Tribology and Materials
Vol. 5, No. 1, 2026, pp. 12-21

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2026.003

The effect of adding silica on the physical, mechanical and wear properties of rubber-based composites

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Keywords

natural rubber
rubber-based composites
silica
mechanical properties
abrasion resistance
fatigue behaviour

History

Received: 24-09-2025
Revised: 06-12-2025
Accepted: 23-12-2025

Abstract

In this study, the influence of inorganic silica addition on the physical, mechanical and tribological (abrasion resistance) properties of a natural rubber compound used in bridge expansion joints was investigated. These joints are subjected to cyclic mechanical strains and harsh service conditions, such as friction induced by movement, pressure, solar radiation and humidity, which accelerate material deterioration and increase maintenance and replacement costs. Natural rubber-based composites were prepared with silica contents of 10, 20, 30 and 50 parts per hundred rubber (phr) to mitigate these adverse effects. The aim of this work was to identify an optimal formulation that reduces permanent deformation, enhances fatigue performance, improves swelling resistance and optimises tribological behaviour. The vulcanisation characteristics (optimum cure time, scorch time and maximum torque), Mooney viscosity, specific gravity, water and oil swelling, microstructure, international rubber hardness degree (IRHD), fatigue life, compression set and abrasion resistance were evaluated. The results showed that increasing silica content reduced vulcanisation and scorch time while increasing maximum torque, Mooney viscosity and specific gravity, indicating the formation of a stiffer rubber network. Compared with the unfilled compound, silica-filled formulations exhibited higher hardness, improved fatigue resistance, lower compression set and reduced oil swelling. Abrasion resistance testing revealed a slight increase in wear with increasing silica content, which was attributed to the presence of rigid silica agglomerates. However, this effect was compensated by the overall improvement in mechanical stability and resistance to aggressive service environments.

1. Introduction

Bridge expansion joints provide critical structural reinforcement against deformations resulting from traffic loads, temperature changes and ground movements to prevent the failure of other structural components, including beams, slabs and trusses [1,2]. These joints are usually installed perpendicular to the longitudinal direction of the bridge. A rubber component protects other components in these joints from possible damage caused by water, salt and other elements carried by runoff. In one case, a rubber expansion joint was specifically designed to link the deck of an existing bridge to a new ductile bridge on an Italian motorway. This joint was also required to bridge stiffness differences between two bridges built to different design requirements and at different times. These joints are also critical to enhancing the performance of bridges during earthquakes [3], since their efficiency is dictated by design codes, reinforcement plans and the efficacy of selected materials [4]. For such applications, three basic types of bearings are commonly used: lead rubber bearings (LRBs), high damping rubber bearings (HDRBs) and natural rubber bearings (NRBs).

The conventional laminated rubber bearing consists of alternating layers of rubber and steel shims, with two steel plates at the top and bottom. In this arrangement, the rubber layers offer horizontal flexibility while the steel shims add vertical stiffness. For base isolation, HDRBs and LRBs are mainly used in earthquake-prone areas due to their better damping characteristics. In HDRBs, the damping quality is increased by changing the rubber composition, and in LRBs, one or more central lead seals are attached to the structure [5].

Material choice, namely rubber or steel, heavily determines the type of expansion joint utilised. To illustrate, toe and rail joints of steel expansion joints are preferable for medium- and long-span bridges because of their strength and robustness to large movements. Single-cell joints (due to the presence of a rubber driving surface) offer better shock absorption and increased driving comfort, yet their limited expansion capacity limits their application on small bridges. The rubber is an essential component in single-cell joints and is generally susceptible to corrosion [6].

