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Investigation of the properties of molybdenum disulfide (MoS_2) reinforced ethylene propylene diene monomer (EPDM) rubbers

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Abstract

In this study, Ethylene Propylene Diene Monomer (EPDM) rubber was compounded with molybdenum disulfide (MoS_2), a solid lubricant, at three different loading levels (25, 55, and 90 phr) using a laboratory-scale 1.5-liter mini Banbury mixer. The effects of MoS_2 incorporation on the mechanical, rheological, and morphological properties of EPDM/MoS_2 composites were systematically investigated. The addition of MoS_2 at varying concentrations increased the torque values while reducing the scorch time. Notably, the incorporation of 90 phr MoS_2 led to a 26.21% increase in Mooney viscosity. Mechanical testing revealed that while tensile strength, elongation at break, elasticity, and tear resistance decreased with MoS_2 addition, abrasion resistance was significantly improved. Based on the overall findings, the EPDM composite containing 55 phr MoS_2 exhibited the most balanced and enhanced performance, making it the most promising candidate for high-performance EPDM-based composite applications.

Keywords: EPDM, molybdenum disulfide (MoS_2), rheology, mechanical properties.

1. Introduction

Ethylene Propylene Diene Monomer (EPDM) rubbers have a wide range of industrial applications due to their high resistance to air, ozone, and chemicals. Properties such as thermal stability, flexibility at low temperatures, and electrical insulation make EPDM indispensable in areas such as automotive seals, insulation components, and hose applications [1-2]. However, despite these advantageous features, certain performance parameters of EPDM, such as mechanical strength, abrasion resistance, and surface friction characteristics, can be limiting factors. To overcome these limitations, the modification of the EPDM matrix with various additives has become a widely studied research topic. In particular, additives such as carbon black, silica, nanoclay, graphene, and metal oxides are frequently used to enhance the mechanical and tribological performance of elastomeric matrices [3-5].

In this study, MoS_2, known for its solid lubricant properties, was utilized with the aim of improving surface friction characteristics. MoS_2 is a notable additive material due to its low coefficient of friction, layered crystal structure, and high thermal stability. Previous studies have demonstrated that MoS_2 acts as both a friction-reducing and reinforcing agent within elastomeric systems [6-8]. In this context, MoS_2 was incorporated into the EPDM rubber at different concentrations, and the surface friction behavior and mechanical properties of the composites were investigated. Considering that the amount of fillers and the quality of dispersion play a decisive

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role in overall performance, critical effects on parameters such as tear resistance and tensile behavior were specifically evaluated.

2. Material and Method

In this study, a commercially available oil-extended EPDM rubber (Keltan 8550) was used as the matrix material, while sulfur, also commercially available, was employed for the vulcanization process. Table 1 presents the proportions of the materials used in the production of EPDM and EPDM/MoS_2 composites in parts per hundred rubber (phr). The MoS_2-reinforced EPDM composites were first compounded using a laboratory-scale mini Banbury mixer. A 1.5-liter laboratory-grade mini banbury was used in the production of EPDM rubber. Activators were first added to the EPDM rubber and the mixture was masticated for 40 seconds. Oil, carbon black, white filler, and MoS_2 were then gradually added and mixed for 40 seconds until the temperature reached 100-105 °C. Once the mixture reached the desired temperature, accelerators such as sulfur, MBT (2-mercaptobenzothiazole), and TMTD (tetramethyl thiuram disulfide) were added, and the mixture was mixed for 40 seconds until it reached 110-115 °C. Rheometer tests were conducted in accordance with the ASTM D5289 standard at 200 °C for 5 minutes. The test sheets were obtained by vulcanizing the mixtures at 180 °C for 20 minutes using a press. Tensile tests were performed in compliance with the ASTM D638 standard. The tests were conducted on a Zwick brand tensile testing machine at a crosshead speed of 200 mm/min. Permanent deformation (compression set) tests were carried out according to the DIN 53517 standard at 100 °C for 22 hours under 25% compression. Hardness measurements were performed according to the DIN 53505 standard, and the results were expressed in Shore A units. Density tests were conducted based on the Archimedes principle following the ISO 1183 standard.

