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Effects of Gold Mine Tailings as an Additive on the Tribological Performance of Lubricating Polyurea Grease

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Abstract: Lubricating greases with varying proportions of gold mine tailings or SiO_2 as additives were prepared, and their friction and wear performance were evaluated using a four-ball tribometer. Scanning electron microscopy and three-dimensional surface profilometry were employed to analyze the thickener properties and wear patterns on the steel balls. The results indicated that the addition of gold mine tailings significantly improved the friction-reducing and wear-resistant properties of the base grease compared with SiO_2. At the optimal concentration of 3 wt%, the addition of gold mine tailings reduced the coefficient of friction and wear scar diameter of the base grease by 43.2% and 21.1%, respectively, yielding the best performance among the 11 tested samples. Further analysis revealed that silicate and calcium carbonate particles in the gold mine tailings were deposited on the surface, forming a protective layer. This layer, along with the grease film, contributed to substantial reductions in both friction and wear.

Keywords: gold mine tailings; Lubricating greases; friction performance

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1. Introduction

Quartz vein-type gold mines represent one of the most significant gold deposit types in China, accounting for over 50% of both gold deposits and reserves in the country. The flotation process used to extract gold concentrates from these ores generates substantial amounts of tailings. Currently, most of these tailings are stored directly in tailings ponds, leading to environmental issues such as acid rock drainage, dust emissions, and surface runoff. These problems significantly affect agricultural land, human health, and ecosystems [1]. Therefore, tailings should not be viewed as inert, harmless materials but rather as materials that require careful management to mitigate their social and environmental impacts.

Gold mine tailings primarily consist of SiO_2, silicates, and aluminosilicates, making them a valuable geological resource that can be recycled into high-value-added products [2–5]. For instance, Ahmed et al. [4] utilized gold mine tailings as a substitute for traditional quartz sand in the production of ultra-high-performance concrete. Their findings revealed that concrete created with gold mine tailings was not only more cost-effective but also eco-friendlier and more durable than concrete created with quartz sand [4]. Similarly, Hu et al. [5] developed slow-release silicon fertilizers from iron tailings through solid-phase sintering, which improved crop growth performance. However, producing these products requires the purification and separation of tailings to obtain high-purity SiO_2, leading to a complex process and high production costs. Thus, exploring new methods for the high-value utilization of tailings remains essential [6].

Lubricating greases, referred to as greases hereinafter, are composed of base oils, thickeners, and additives. The literature highlights the application of SiO_2 as an additive in greases. For instance, Liu et al. [7] added nano-SiO_2 to grease and discovered that the colloidal stability, structural strength, and shear resistance of the grease improved with an increase in SiO_2 content. Chen et al. [8] incorporated nano-SiO_2 into lithium-based grease and found that it significantly enhanced both the extreme pressure and friction-reducing properties of the grease. The optimal addition increased the P_B and P_B values of the base grease by 63.5% and 98.4%, respectively. Shuvalov Sergey A. et al. [9] incorporated SiO_2 as an additive into composite lithium-based grease, significantly improving both its wear and scratch resistance. Khairul et al. [10] developed a food-grade grease using fumed SiO_2 as a thickener, which exhibited better consistency, oil separation, and aging resistance than commercial food-grade greases in various performance tests. Jolanta et al. [11] added SiO_2 as a modifier to petroleum-based grease, significantly enhancing its fatigue resistance and rheological properties. These findings indicate that the inclusion of SiO_2 as an additive can enhance the wear and friction-reducing properties of greases while improving their thickening effectiveness and rheological characteristics.

Other silicates and aluminosilicates have also been reported as additives in greases. For instance, Xia et al. [12] incorporated modified kaolin into a polytetrafluoroethylene grease and found that it improved both the wear resistance and contact resistance of the grease. Qu et al. [13] utilized silicates as a modifier to create a composite titanium-based grease with self-healing properties. Their study revealed that the self-healing mechanism occurs when the modifier particles form an adsorbed film on the surface of the steel substrate through a series of physicochemical reactions, effectively repairing the wear surfaces.

The literature reviewed above indicates that incorporating SiO_2 and silicates/aluminosilicates into greases improves their friction-reducing, wear-resistant, and thickening properties. Given that gold mine tailings primarily consist of SiO_2 and silicates/aluminosilicates, in the present study, we explored the use of gold mine tailings as an additive in greases. Specifically, we investigated their effects on the friction and lubrication performance, as well as the underlying lubrication mechanisms, comparing these effects with those observed in greases containing equivalent amounts of SiO_2. In contrast to processes that produce silica fertilizers or flocculants from tailings, utilizing tailings as grease additives eliminates the need for separation and purification. This approach facilitates the value-added utilization of tailings, offering a significantly valuable pathway.

2. Experimental

2.1. Treatment of Gold Mine Tailings

Gold mine tailings were sourced from Shaanxi Geological and Mineral Sixth Geological Team Co., Ltd., Xi'an, China. Before use, the tailings were dried to remove moisture and were passed through a standard 140-mesh sieve (aperture: 0.105 mm) to eliminate larger particles. The sieved tailings were then ground for 3 h at a speed of 300 r/min, yielding a fine material that was subsequently used as an additive in the grease.