Silica increases the strength of silicone rubber both by physical filler-matrix interaction and also by hydrogen bonding between silanol groups on the surface of silica and oxygen atoms in the backbone of silicone rubber [7]. Silica remains especially preferred as a reinforcing filler for various rubber formulations, particularly for enhancing tear strength and abrasion resistance, and reducing rolling resistance compared to carbon black [8]. Two major types of synthetic amorphous silica are precipitated silica and fumed silica, which differ in particle size and fabrication process. Fumed silica is produced by hydrolysis of silicon tetrachloride in a flame, while precipitated silica is obtained through acid precipitation of sodium silicate [9]. Because fumed silica is relatively pure and has a low moisture content, it is often used in specialised applications, such as silicone rubber for medical use or electrical insulation. The same applies to product transparency [10]. Fumed silica is not widely used over precipitated silica because of its cost, low bulk density and difficulty in handling, but it is less commonly used in tire and mechanical rubber products. Moreover, silica dispersion is lacking in latex mixtures, which leads to poor mechanical properties of vulcanised rubber products [11,12].

The effectiveness of isolation bearings in improving the seismic performance of bridges has been widely investigated. Previous studies have demonstrated the benefits of incorporating rubber-based materials and HDRBs in seismic protection systems. For instance, Rajagopal et al. [13] reported that the incorporation of crumb rubber and microsilica can enhance the mechanical and environmental performance of structural materials, while Tubaldi et al. [14] compared different models of HDRBs for seismically isolated bridges and highlighted their effectiveness in seismic applications. These bearings are constructed by alternating layers of filled natural rubber and steel shims, which increase vertical load capacity and promote energy dissipation [5,15]. Other investigations have focused on analysing the seismic behaviour of base-isolated highway bridges with different types of rubber bearings from laminated rubber materials (NRBs, HDRBs and LRBs) on a nonlinear dynamic scale [16]. Cyclic loading test methods were also implemented to assess the ultimate shear failure mode and frictional sliding properties for laminated rubber bearings under low-frequency stress. The tests provided an interesting comparison of the energy dissipation behaviour of LRBs, single-sided friction sliding rubber bearings and rubber bearings with end plates on laminated rubber bearings, allowing a comparison of their relative performance [17,18].

The current study seeks to enhance the mechanical and wear properties of rubber bridge joints using silica as an inexpensive reinforcing filler. The proposed approach aims to prolong the service life of expansion joints and reduce material costs by optimising key physical, mechanical and wear properties.

2. Experimental preparation

2.1 Materials

All ingredient contents are expressed in parts per hundred rubber (phr), which represents a relative formulation unit rather than an absolute weight fraction. In this research, Kumho Tire provided SMR5 natural rubber (100 phr). The carbon black N330 (36 phr) was supplied by Pars Carbon Black (Iran) and characterised by an average primary particle size of approximately 26 – 30 nm, according to the manufacturer's technical datasheet. Precipitated silica Perkasil KS 300 was obtained from Babylon Tire Factory (Iraq) and added in different amounts (10, 20, 30 and 50 phr). The average particle size of the used silica was approximately 20 nm, according to the manufacturer's technical datasheet. Zinc oxide (5.0 phr) with an average particle size of approximately 0.2 µm, supplied by TP Polymer (India), was used as the activator. *N*-Isopropyl-*N*'-phenyl-1,4-phenylenediamine (IPPD) (1.0 phr) was an antioxidant and was acquired from Shenyang Sunnyjoint Chemicals (China). ITT (India) provided sulphur (2.5 phr) and N-cyclohexyl-2-benzothiazole sulfonamide (CBS) (1.2 phr) as vulcanising agent and accelerator, respectively. The complete composition of the used rubber samples is given in Table 1.

Table 1. Components of rubber samples

Component	Function	Content, phr
Natural rubber	base polymer	100.0
Zinc oxide	activator	5.0
IPPD	antioxidant	1.0
Carbon black	reinforcing filler	36.0
CBS	accelerator	1.2
Sulphur	vulcanising agent	2.5
Precipitated silica	reinforcing filler	0 | 10 | 20 | 30 | 50

Zinc oxide content was consistent with standard industrial rubber compounding practice. No stearic acid was incorporated into the formulations. The activator system employed in this study follows the standard formulation routinely used at the Babylon Tire Factory laboratory for this specific rubber compound. Although zinc oxide is commonly used in combination with stearic acid in many rubber systems, the selected formulation was maintained unchanged to reflect actual industrial practice and to ensure consistency across all tested samples.