Table 1. Formulations of EPDM Rubber

	EPDM	EPDM/25MoS_2	EPDM/55MoS_2	EPDM/90MoS_2
EPDM	100	100	100	100
Carbon Black	50	50	50	50
White Filler	20	20	20	20
Oil	40	40	40	40
Zinc Oxide	4	4	4	4
Stearic Acid	2	2	2	2
Sulphur	1	1	1	1
MBT	0.5	0.5	0.5	0.5
TMTD	1	1	1	1
Molybdenum Disulfide (MoS_2)	0	25	55	90

3. Results and Discussion

The rheometer test results of the prepared EPDM rubber and MoS_2-reinforced EPDM composites, including important rheological parameters such as minimum and maximum torque (ML and MH), scorch time (ts_2), and optimum cure time (t_{90}), are presented in Table 2. In Table 2, the Mooney viscosity values—representing the resistance to flow—and the Cure Rate Index (CRI), defined as the curing rate index, are also provided for both EPDM rubber and EPDM/MoS_2 composites. The Mooney viscosity value of pure EPDM rubber was measured as 64.1 MU, while the addition of 25 phr, 55 phr, and 90 phr of MoS_2 led to significant increases in viscosity, yielding values of 69.3, 75.3, and 80.9 MU, respectively. Depending on the increasing MoS_2 content, the Mooney viscosity values increased by 8.11%, 17.4%, and 26.2%. The strong interaction between the polymer and the filler slowed down the mobility of the polymer chains; therefore, the high loading levels of MoS_2 significantly increased the viscosity of the EPDM compounds. When the CRI results which represent the difference between t_{90} and ts_2, were evaluated, it was observed that the addition of MoS_2 filler to EPDM rubber reduced the CRI values. For the compound containing 55 phr MoS_2, the decrease in CRI was calculated as 33.38%. A proportional increase in hardness was also observed with the increasing MoS_2 content, consistent with the results reported in previous studies in the literature.

Table 2. Rheological and Physical Test Results

	EPDM	EPDM/25MoS$_2$	EPDM/55MoS$_2$	EPDM/90MoS$_2$
		Rheological Results		
ML (dNm)	1.03	1.30	1.60	1.73
MH (dNm)	12.72	14.23	15.54	17.43
CE=MH-ML	11.69	12.93	13.94	15.7
t_{s2} (min)	0.39	0.34	0.30	0.31
t_{90} (min)	1.17	1.21	1.33	1.48
CRI, min	128.2	114.9	97.1	85.4
		Viscosity Results		
Mooney Viscosity, (MU)	64.1	69.3	75.3	80.9
		Shore Hardness and Density Results		
Density (g/cm^3)	1.08	1.15	1.23	1.32
Hardness (Shore A)	59	65	73	75

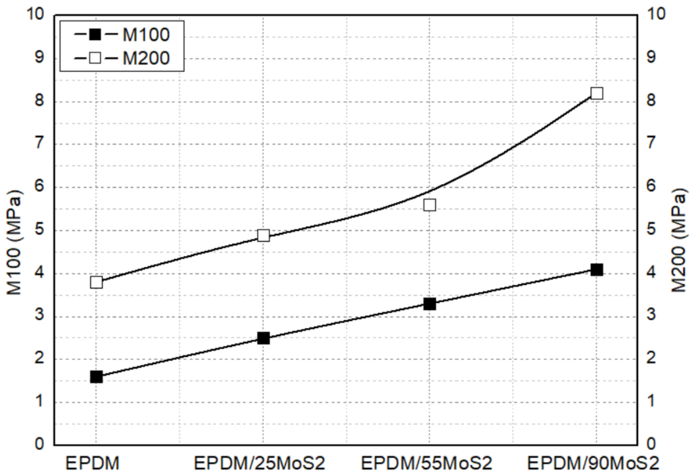


Fig. 1. M100 and M200 Modulus Values of EPDM and MoS_2-Reinforced EPDM Composites**.**