2.2. Preparation of Lubricating Greases

An appropriate amount of base oil KN4016 was added to a reaction kettle and heated to 90 °C. The calculated thickening agents (isocyanate and dodecylamine) were then introduced, and the mixture was stirred at a constant temperature for 60 min. Subsequently, the temperature was increased to 220 °C for 60 min of high-temperature refining, resulting in the formation of PG. This grease served as the base grease and was cooled to 200 °C. Next, the sieved and ground tailings or SiO_2 were incorporated into the grease, and the mixture was thoroughly stirred to ensure even dispersion. Once a homogeneous blend

was achieved, the mixture was allowed to cool naturally to room temperature. Finally, it was processed through a three-roll mill three times, producing greases with mass fractions of 1%, 2%, 3%, and 5% of either tailings or SiO_2. The base grease is denoted as PG, while the greases with added tailings are labeled as PG-X% KF, and those with added SiO_2 are labeled as PG-X% SiO_2.

2.3. Characterization of Greases

The dropping point of the greases with added tailings or SiO_2 was measured using a dropping point tester covering a wide temperature range, in accordance with the GB/T 3498-2008 standard [14]. To assess evaporative loss, an evaporative loss tester was used, following the GB 7325-1987 standard [15]. The cone penetration of the greases was determined using a cone penetration tester, which also facilitated the evaluation of their consistency grade, in line with the GB/T 269-1991 standard [16]. Additionally, the water washout loss of the greases was measured using a water washout tester, as per the SH/T 0109 standard [17].

2.4. Tribological Performance Testing

Friction and wear tests were performed using a four-ball tribometer manufactured by Xiamen Tenkey Automation Co., Ltd., Xiamen, China. In each test, the upper ball, composed of GCr15 steel (12.7 mm in diameter, hardness of 59-61 HRC), was pressed against three fixed lower balls of the same material and specifications. The tests were conducted under a load of 392 N at a rotational speed of 1200 r/min for a duration of 60 min. For each test, 10 g of grease was added to the oil reservoir to ensure that the contact points on the steel balls were fully submerged. The coefficient of friction (COF) was measured three times, and the average value was calculated. The wear scar diameter (WSD) was measured using an optical microscope; three measurements were taken, and the average value was calculated. Additionally, wear marks on the steel balls were observed and measured using a Keyence VHC-1000 microscope, which was manufactured by Xiamen Tenkey Automation Co., Ltd., Xiamen, China.

3. Results and Discussion

3.1. Characterization of Tailings and SiO_2 Particles

The crystalline structure and chemical composition of gold mine tailings and SiO_2 particles were characterized using X-ray diffraction (XRD). As shown in Figure 1a, the primary diffraction peaks of the gold mine tailings—specifically (100), (101), (102), (110), (202), (200), (112), (201), and (203)—closely resemble those of the standard SiO_2 diffraction pattern, indicating that SiO_2 was the dominant component of the tailings. Additionally, the XRD analysis revealed the presence of minor quantities of illite, chlorite, potassium feldspar, plagioclase, and iron dolomite in the tailings. Figure 1b,c show scanning electron microscopy (SEM) images of the SiO_2 and tailings, respectively. The SiO_2 particles exhibited a relatively uniform size distribution, whereas the tailings consisted of both large particles and a considerable amount of finer materials.

3.2. Effects of the Additive Amount on the Physicochemical Properties of Greases

Tailings or SiO_2 powder were added to the base PG after reheating at mass fractions of 1%, 2%, 3%, 4%, and 5%. Table 1 presents the basic physicochemical properties of the greases containing tailings and SiO_2. The cone penetration of the base grease decreased with the addition of both materials due to their thickening effect. As the amount of additive increased, the cone penetration continued to diminish. Specifically, the addition of 5% tailings reduced the cone penetration of the base grease to 0.86 times its original value,

while the addition of 5% SiO_2 reduced it to 0.95 times the original value, indicating that tailings had a more pronounced thickening effect. Furthermore, the water washout loss rates of the greases with added tailings and SiO_2 decreased as the amount of additive increased. The greases containing tailings exhibited lower loss rates than those with SiO_2, suggesting that the tailings-modified greases had a higher viscosity and were less prone to water loss. Under prolonged high-temperature conditions, oil evaporation significantly affects grease performance; thus, a lower oil evaporation loss rate is preferable. The greases formulated in this study exhibited low oil evaporation loss rates, all of which meet national standards. Table 1 also indicates that adding tailings and SiO_2 to the base grease had minimal impact on the dropping point, with both formulations maintaining relatively high values. The dropping points of the greases containing tailings were comparable with that of the base grease, while those of the greases with SiO_2 were increased. Additionally, the incorporation of both tailings and SiO_2 increased the PB of the grease, improving its load-carrying capacity. Notably, the greases with 3% tailings and 5% SiO_2 exhibited the highest PB value of 588 N.