The precipitated silica Perkasil KS 300 is predominantly used in dynamic rubber applications, such as tire compounds, due to its high specific surface area, controlled aggregate structure and surface rich in silanol groups. These characteristics generally provide strong reinforcing potential in rubber matrices, contributing to enhanced durability, tear resistance and abrasion-related performance under cyclic loading conditions. Although Perkasil KS 300 is commonly applied in tire formulations, it was considered suitable for the present study because bridge expansion joints are also subjected to repetitive mechanical deformation, traffic-induced cyclic loading and thermal fluctuations, which resemble the dynamic service environment encountered in tire applications. Therefore, this silica was adopted as a representative industrial reinforcing filler to evaluate its influence on rubber compounds intended for bridge expansion joints.

It is acknowledged that the presence of surface silanol groups imparts a polar character to silica, which may limit its compatibility with non-polar natural rubber. In the present work, no silane coupling agent, such as bis(triethoxysilylpropyl)tetrasulfide (TESPT), was employed. Consequently, silica dispersion was achieved solely through mechanical mixing using a two-roll mill. The role of silica in this study is therefore interpreted primarily in terms of its physical reinforcing effect associated with filler loading, rather than chemical coupling mechanisms. The general properties and specifications of the used silica are summarised in Table 2.

2.2 Preparation of samples

Rubber samples were prepared using a laboratory two-roll mill (Fig. 1) following the general guidelines of ASTM D3182, with the compounding procedure adapted to reflect the actual laboratory practice. Initially, natural rubber was masticated on the two-roll mill for approximately 3 to 4 minutes to achieve adequate plasticity. The mill rolls temperature was maintained at 40 to 50 °C during mixing.

Table 2. Characteristics of the used precipitated silica

Characteristic	Value
Specific surface area (BET method), m^2/g	130
Density, g/cm^3	2.0
pH (10 % aqueous suspension)	7.0
Moisture loss (2 h at 105 °C), %	6
Loss on ignition (2 h at 1000 °C), %	4
Residue on a 40-micron filter (max), %	0.2
Bulk density (powder), kg/m^3	250
Bulk density (granulate), kg/m^3	300
Silica as SiO_2, %	98
Aluminium as Al_2O_3, %	0.2
Sodium sulfate (Na_2SO_4), %	1.5
Iron as Fe_2O_3 (max), %	0.06
Copper and manganese (max), ppm	5

Figure 1. Laboratory two-roll mill and samples

After mastication, zinc oxide and the antioxidant (IPPD) were added sequentially and mixed for approximately 2 minutes to ensure uniform distribution. Carbon black and precipitated silica were then incorporated gradually in small portions, and mixing was continued for an additional 6 to 8 minutes until a visually homogeneous compound was obtained. Finally, sulphur and the accelerator (CBS) were added at the last stage of mixing, and blending was continued for 2 to 3 minutes to avoid premature vulcanisation (scorch). The total mixing time for each composition was approximately 15 to 18 minutes. Throughout the compounding process, care was taken to maintain clean roll surfaces and consistent mixing conditions to ensure reproducibility.

The compounded rubber sheets were vulcanised using a hot hydraulic press at 150 ± 2 °C under a pressure of 10 MPa, following the ASTM D3182 recommendations. The optimum cure time was determined from rheometric cure curves obtained in accordance with ASTM D2084. After curing, the samples were cooled under pressure for 5 minutes to prevent post-curing deformation and ensure uniform thickness. All vulcanised samples were conditioned for 24 hours at 23 ± 2 °C and 50 ± 5 % relative humidity in accordance with ISO 23529 prior to testing.