Figure 1 compares the M100 (100% elongation modulus) and M200 (200% elongation modulus) values of pure EPDM and MoS_2-reinforced EPDM composites. As the MoS_2 content increases, a noticeable rise is observed in both M100 and M200 values. This indicates that MoS_2 exerts a reinforcing effect within the elastomer matrix and enhances the material's resistance to deformation. In the pure EPDM sample, the M100 value is approximately 2.5 MPa, while in the composite containing 90 phr MoS_2, it reaches about 4 MPa. Similarly, the M200 value increases from approximately 5 MPa in pure EPDM to around 8.5 MPa in the 90 phr MoS_2 composite. These increases demonstrate that MoS_2 acts as a physical barrier between the elastomer chains, improving load transfer and limiting chain mobility, thereby enhancing rigidity. The pronounced increase in the M200 value, in particular, suggests that MoS_2 becomes more effective at higher elongation levels. This supports the existence of a filler–matrix interaction that allows the material to resist deformation more strongly under progressive strain. Consequently, the addition of MoS_2 not only improves the surface friction characteristics but also significantly enhances the mechanical rigidity and load-bearing capacity of the elastomer.

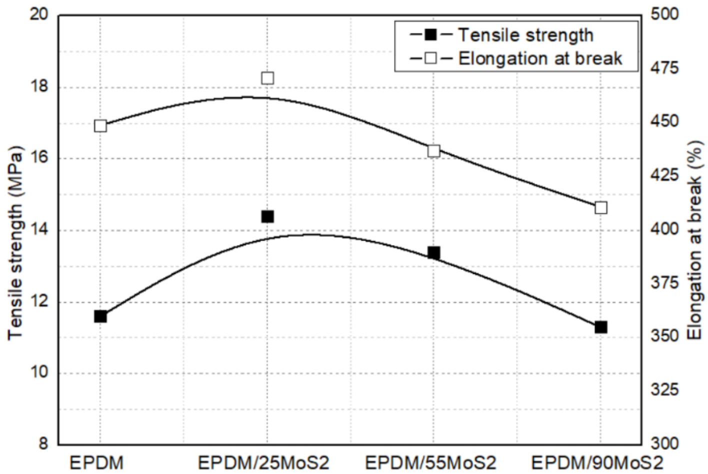


Fig. 2. Tensile Strength and Elongation at Break Values of EPDM and MoS_2-Reinforced EPDM Composites.

Figure 2 compares the tensile strength (MPa) and elongation at break (%) of pure EPDM and composites containing 25, 55, and 90 phr of MoS_2. The results indicate that the addition of MoS_2 has a dual effect on the mechanical performance. In the pure EPDM sample, the tensile strength is approximately 11.5 MPa, which increases to about 14.5 MPa with the addition of 25 phr MoS_2. This increase demonstrates that a low content of MoS_2 is homogeneously distributed within the elastomer matrix, effectively supporting load transfer and delaying crack propagation under tensile stress. However, when the MoS_2 content is increased to 55 phr and particularly to 90 phr, a significant decrease in tensile strength is observed. In the composite containing 90 phr MoS_2, the tensile strength drops to approximately 11 MPa. This indicates that a high filler loading disrupts the matrix continuity, leading to stress concentration and brittleness. A similar trend is observed for elongation at break. In pure EPDM, the elongation at break is around 450%, which increases to 475% with 25 phr MoS_2. However, at higher MoS_2 contents, these values decrease to 435% and 415%, respectively. This decline suggests the formation of filler agglomerates within the matrix, restricting the mobility of the elastomer chains and consequently reducing the elastic deformation capacity. Overall, low levels of MoS_2 reinforcement provide beneficial effects on both strength and elongation, whereas higher filler contents result in stiffening and increased brittleness.