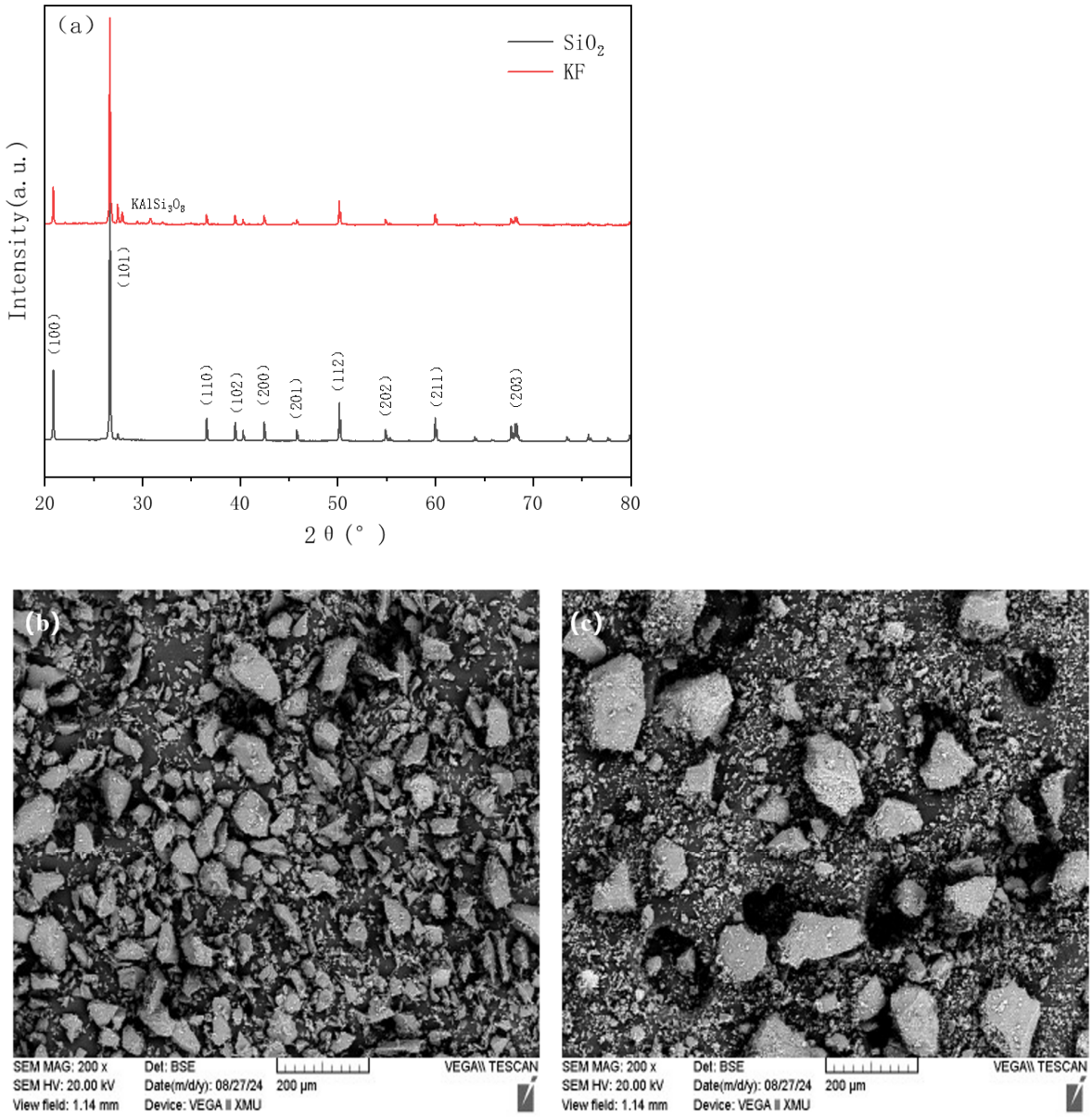


Figure 1. (**a**) XRD patterns of tailings and SiO_2 particles. (**b**) SEM image of SiO_2 particles. (**c**) SEM image of tailings.

Table 1. Physicochemical properties of greases containing tailings and SiO_2.

Additive Level	National Lubricating Grease Institute (NLGI) Grade	Cone Penetration (0.1 mm)	Dropping Point (°C)	Oil Evaporation Loss Rate (%)	Water Washout Loss Rate (%)	P_B/N
PG	#1	338	333	0.120	6.70	196
1% KF	#1	323	330.3	0.236	6.30	392
2% KF	#1	319	336.3	0.120	4.80	441
3% KF	#1	315	333.3	0.350	4.72	588
4% KF	#1	312	332.3	0.186	3.30	392
5% KF	#2	292	336.3	0.348	3.13	392
1% SiO_2	#1	333	334.3	1.680	6.33	196
2% SiO_2	#1	330	337.0	0.240	5.80	235
3% SiO_2	#1	328	339.7	1.900	5.26	235
4% SiO_2	#1	326	337.3	0.156	4.50	491
5% SiO_2	#1	322	>343	0.230	4.24	588

3.3. Friction Performance of Greases

The friction properties of the greases were evaluated using a four-ball tribometer. Figure 2a presents the COF values for PGs incorporating different proportions of gold mine tailings or SiO_2. The COF for the tailings-modified grease formulation initially increased before decreasing, reaching a minimum value of 0.054 at a tailings content of 3%, representing a 43.2% reduction compared with the base grease. This behavior is attributed to the concurrent release of the base oil from the grease, which allowed the tailings particles to migrate from the colloidal structure to the friction surface. This migration increased the load-carrying capacity of the grease film and facilitated a transition from sliding to rolling friction, thereby reducing the friction [18]. In contrast, the COF for the SiO_2-containing grease formulation was lowest (0.090) at an additive level of 1%, corresponding to a 5.3% reduction from the base grease. As the SiO_2 content increased beyond this level, the average COF increased. This trend may be due to the enhanced structural integrity of the grease as the additive concentration increased, causing the base oil to become more tightly confined within the system, making it more difficult to release. Conversely, greases with lower additive concentrations had reduced structural strength, facilitating oil separation and achieving effective lubrication [7]. Figure 2b shows the WSDs of the PGs with varying proportions of gold mine tailings or SiO_2. The WSD results align with the COF findings. For the tailings-modified grease formulation, the WSD initially decreased with an increase in tailings content, reaching a minimum at 3% before increasing. Conversely, for the SiO_2-modified grease formulation, the WSD increased with the SiO_2 concentration.