3. Physical, mechanical and wear properties testing

All physical, mechanical and tribological properties were measured using at least three independent specimens per composition under identical testing conditions. The reported results correspond to the average values. The repeatability of the measurements was verified, with only minor variations. Therefore, the discussion focuses on comparative trends among formulations rather than statistical dispersion, and standard deviations are not included.

3.1 Physical properties

Rheological measurements were performed using a moving die rheometer in accordance with ASTM D2084 to evaluate the vulcanisation behaviour of the rubber compounds. Although SI units are generally recommended, cure time and scorch time are conventionally reported in minutes in rubber rheology studies, as directly obtained from a moving die rheometer. The vulcanisation characteristics were determined at 150 °C to assess cross-linking development. In the present study, only the extracted rheological parameters (cure time, scorch time and maximum torque) were recorded and archived during testing, while the laboratory system did not retain the full torque-time cure curves. Therefore, the discussion of vulcanisation behaviour is limited to the measured parameters.

Mooney viscosity was measured using a Mooney viscometer according to ASTM D1646 at 100 °C to evaluate the processability of the rubber compounds. Specific gravity was determined following ASTM D792 using an electronic balance based on Archimedes' principle.

Water and oil swelling behaviour, representing a physical response of the rubber compounds to fluid absorption, was evaluated in accordance with ASTM D471. Three specimens were prepared for each vulcanised rubber composition, and their initial masses were recorded with an accuracy of ± 0.001 g. The specimens were immersed in water or commercial mineral-based hydraulic oil (ISO VG 46) at a temperature of 23 ± 2 °C for 72 h, in accordance with ASTM D471. After immersion, the specimens were removed, surface oil was carefully wiped off and the final masses were recorded to determine the swelling behaviour.

Microstructure analysis of the samples was performed using a scanning electron microscope (SEM), which uses a focused electron beam to scan the sample's surface, creating a high-resolution image of the topography and microstructure. The samples used in the examination were prepared by taking a small piece of rubber measuring 1 mm and coating it with carbon using a sputter coater to obtain a suitable surface for examination.

3.2 Mechanical and wear properties

The hardness of the rubber samples was measured in terms of international rubber hardness degree (IRHD) using an IRHD hardness tester in accordance with ASTM D1415. Five measurements were taken at different locations on each specimen and the average values were reported.

The flexing test was performed according to the ASTM D430 (Method B) and ASTM D813. The test involves periodically bending the specimen to induce repeated mechanical stresses that simulate service conditions. Specimens are prepared to standard dimensions and a first crack is created in the centre of the specimen using a pressing tool to ensure crack growth begins during flexion.

A compression set test was carried out in accordance with the ASTM D395 (Method A). For each composition, disc-shaped rubber specimens with a diameter of 30 mm and a thickness of 12 mm were prepared. The compression mould consisted of three parts: a middle plate with dimensions of 118 × 118 × 12 mm, containing four circular cavities of 30 mm diameter and 12 mm thickness, and a base plate and a cover plate with dimensions of 113 × 113 × 17 mm.

The specimens were compressed using a compression set tester to a constant deflection corresponding to the mould geometry. Compression was applied at a temperature of 70 ± 2 °C for a duration of 30 minutes. After completion of the compression period, the specimens were removed from the mould and allowed to recover at room temperature for 30 minutes before measuring the final thickness. The compression set was calculated as the percentage of permanent deformation relative to the original specimen thickness.

Abrasion wear was evaluated according to ASTM D5963 (Method B) with the abrasion tester. Cylindrical rubber specimens with a diameter of 16 mm and a thickness of 6 mm were used. During testing, a constant normal load of 10 N was applied, and the specimens were subjected to a controlled sliding motion against an abrasive surface. The abrasive surface was a silicon carbide abrasive paper (grit size P60), fixed to the rotating drum.

The test was conducted over a fixed sliding distance of 40 m, at a constant drum rotational speed of 40 rpm, corresponding to a sliding time of approximately 60 s per specimen. Abrasion performance was quantified in terms of volume loss, where lower volume loss indicates higher abrasion resistance. All tests were performed under identical conditions to ensure reliable comparison among different compositions.

