were perfectly dispersed within the asphalt bind. By using this analysis, deep insights into the surface morphology and microstructural nature of the specimen could be obtained. Changes in surface characteristics, homogenization and the structural integrity of the material with different percentages (5%, 10%, and 15%) that have been applied using polycarbonate materials as modifiers to the improvement of asphalt matrix were also studied. The addition of polycarbonate materials in the samples is noted to influence the void structure, crack formation, and particle distribution within the asphalt matrix. As the percentage of modifiers increases (from 5% to 15%), there are notable changes in the texture and cohesion of the matrix, as well as the distribution of the modifier within the mixture.

The analysis suggests the atomic concentration, which shows us how many atoms are in a fixed place within the materials. The atomic concentration of carbon and oxygen was also observed to change as modifiers were incorporated into the asphalt mix. The mass concentration of carbon in the asphalt matrix showed a rise at 5% dosage, and the number of oxygen atoms did not change compared with the control. The carbon and oxygen level increased by significantly at 10% addition. The atomic quantity of sulfur and it some other elements found from the asphalt binder was mentioned to reduce by way of comparison. On the other hand, at lower percentages, a decrease in carbon and oxygen concentration was observed with 15% addition showing its highest proportionality signifying greater incorporation of the polycarbonate modifier. Also, it was found that the sulfur atom concentration of asphalt components decreased even more as the proportion of polycarbonate became dominant

From modifier distribution point of view; with 5% addition, the modifier is distributed relatively homogeneously but may not totally destroy the original asphalt network. Slight changes in the surface roughness and particle bonding were detected. The modified mixture at 10% show more homogeneity, as a consequence of the microstructure influence. The interaction of polycarbonate resulted in long cracks and voids filled component-wise, so the binding properties was improved. While at 15% the combination does have fairly mean changes as densification and the surface morphology. Polycarbonate has a greater atomic presence of carbon and oxygen, which indicates that it markedly affects the overall composition and may lead to increased strength in some percentages.

Polycarbonate being added to the asphalt as a polymer modifier can enhance the physical properties of asphalt according to Becker and Mendez (2001). For example, adding some part of polycarbonate into the mixture results in increasing stiffness and resistance against rutting while decreasing temperature susceptibility. From reports, SEM data (especially atomic weight and atomic concentration) provide useful information for a better understanding of how the modifier incorporated with the asphalt mixture, related to its enhanced mechanical performance. In addition, the combined SEM with atomic weight and concentration measurements aids in determining what various polycarbonate dosages do to the microstructure of asphalt as it gives vital insights for an improved optimal dosage level of modifier (Raad and Saboundjian, 1998; Hamid et a1. 2008; Sengoz and Isikyakar 2008; Bhatar)d Mittal 2016). Despite this, predictive models should enable researchers and engineers to design asphalt mixtures with certain distribution of atomic and weight concentration for specific conditions. This solution includes performing performance tests in order to get the best modifier ratios. Meanwhile, a comprehensive testing for fatigue, rutting resistance, and moisture susceptibility is essential to evaluate the impact of different concentrations on mechanical properties (Swami et al (2012; Li and Li 2013; Mazumder et al 2016; Hasan et al 2016; Abdullah et al 2017). Therefore, modifiers must meet specific standards to ensure safety and performance, so manufacturers must consider these concentrations during the development process (Soleymani et al 2004; King et al 1999; Yildirim, 2007; Rahman et al 2013). However, both atomic and weight concentrations significantly impact the mechanical and physical properties of modified asphalt mixtures. Optimizing these factors leads to improved performance characteristics such as stiffness, durability, and resistance to environmental challenges, ultimately enhancing the longevity and reliability of asphalt pavements.

A careful balance is key to achieving the desired properties while maintaining workability and cost-effectiveness (Anderson and Bonaquist, 2012; Santagata et al, 2013; Cardone et al 2014)

IV. Conclusions

In view of this study, it is concluded as follows:

1. Waste polycarbonate (PC) particles improved phase distribution and interfacial adhesion within the asphalt binder, contributing to better structural integrity and reinforcement.
2. The incorporation of polycarbonate enhanced binder stiffness and thermal stability, which are crucial for reducing rutting and deformation under high-temperature conditions.
3. SEM analysis confirmed that polycarbonate particles dispersed effectively within the binder matrix at optimal concentrations, whereas excessive dosage led to phase separation, necessitating dosage optimization.

It is noted that the utilization of waste polycarbonate in asphalt binder supports sustainable road construction practices, reducing plastic waste while enhancing pavement performance, and it is recommended that further studies should explore long-term durability assessments, field performance evaluations, and compatibility with different asphalt grades to optimize polycarbonate-modified asphalt for practical applications.

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