To better understand the observed trends, we analyzed the wear surfaces of the steel blocks to investigate the differences in anti-wear performance among greases with varying additive concentrations. As shown in Figure 3, the wear on the steel ball surface was severe, with wear scars appearing in a regular circular shape. Additionally, the surface exhibited numerous large pits, grooves, and burn marks. When SiO_2 was used as an additive in the grease at a doping level of 1%, the wear observed was relatively minor. The wear scars exhibited significantly reduced serrated edges on either side, although shallow pits and burn marks were still evident, as shown in Figures 2b and 3b. The average WSD was 682 μm, representing a 4.6% reduction compared with the original PG. However, as the SiO_2 particle content increased, the average WSD increased, as reflected by the formation of deeper grooves. This suggests that SiO_2 particles were effectively dispersed within the grease at a concentration of 1%. Exceeding this concentration led to particle agglomeration, which caused abrasive wear on the friction surfaces, increasing the overall wear. Furthermore, with an increase in the concentration, the grease exhibited higher structural strength, tightly binding the base oil within the system and making it

more difficult for the oil to be released. In contrast, at lower concentrations, the grease facilitated the formation of an oil film through the precipitation of the base oil, reducing the COF [19,20].

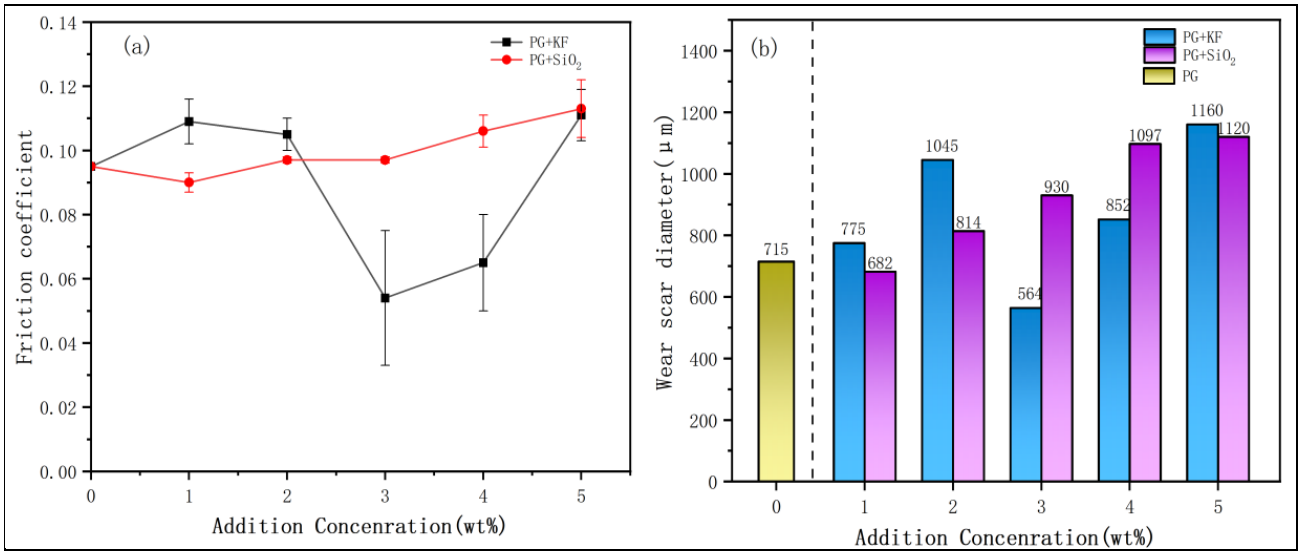


Figure 2. Lubricating performance of tailings and SiO_2 particles: (**a**) anti-friction; (**b**) anti-wear.

The effects of tailings particles as an additive differed significantly from those of SiO_2 particles. When tailings particles were added at concentrations of 1% and 2%, the wear performance of the grease declined. However, when the concentration was increased to 3%, the wear performance improved to its optimal level, with an average WSD of 564 μm—the smallest WSD among the 11 greases tested and 21.1% smaller than that of the original PG. At this optimal concentration, the wear scars exhibited a regular circular shape, with a smooth surface and shallow wear marks. As the tailings content was further increased, the average WSD of the steel balls increased, accompanied by deeper grooves and larger burn areas on the surface. This increase in wear is attributed to excessive tailings adhering to the wear surfaces, repeatedly sticking and tearing along the sliding direction and ultimately leading to increased wear [21,22]. These results indicate that tailings particles have better dispersibility than SiO_2 particles, yielding a more uniform and stable distribution within the grease. Consequently, at high concentrations, the friction performance of the grease can be significantly enhanced with the addition of tailings.

The variations in COF throughout the four-ball testing are presented in Figure 4. When the additive concentration of tailings or SiO_2 was 1% and 2%, the COF for the SiO_2-modified grease was slightly lower than that for the tailings-modified grease. However, when the concentration increased from 3% to 4%, the COF for the SiO_2-modified grease surpassed that for the tailings-modified grease, with only minor differences being observed at 5% addition. Across the five different concentrations, the COF for the grease with 1% SiO_2 remained relatively stable, while increasing the SiO_2 content resulted in more pronounced fluctuations in the COF curve. It is generally accepted that incorporating particles into grease can significantly increase the variability of its COF curve; only when the particle size and concentration are sufficiently low is this effect minimized. Therefore, it can be inferred that SiO_2 exhibited good dispersion at a concentration of 1%. In contrast, for the grease containing tailings, the COF curve was initially flat at a 1% and 2% addition, followed by a slight increase. At a 3% addition, the COF curve closely resembled that of the base grease, exhibiting a significant decrease. When the concentration increased to 4%, the fluctuations in the COF curve became more pronounced. This suggests that the

tailings began to agglomerate, leading to incomplete dispersion of the added particles, which aligns with the COF results. Considering both friction and wear performance, the optimal additive levels for the grease formulation were determined to be 3% for tailings and 1% for SiO_2.