4. Results and discussion

4.1 Physical properties

Table 3 and Figure 2 show that increasing the silica content in natural rubber from 0 to 50 phr resulted in a decrease in the curing time from 1.96 to 1.91 min. However, the scorch time was not affected by the addition of silica. This suggests that a good and uniform specimen can be obtained. Increasing the silica content from 0 to 50 phr also resulted in higher maximum torque values, which increased from 26.0 to 31.6 Nm, indicating a higher cross-link density. These higher maximum torque values suggest a greater tendency for combustion during manufacturing, so a more accurate treatment is necessary than that of the standard composition. These findings indicate higher stiffness of the rubber matrix and the formation of stronger rubber chain bonds with increased silica content. This improvement in the rubber structure is attributed to stronger bonds between the rubber chains and the additive, which contribute to increased hardness and durability.

An increase in viscosity of the composites compared to the standard sample, up to 19 Mooney units for the composite with the highest silica content, indicates the ability of the composite to incorporate such a high silica content. Increasing the overall viscosity or hardness of the rubber may affect its properties and use in various applications.

Table 3. Vulcanisation characteristics and physical properties

Property	Silica content, phr				
	0	10	20	30	50
Cure time, min	1.96	1.95	1.94	1.94	1.91
Scorch time, min	1.12	1.10	1.15	1.10	1.12
Maximum torque, dNm	26.0	27.1	27.1	29.4	31.6
Viscosity, Mooney unit	15	16	16	18	19
Specific gravity	1.120	1.150	1.175	1.192	1.210
Swelling (water), %	0.03	0.03	0.04	0.03	0.03
Swelling (oil), %	36	35	34	33	30

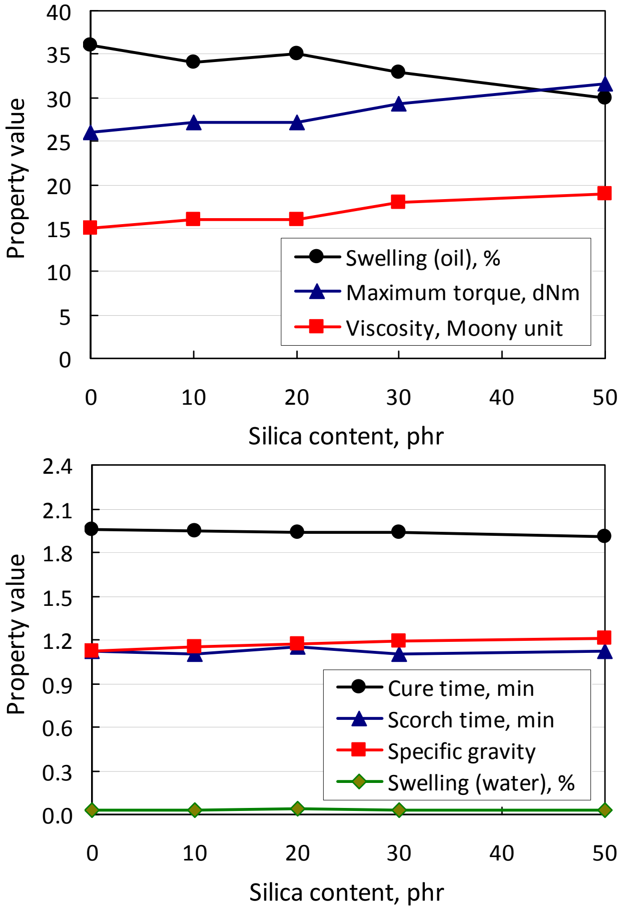

Figure 2. Change of vulcanisation characteristics and physical properties with the addition of silica

The specific gravity of rubber-based composite samples increases with the percentage of added silica, albeit at a slight rate, as shown in Figure 2. This is because the reinforcement is an organic material with a low specific gravity and because it constitutes only a small part of the final compound. Its addition to the natural rubber compound may lead to a slight increase in density, but this effect is not statistically significant, as reported by Akuwueke et al. [19] and Malas et al. [20].