Figure 3 illustrates the effect of MoS_2 addition on two important mechanical parameters of the EPDM matrix: compression set and tear strength. These data are critical for evaluating both the elastic recovery capacity of the composites and their resistance to crack propagation. In the pure EPDM sample, the compression set is approximately 21%. With the addition of MoS_2, this value decreases to around 13.5% at 25 phr, then increases to approximately 16% at 90 phr. This trend indicates that low levels of MoS_2 enhance the elastomer's recovery capability and limit plastic deformation. This improvement can be attributed to the formation of a network of MoS_2 particles within the matrix that supports load transfer and facilitates elastic recovery. However, at higher filler contents, particle agglomeration diminishes this beneficial effect, resulting in increased compression set. Tear strength, which is approximately 40 N/mm in pure EPDM, and slightly decreases to about 36 N/mm at 90 phr. This observation suggests that MoS_2 can enhance tear resistance through interfacial reinforcement and crack propagation inhibition, but excessive filler content may lead to brittleness, limiting this effect. Overall, these results indicate that MoS_2, when used in appropriate proportions, can reduce compression set and improve elastic behavior while strengthening mechanical integrity against crack propagation. However, exceeding the optimal filler content weakens the filler–matrix interaction and leads to a decline in mechanical performance.

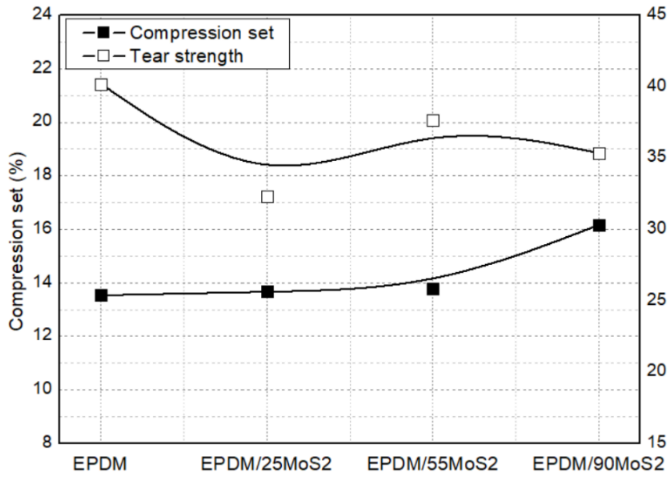


Fig. 3. Compression Set and Tear Strength Values of EPDM and MoS_2-Reinforced EPDM Composites

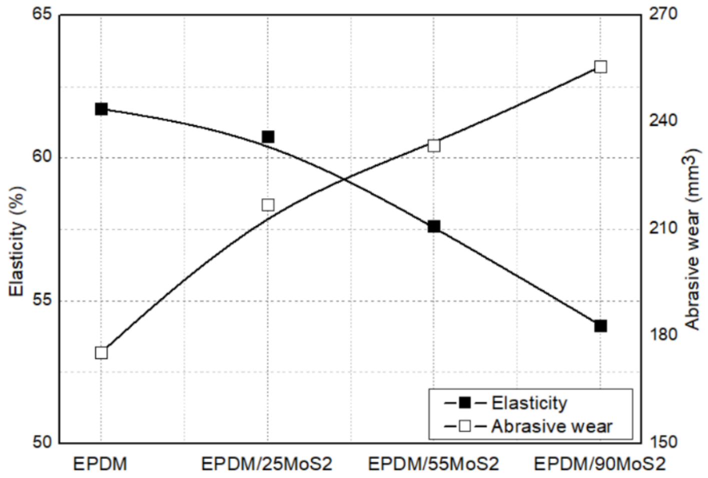


Fig. 4. Elasticity and Abrasive Wear Values of EPDM and MoS_2-Reinforced EPDM Composites