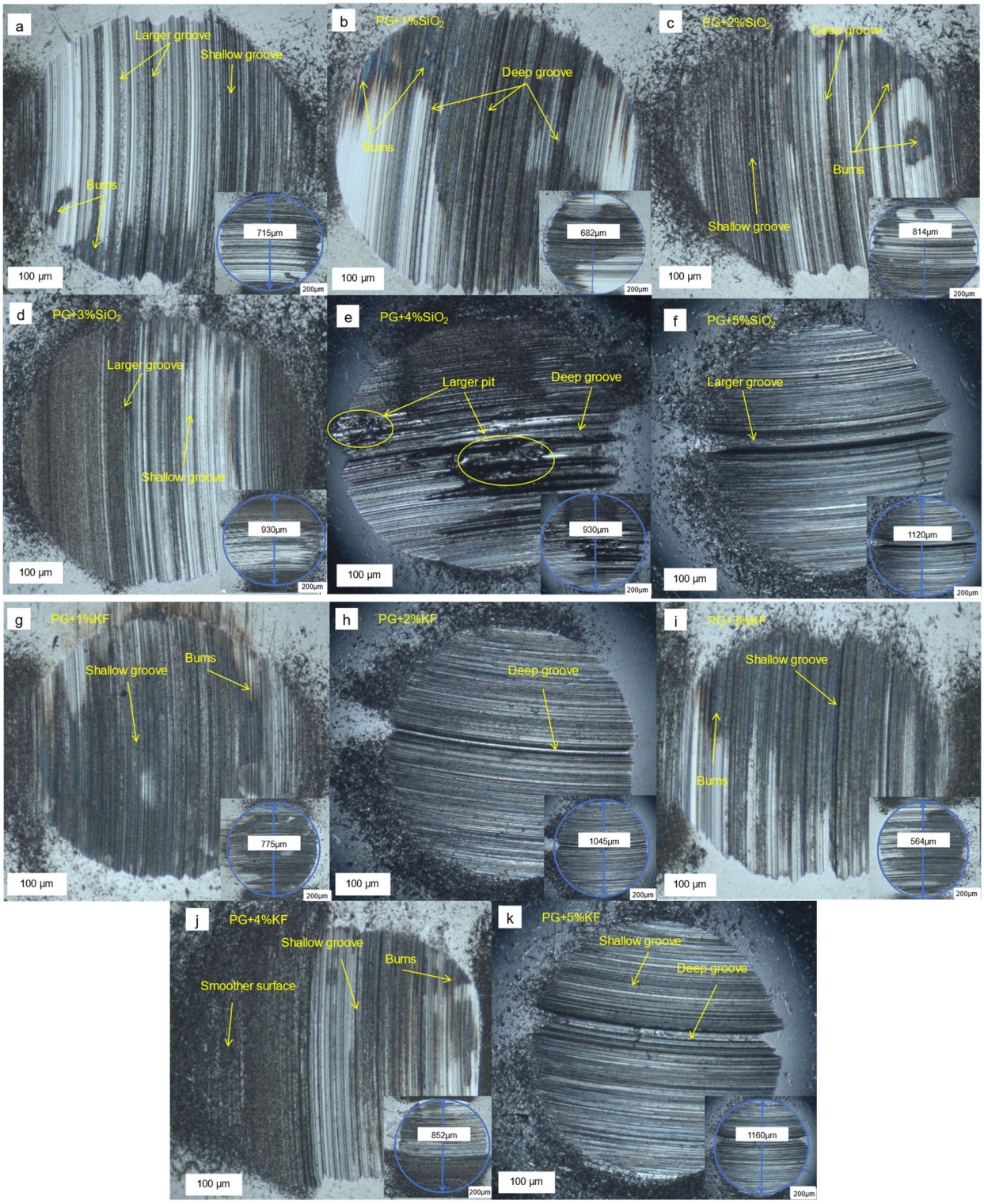


Figure 3. High- and low-magnification micrographs of the wear surfaces: (**a**) PG; (**b**) PG + 1% SiO_2; (**c**) PG + 2% SiO_2; (**d**) PG + 3% SiO_2; (**e**) PG + 4% SiO_2; (**f**) PG + 5% SiO_2; (**g**) PG + 1% KF; (**h**) PG + 2% KF; (**i**) PG + 3% KF; (**j**) PG + 4% KF; (**k**) PG + 5% KF.