The water swelling values are very low (between 0.03 and 0.04 %) in response to silica, showing only a small increment at silica content of 20 phr. This is because the water-absorption behaviour of the rubber compounds is unaffected by the increase in silica content, and because the rubber is a hydrophobic material and exhibits very low water swelling [21,22]. At the same time, it is noticed that the oil swelling decreases from approximately 36 % for unreinforced rubber to approximately 30 % at a silica content of 50 phr. This is consistent with better oil resistance of the compound with a higher content of silica, as the fluid becomes less permeable into the rubber structure due to the presence of solid particles. This is extremely important for sealing applications and for automotive parts that operate in oily media. Similar trends have been reported by Chu et al. [23], who highlighted the influence of filler-matrix interactions and filler dispersion on the swelling resistance and tribological performance of rubber-based composites. The reduction in oil swelling noticed in the present study can be attributed to the restricted mobility of polymer chains and reduced fluid permeability induced by the presence of rigid silica particles within the rubber matrix.

The SEM micrographs shown in Figure 3 reveal clear differences in surface morphology between the unreinforced rubber compound (Fig. 3a) and the composite reinforced with the highest silica content (Fig. 3b). Silica particles generally exhibit angular and irregular morphologies, in contrast to the more spherical and lumpy appearance typically associated with carbon black. In silica-filled systems, agglomerates may appear as irregularly sized clusters, particularly when reinforcing filler-matrix coupling is limited. It should be emphasised that

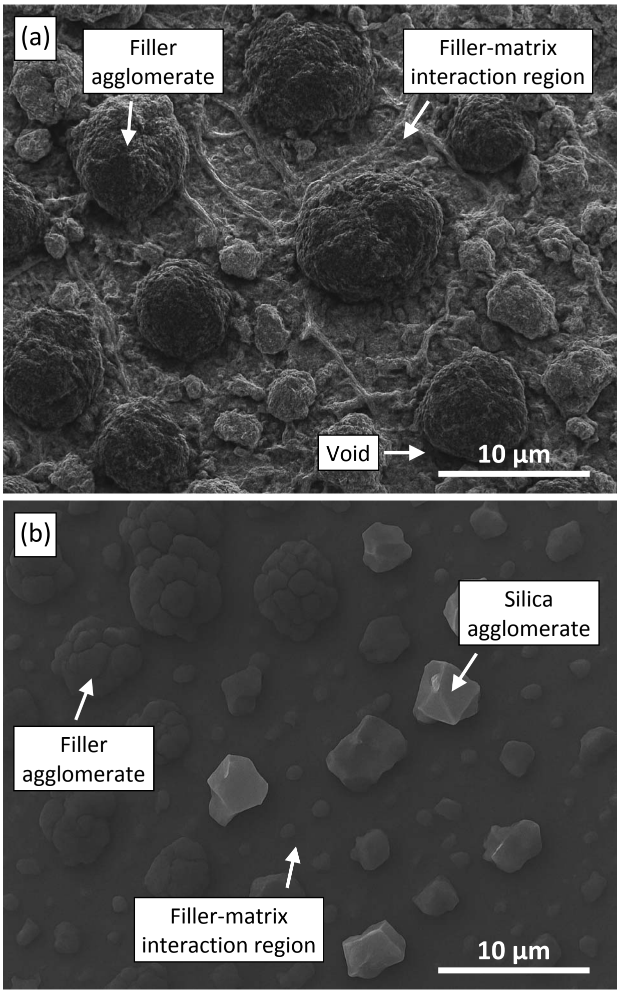

Figure 3. SEM micrographs of rubber samples: (a) unreinforced natural rubber and (b) silica-filled (50 phr) composite

no silane coupling agent (such as TESPT) was used in the present study. Such agents are commonly used to enhance silica-rubber interfacial bonding. However, in the tested samples, silica dispersion and filler-matrix interaction were achieved solely through mechanical mixing in a two-roll mill, without the use of chemical coupling agents. Figure 3 indicates improved filler distribution and reduced void formation in the silica-rich sample, despite the absence of a coupling agent.