Figure 4 evaluates the effects of MoS_2 addition on the elastic behavior and abrasive wear of EPDM composites. The results indicate that MoS_2 has opposing effects on these two properties: as the filler content increases, elasticity decreases, while abrasive wear increases. In pure EPDM, the elasticity is approximately 61.7%, which decreases to 54% in the composite containing 90 phr MoS_2. This reduction can be attributed to the restriction of free movement of the elastomer chains by MoS_2. At high filler loadings, particle agglomeration within the matrix further limits chain mobility, weakening the elastic response. This demonstrates that the rigid and structural nature of MoS_2 adversely affects the recovery capacity of the elastomer after deformation. Similarly, abrasive wear increases with higher MoS_2 content. The wear volume of pure EPDM is approximately 175 mm^3, whereas it reaches 255 mm^3 in the composite containing 90 phr MoS_2. This observation indicates that MoS_2 negatively influences the material's behavior under abrasive loading. The hard filler particles induce localized stress concentrations on the material surface, accelerating the formation of microscopic cracks and consequently reducing wear resistance. These results suggest that while MoS_2 addition may have potential benefits in static applications or systems where friction control is prioritized, it can impose limiting effects on elasticity and wear resistance in applications subjected to elastic and dynamic loads. High filler content, in particular, leads to performance reductions characterized by decreased elasticity and increased wear.

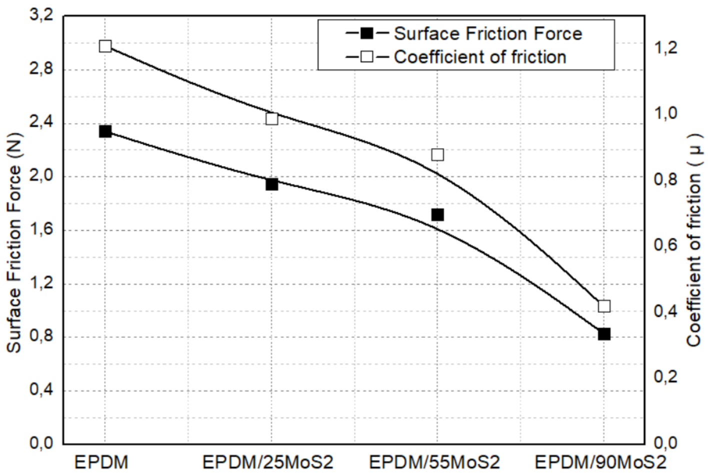
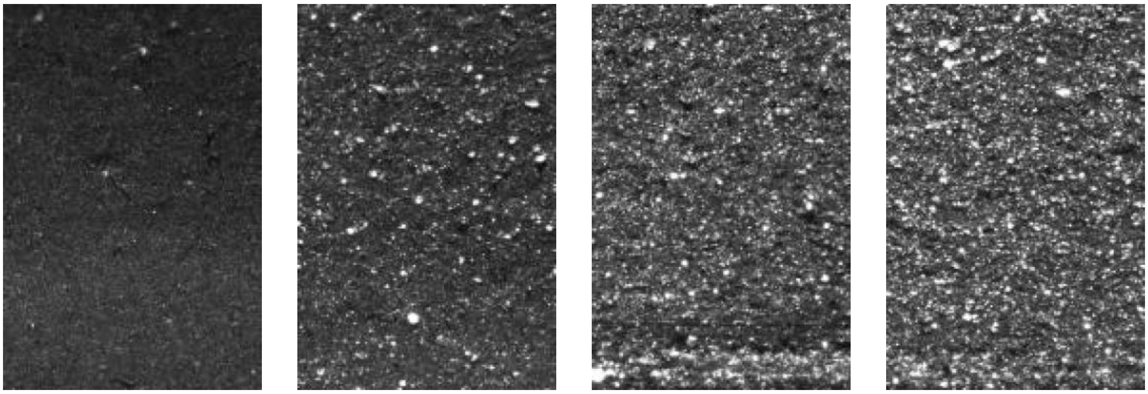


Fig. 5. Surface Friction Force and Coefficient of Friction Values of EPDM and MoS_2-Reinforced EPDM Composites.