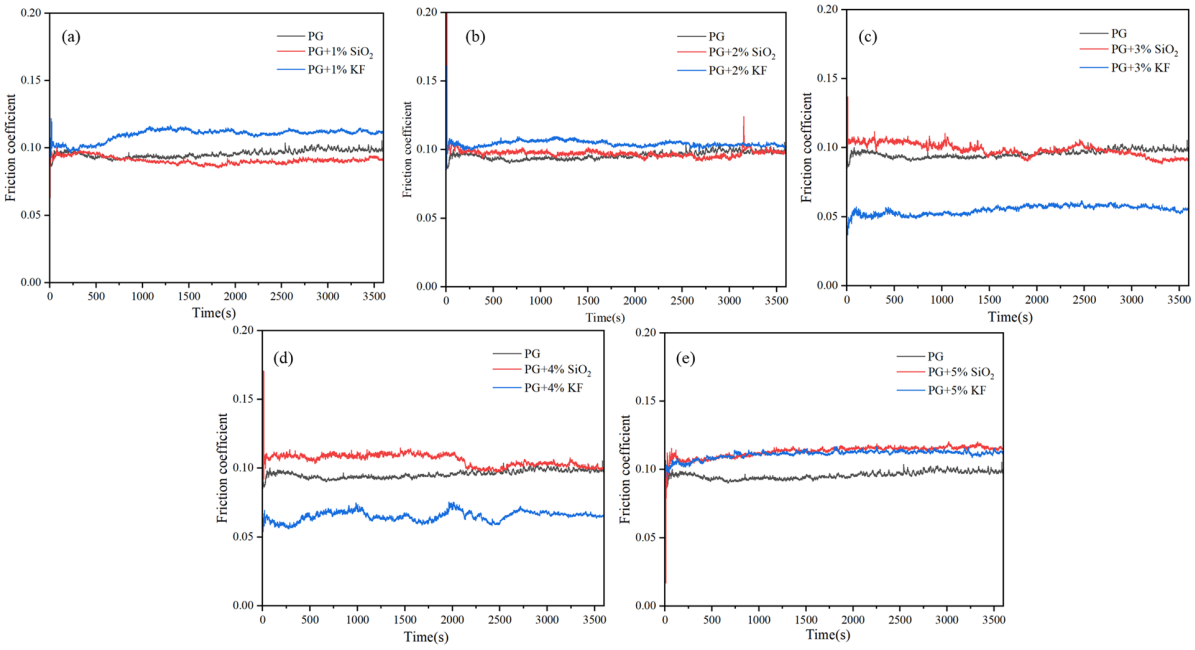


Figure 4. COF curves for the greases: (**a**) 1%; (**b**) 2%; (**c**) 3%; (**d**) 4%; (**e**) 5%.

3.4. Microstructure of Greases

Figure 5 shows SEM images of the base grease, grease with 1% SiO_2, and grease with 3% tailings. The microstructure of the base grease exhibits significant aggregation of thickener particles, characterized by numerous voids and irregular materials in various forms, including flakes and elongated shapes. This suggests that the additive was not uniformly mixed, resulting in incomplete dispersion, which led to an increase in cone penetration and a decline in the friction performance. With the addition of SiO_2, the thickener exhibited a short-chain aggregation structure, while the irregular materials were absent. This indicated that the colloidal structure of the grease may have formed short-chain aggregates of varying sizes due to hydroxyl bonding on the surface of SiO_2 and intermolecular forces. These aggregates interlinked to create a spatial framework that confined and stabilized the base oil, thus maintaining the integrity of the colloidal structure [7]. In the grease containing tailings, we observed not only the aggregates but also many elongated, plate-like materials. Previous analyses suggest that these materials were silicates and aluminosilicates, which enhanced the wear resistance of the grease [23].

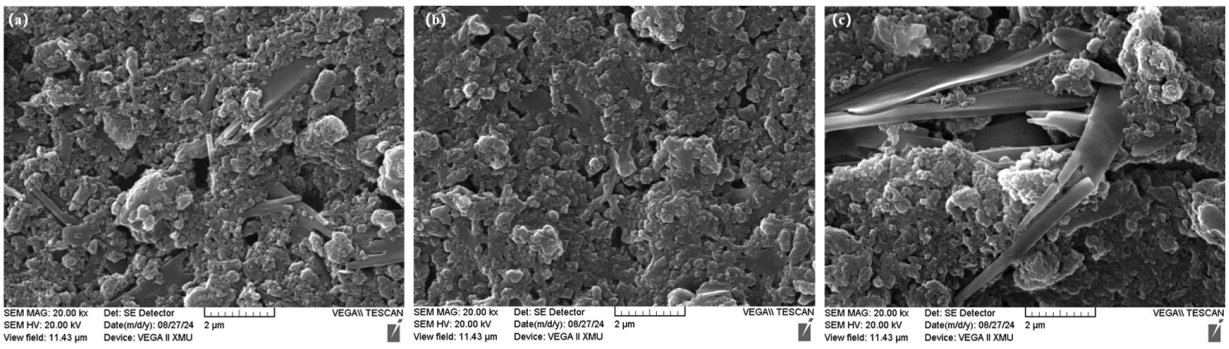


Figure 5. SEM images of the greases: (**a**) PG; (**b**) PG + 1% SiO_2; (**c**) PG + 3% KF.

3.5. Analysis of Friction and Wear Mechanisms

According to the analyses presented above, we believe that when only a small amount of SiO_2 particles were added, they were evenly dispersed within the grease without signifi-

cant agglomeration. These SiO_2 particles settled on the wear surfaces, filling the voids and preventing direct interfacial contact. Consequently, the friction surfaces became smoother, as shown in Figure 6a. Additionally, the presence of SiO_2 facilitated the transition of the sliding friction between the contact surfaces to rolling friction. This change reduced the collisions between the peaks on the rough surfaces of the contact pair, reduced the COF, and enhanced the wear resistance [24]. As the SiO_2 content in the grease increased, significant agglomeration of SiO_2 particles occurred. Figure 6b shows that this aggregation scratched the wear surfaces, disrupting the formation of the protective deposition layer and promoting the detachment of its fragments. This led to a sharp decline in the tribological performance of the grease. In contrast, the tailings exhibited excellent dispersibility in the grease. Even at a concentration of 3%, the tailings remained stably dispersed in the lubricant composed of small particles. Because of this characteristic, PG + 3% KF exhibited the best overall tribological performance among the 11 test samples. On the one hand, the tailings settled and adsorbed in the friction contact area under the influence of gravity, filling the grooves on the wear surfaces and forming a lubricating protective film with outstanding tribological properties. This protective film adhered to the friction surfaces, effectively preventing direct contact and reducing wear, which enhanced the anti-wear performance of the grease. On the other hand, as friction progressed, other substances in the tailings—excluding SiO_2—formed a protective layer on the surface of the steel ball wear spots. This layer comprised inorganic compounds such as illite, Al_2O_3, and FeO. The combined action of this protective layer and the grease film effectively prevented direct contact between the surfaces of the friction pair, reducing both friction and wear [25].