This microstructural analysis is consistent with the physical and mechanical test results, in which the unreinforced compound exhibited the lowest hardness, fatigue resistance and oil resistance, while the composite reinforced with the highest silica content showed higher hardness, improved fatigue life, reduced oil swelling and a near-optimal compression set.

SEM micrographs are presented for representative samples, i.e. the unreinforced rubber compound and the composite reinforced with the highest silica content. These two samples were selected as they represent the lower and upper limits of filler content, providing the most pronounced contrast in microstructure and filler-matrix interaction. Intermediate compositions exhibited similar morphological trends and, therefore, were not included for brevity. In the SEM micrographs, arrows highlight morphological features such as filler agglomerates, voids and regions of filler-matrix interaction, rather than chemically distinguish individual components. SEM imaging alone does not allow definitive chemical identification of carbon black and silica particles without complementary analytical techniques such as energy-dispersive X-ray spectroscopy. Instead, variations in contrast and surface texture provide qualitative insight into filler dispersion and aggregation within the rubber matrix.

4.2 Mechanical and wear properties

Table 4 and Figure 4 show that as the silica content increases from 0 to 50 phr, the IRHD hardness increases from approximately 50 to approximately 64. This gradual increase in hardness reflects the reinforcing effect of the silica particles as a rigid filler, increasing the rubber's stiffness and limiting the mobility of the polymer chains.

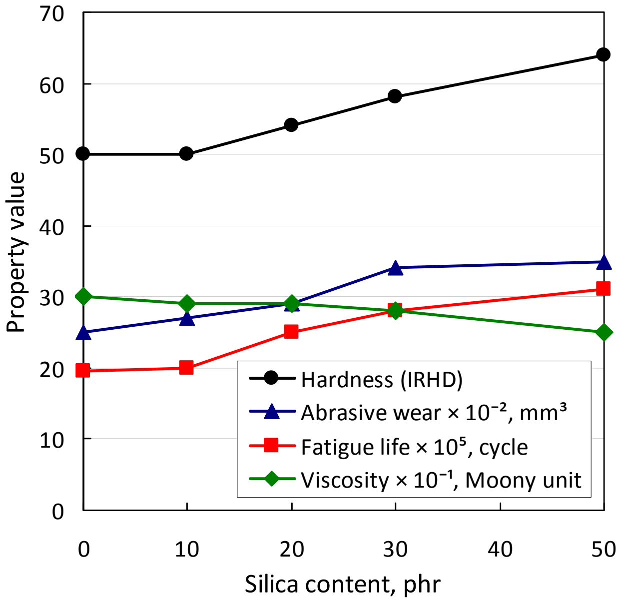

Figure 4. Change of vulcanisation characteristics and physical properties with the addition of silica

When analysing the fatigue results, a striking increase from approximately 195,000 cycles for unreinforced rubber to approximately 310,000 cycles at a silica content of 50 phr is evident. With an increase in cycles prior to failure, reflecting increased fatigue resistance, as the silica content increases, a contribution of silica to internal load transfer is noticed, reducing stress concentrations at specific locations. This is attributed to the presence of a filler network in the rubber, which enhances the fatigue performance of the polymer matrix under repeated load.

The noticed improvement in hardness and fatigue resistance with increasing silica content is consistent with recent findings reported in the literature. Choophun et al. [12] demonstrated that the incorporation of inorganic fillers into rubber-based composites significantly enhances stiffness and resistance to cyclic deformation due to the formation of a reinforced filler network capable of redistributing applied stresses. Such behaviour is

Table 4. Mechanical and wear properties

Property	Silica content, phr				
	0	10	20	30	50
Hardness (IRHD)	50	50	54	58	64
Fatigue life, cycle	195,000	200,000	250,000	280,000	310,000
Compression set, %	3	2.9	2.9	2.8	2.5
Abrasive wear, mm^3	0.25	0.27	0.29	0.34	0.35

particularly relevant for applications subjected to repeated mechanical loading, such as bridge expansion joints.