Figure 5 illustrates the effect of MoS_2 content on the surface friction force and coefficient of friction of EPDM/MoS_2 composites. The results clearly show that as the MoS_2 content increases, both the surface friction force and the coefficient of friction significantly decrease. In the pure EPDM sample, the surface friction force is approximately 2.4 N, and the coefficient of friction is around 1.0. These values indicate that the natural structure of the elastomer exhibits high surface interaction and adhesion tendencies. However, with increasing MoS_2 content, these values steadily decline. At 25 phr MoS_2, the friction force decreases to about 2.0 N and the coefficient of friction to 0.85. For 55 phr MoS_2, the corresponding values are 1.5 N and 0.65, respectively. In the composite containing 90 phr MoS_2, the friction force drops to 0.3 N and the coefficient of friction to 0.35. This substantial reduction is attributed to the solid lubricant properties of MoS_2. Its layered crystal structure reduces interfacial shear resistance, minimizing friction in tribological systems. Well-dispersed MoS_2 particles within the elastomer matrix form a microscopic film on the surface, providing molecular-level lubrication during sliding.



(a) EPDM (b) EPDM/25MoS_2 (c) EPDM/55MoS_2 (d) EPDM/90MoS_2

Fig. 6. Dispersion Images of EPDM and EPDM/MoS_2 Composites.

Table 3. Dispersion Test Results of EPDM and EPDM/MoS_2 Composites

	X	Y	Z	White area, %	Dispersion, %	Average Agg. Size, [µm]	Agg. Size Std. Dev [µm]
EPDM	4.65	9.96	92.7	2.53	97.47	2.62	2.26
EPDM/25MoS_2	1.00	8.52	61.1	13.61	86.39	3.64	4.29
EPDM/55MoS_2	1.00	1.67	11.7	30.88	69.12	4.09	6.73
EPDM/90MoS_2	1.00	1.00	-	36.45	63.55	4.24	7.64

Figure 6 and Table 3 present the dispersion images and results obtained from the dispersion tests of EPDM and MoS_2-reinforced EPDM composites at various filler contents. As shown in Table 3, the filler materials in the structure of EPDM and EPDM/MoS_2 composites were found to be dispersed at levels ranging from 63% to 97%. The average particle size of the dispersed fillers ranged from 2.62 to 4.24 µm, while the white area, representing undispersed regions, ranged from 2.53% to 36.45%. Considering the white area, dispersion rate, and average filler size, the best results were achieved in the EPDM composite containing 25 phr MoS_2. The dispersion images and image analysis data indicate that up to 25 phr MoS_2, the additive is relatively homogeneously distributed within the matrix; however, at 55 phr and higher contents, significant particle agglomeration and structural heterogeneities are observed. This demonstrates that the beneficial effects of MoS_2 are valid only up to a certain filler threshold, beyond which structural weaknesses become predominant. The decline in dispersion quality is a primary reason for the observed mechanical property losses. When used in high amounts, MoS_2 tends to agglomerate, leading to weak interfacial bonding with the elastomer matrix.

4. Conclusion

In this study, the effects of MoS_2 addition on EPDM-based elastomer systems were comprehensively analyzed. The incorporation of MoS_2 increased the EPDM system's viscosity, limiting processability, while simultaneously reducing cure times and accelerating vulcanization kinetics. From a mechanical performance perspective, low filler contents, particularly 25 phr, improved critical properties such as tensile strength, elasticity, and compression set. However, as the filler content increased, dispersion quality deteriorated, leading to agglomeration, which in turn caused reductions in tear strength, elongation at break, and wear resistance. MoS_2 significantly reduced surface friction force and coefficient of friction, enhancing the sliding behavior of the EPDM matrix. This property renders MoS_2 a functional additive in dynamic applications where low friction is required. Overall, these findings indicate that MoS_2 provides both structural and functional enhancements to EPDM systems; however, its effectiveness is highly dependent on filler content and dispersion quality. When appropriate proportions and process control are applied, MoS_2 can serve as a functional modification agent in high-performance technical applications of EPDM-based elastomers.

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