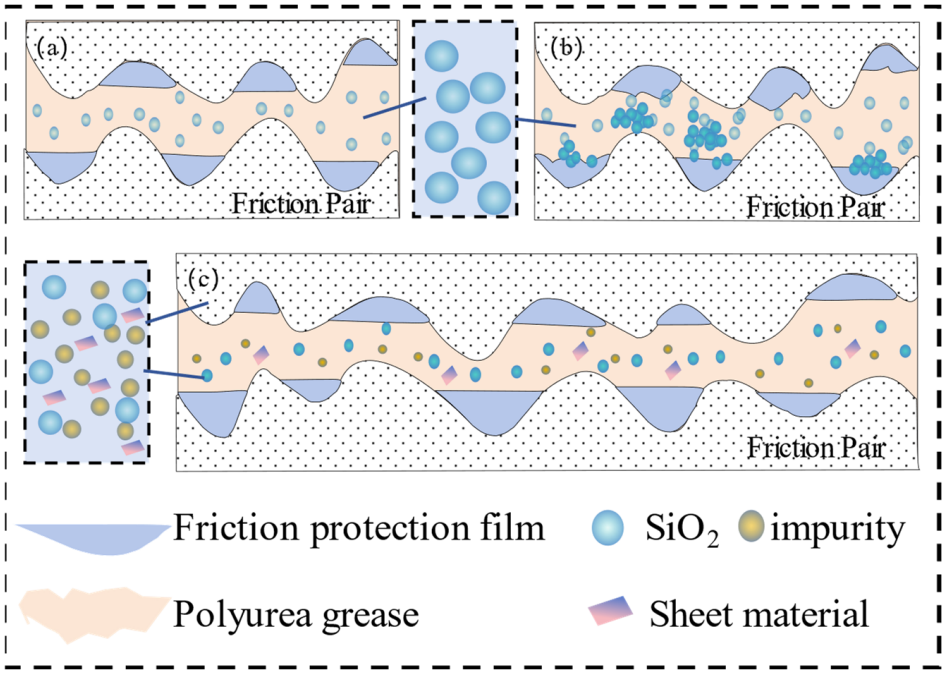


Figure 6. Friction mechanisms of tailings and SiO_2 particles in the grease: (**a**) SiO_2 are dispersed; (**b**) SiO_2 is agglomerated; (**c**) tailings are dispersed.

4. Conclusions

(1) The addition of SiO_2 and tailings, when used separately, significantly reduced both the COF and WSD of the base PG. At a SiO_2 concentration of 1%, optimal tribological performance was observed, with reductions of 5.3% and 4.6% in the COF and WSD, respectively, relative to the base grease. In contrast, the best performance with tailings

was achieved at a concentration of 3%, corresponding to reductions of 43.2% in the COF and 21.1% in the WSD compared with the base grease.

(2) SEM analysis and observations of the steel ball wear surfaces revealed that SiO_2 primarily acted by filling the grooves created by wear during friction. In addition to SiO_2, the tailings contained layered materials such as illite and silicoaluminate, which not only helped fill these grooves but also formed a protective film on the friction surface. This film exerted polishing and grinding effects on the friction pair, further reducing friction. The combination of these two mechanisms significantly enhanced the anti-wear and friction-reducing properties of the grease.