Regarding the compression set, it gradually decreases from approximately 3 % to approximately 2.5 % with increasing silica content. The low compression set indicates that, when the load is released, the rubber remains somewhat stable in its original shape, reducing permanent compression displacement. This shows that the addition of silica improves the dimensional stability of the compound during loading over a prolonged or continuous period [22].

Abrasion resistance is considered a tribological property related to surface interactions under sliding/rolling contact rather than a bulk material property. The increase in abrasive wear from approximately 0.25 to 0.35 mm^3 with increasing silica content indicates that rubber has been more readily removed from the surface, resulting in a slight decrease in wear resistance. Such a trend suggests the formation of hard silica agglomerates, which lead to local surface roughness and three-body wear, thereby causing higher abrasive wear during sliding. This promotes cutting and rubber fragmentation extraction from the matrix, resulting in higher material loss.

From an engineering application perspective, the measured physical, mechanical and wear properties are directly related to the functional requirements of bridge expansion joints. The reduction in oil swelling noticed with increasing silica content indicates improved resistance to hydraulic fluids, oils and contaminants commonly present in bridge environments, contributing to long-term dimensional stability and sealing performance.

Enhanced hardness and reduced compression set support improved load-bearing capability and elastic recovery under sustained compressive stresses, which are essential for maintaining joint integrity during repeated thermal expansion and contraction. The noticed improvement in fatigue life reflects increased resistance to cyclic deformation induced by traffic loading, while abrasion behaviour provides insight into surface durability under continuous movement.

Collectively, these properties demonstrate that silica-filled rubber-based composites, particularly with higher silica content, are better suited to meet the durability and performance demands of bridge expansion joints exposed to combined mechanical, environmental and operational stresses.

4.3 Practical applications and future research prospects

The research demonstrates that the use of precipitated silica as a reinforcing material in expansion joint rubber has the potential to contribute to the enhancement of specific essential properties, such as hardness, fatigue resistance, oil swelling, and permanent compression response. This results in better service life of the joints and reduced maintenance requirements for bridges under heavy traffic loads and harsh conditions. The formulated materials can be used as a basis for other rubber materials for seismic isolation applications and for rubber cushions and gaskets in civil and mechanical structures.

In future research, it should be investigated how to increase silica dispersion and its interaction with the rubber by employing silane-type bonding agents. This should be combined with mechanical, thermal and environmental aging tests such as those simulated in actual service conditions. Moreover, the experimental performance of the developed joints must be verified in models or full-scale joints to assess their structural engineering feasibility.

5. Conclusion

The experimental results clearly demonstrate that incorporating precipitated silica as a reinforcing filler improves the overall performance of the rubber compound intended for bridge expansion joint applications. Increased silica content led to higher hardness and reduced rubber extensibility, indicating enhanced resistance to deformation.

Silica-filled rubber-based composites showed improved resistance to cyclic loading, as evidenced by enhanced fatigue performance and reduced compression set. These properties contribute to better elastic recovery and dimensional stability under repeated mechanical stresses.

From a physical perspective, silica addition had a negligible influence on water absorption but significantly reduced oil swelling. This behaviour indicates improved resistance to oil-rich environments commonly encountered in bridge service conditions.

Vulcanisation characteristics were moderately affected by silica addition, with a slight reduction in the optimum cure time and an increase in the maximum torque, suggesting the formation of a stronger rubber network without adversely affecting processing safety.

Based on the combined physical, mechanical and wear results, silica-filled rubber-based composites, particularly those with higher silica content, demonstrate improved suitability for use in bridge expansion joints. Future work may focus on improving silica dispersion and on exploring hybrid filler systems to optimise performance and durability further.

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