Author Contributions: Conceptualization, B.Z.; Methodology, X.L., R.W. and B.Z.; Software, X.L., H.W. and J.W.; Validation, X.L.; Formal analysis, H.W., R.W., B.Z. and W.W.; Investigation, X.L.; Resources, H.W. and X.H.; Data curation, B.Z., J.W. and W.W.; Writing—original draft, X.H.; Writing—review & editing, W.W. and X.H.; Visualization, R.W. and J.W.; Supervision, R.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Xiaodong Liu, Heping Wang and Rongshe Wang were employed by Shaanxi Geological and Mineral Sixth Geological Team Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sun, Z.; Xie, X.; Wang, P.; Hu, Y.; Cheng, H. Heavy metal pollution caused by small-scale metal ore mining activities: A case study from a polymetallic mine in South China. *Sci. Total Environ.* **2018**, *639*, 217–227. [CrossRef] [PubMed]
2. Cacciuttolo, C.; Cano, D.; Custodio, M. Socio-Environmental Risks Linked with Mine Tailings Chemical Composition: Promoting Responsible and Safe Mine Tailings Management Considering Copper and Gold Mining Experiences from Chile and Peru. *Toxics* **2023**, *11*, 462. [CrossRef] [PubMed]
3. Dey, A.; Rumman, R.; Wakjira, T.G.; Jindal, A.; Bediwy, A.G.; Islam, M.S.; Alam, M.S.; Al Martini, S.; Sabouni, R. Towards net-zero emission: A case study investigating sustainability potential of geopolymer concrete with recycled glass powder and gold mine tailings. *J. Build. Eng.* **2024**, *86*, 108683. [CrossRef]
4. Ahmed, T.; Elchalakani, M.; Basarir, H.; Karrech, A.; Sadrossadat, E.; Yang, B. Development of ECO-UHPC utilizing gold mine tailings as quartz sand alternative. *Clean. Eng. Technol.* **2021**, *4*, 100176. [CrossRef]
5. Hu, P.; Zhang, Y.; Zhou, Y.; Ma, X.; Wang, X.; Tong, W.; Luan, X.; Chu, P.K. Preparation and effectiveness of slow-release silicon fertilizer by sintering with iron ore tailings. *Environ. Prog. Sustain. Energy* **2017**, *37*, 1011–1019. [CrossRef]
6. Qian, L.; Lin, H.; Li, B.; Dong, Y. Physicochemical characteristics and microbial communities of rhizosphere in complex amendment-assisted soilless revegetation of gold mine tailings. *Chemosphere* **2023**, *320*, 138052. [CrossRef] [PubMed]
7. Liu, H.; Wang, X.; Su, H.; Zhao, Q.; Wang, X.; Lou, W.; Zhang, S. Effect of Mass Fraction on Rheological Behaviors and Tribological Properties of Nano-Silica Greases. *Tribology* **2023**, *43*, 916–927.
8. Chen, L.; Chen, G.; Li, H. The Tribological Properties of Silicon Dioxide Powder as Additives in Lithium Base Greases. *Lubr. Eng.* **2014**, *39*, 9–14.
9. Shuvalov, S.A.; Porfiryev, Y.V.; Kolybelsky, D.S.; Zaychenko, V.A.; Popov, P.S.; Gushchin, P.A.; Mishurov, A.S.; Petrova, D.A.; Vinokurov, V.A. Nanoscale Functional Additives Application in the Low Temperature Greases. *Polymers* **2021**, *13*, 3749. [CrossRef] [PubMed]
10. Nizam, M.K.; Mohd Razmi, M.S.; Mohd Ramli, N.; Razali, M.N. Formulation of Food-Grade Grease Using Paraffin Oil, Fumed Silica, and Chitosan. *Mater. Sci. Forum* **2022**, *1069*, 211–218. [CrossRef]
11. Drabik, J.; Trzos, M. Polymer-silica additive as a modifier of tribological properties of ecological grease, improvement of fatigue resistance. *Lubr. Sci.* **2020**, *33*, 133–141. [CrossRef]

12. Xia, Y.; Yang, K.; Feng, X.; Wang, Y. Tribological properties of modified kaolin doped polymer as polytetrafluoroethylene grease additive. *Tribol. Int.* **2022**, *173*, 107612. [CrossRef]
13. Qu, J.; Qu, H.; Wen, Z.; Luo, Y. Self-repairing properties of complex titanium grease containing hydroxyl silicate. *Tribol. Int.* **2020**, *149*, 105685.
14. *GB/T 3498-2008*; Petrolum Products—Determination of Dropping Point of Lubricating Greases (Wide Temperature Range). National Standardization Administration of the People's Republic of China: Beijing, China, 2008.
15. *GB 7325-1987*; Petroleum Products-Lubricating Greases and Oils-Determination of Evaporation Loss. National Standardization Administration of the People's Republic of China: Beijing, China, 1987.
16. *GB/T 269-1991*; Lubricating Grease and Petrolatum-Determination of Cone Penetration, General Administration of Quality Supervision. Inspection and Quarantine of the People's Republic of China: Beijing, China, 1991.
17. *SH/T 0109-2004*; Petroleum Products and Lubricants-Determination of Water Washout Characteristics of Lubricating Greases. National Development and Reform Commission: Beijing, China, 2004.
18. Wu, C.; Li, S.; Chen, Y.; Yao, L.; Li, X.; Ni, J. Tribological properties of chemical composite and physical mixture of ZnO and SiO_2 nanoparticles as grease additives. *Appl. Surf. Sci.* **2023**, *612*, 155932. [CrossRef]
19. Wu, C.; Li, S.; Ni, J.; Yao, L.; Xia, Q. Effect of structure of ZnO and SiO_2 core-shell composite nanoparticles as lubricant additive on tribological properties of greases. *Appl. Surf. Sci.* **2024**, *657*, 159745. [CrossRef]
20. Peng, D.X.; Chen, C.H.; Kang, Y.; Chang, Y.P.; Chang, S.Y. Size effects of SiO_2 nanoparticles as oil additives on tribology of lubricant. *Ind. Lubr. Tribol.* **2010**, *62*, 111–120. [CrossRef]
21. Zhang, K.; Tang, H.; Shi, X.; Xue, Y.; Huang, Q. Tribological performances of α-Zrp as the additive of the grease used for mine hoisting wire rope. *Wear* **2022**, *504–505*, 204428. [CrossRef]
22. Zhang, K.; Tang, H.; Shi, X.; Xue, Y.; Huang, Q. Effect of TiCMXenes additive on the tribological properties of lithium grease at different temperatures. *Wear* **2023**, *526–527*, 204953. [CrossRef]
23. Li, Q. Tribological Properties of Several Silicate Powder as Grease Additives. Master's Thesis, North China Electric Power University, Beijing, China, 2022.
24. Rawat, S.S.; Harsha, A.P.; Deepak, A.P. Tribological performance of paraffin grease with silica nanoparticles as an additive. *Appl. Nanosci.* **2019**, *9*, 305–315. [CrossRef]
25. Chen, L.; Chen, G.-X.; Chen, H.-L.; Liu, Y. Study on Tribological Performance of Lithium Grease Using Ultrafine Silicon Material (Si-Al Type) as Additive. *Pet. Refin. Chem. Ind.* **2014**, *45*, 78–84.

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