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Enhancement of Mechanical and Dynamic Properties of Elastomeric Nanocomposites for Structural Vibration Isolation: A Review of Materials, Mechanisms, and Applications

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Abstract. Elastomeric materials, particularly natural rubber (NR), exhibit exceptional mechanical resilience, energy absorption, and damping characteristics, making them vital in various engineering applications involving dynamic loading and vibration control. However, inherent limitations such as poor ozone resistance, thermal instability, and insufficient mechanical stiffness necessitate material modification to meet the demands of advanced structural systems. This review presents a comprehensive examination of recent advancements in the reinforcement of elastomeric matrices with nanostructured fillers, focusing primarily on zinc oxide (ZnO), multi-walled carbon nanotubes (MWCNTs), and sodium bicarbonate ($NaHCO_3$). The effects of these additives on the tensile strength, elongation at break, tear resistance, fatigue life, dynamic stiffness, and damping capacity of rubber-based composites are critically analyzed. Additionally, the study explores the integration of optimized rubber formulations into viscoelastic foundations for structural elements such as plates subjected to free and transient vibration loading. Emphasis is placed on the interplay between molecular chain structure, cross-linking mechanisms, filler dispersion, and their collective impact on the macroscopic behavior of the composite system. Numerical simulation approaches, including finite element modeling using SOLIDWORKS, are also reviewed to highlight their role in predicting the structural response of plate-foundation systems. The article consolidates experimental findings and theoretical models to guide future research and development of high-performance elastomeric systems in vibration mitigation and structural damping applications.

Keywords: natural rubber (NR), nano-composites, structural vibration isolation.

Introduction

The capacity to describe the mechanical response of elastomeric materials is a significant technological issue that needs to be fully comprehended, so it should be highlighted in detail [1]. Even though elastomers can be manufactured from diverse organic materials, all elastomers are polymers composed of extremely long-drawn molecular chains [2].

Elastomers are both synthetic and natural rubber. These elastomers are amorphous polymers with numerous combined components to form a rubber compound. The heating process and the chemical reaction of the elastomers called is vulcanization, which transforms the raw elastomeric materials into solid and elastic rubber materials [3]. As a result, elastomers are commonly referred to as rubber, and when subjected to stress, they have a high capacity for great deformation, distinguishing them from plastics. Put another way, they can be extended to one hundred percent of their original length without permanently deforming. Deformation is allowed through the polymer chain's arrangement and molecular structure of the elastomer. At rest, the polymer chain is incredibly warped and entangled, while the chain becomes linear when stress is applied [4–7]. These chains return to the normal, unstressed state after being released from stress. To ensure the chain is unstructured at rest, the elastomer's molecular structure should not be permitted to align itself and form a crystalline structure. Adding groups to polymer chains or utilizing more than one kind of monomer is the most common method of avoiding crystallization and regulating the aligned chains. Thus, the final product chain of an elastomer is cross-linking [8–11].

Cross-linking is the process of combining polymer chains and joining them with chemical bonds. These connections of chains limit motion while the strength is also increased [12]. Due to the inexpensive and availability of elastomeric components, they have a wide range of applications in real life and especially in engineering, such as tires, engine mounts, vibration isolators, gaskets, biomechanics, medical/dental, and solid propellants. They are also widely used due to their energy absorption and exceptional damping properties, as well as their flexibility, rebound, long-term use, and capability to resist humidity, high temperatures, and stress. Also, non-toxic. Elastomers are one-of-a-kind materials. It often behaves like a very viscous fluid through processing and molding. Elastomers can be subjected to substantial reversible elastic deformation when their polymer chains are bonded by the curing (or vulcanization) process. It will return to its former shape after removing the effective force, except if a failure occurs. The elastomer's one-a-kind properties, such as [13,14]:

i. Large deformations under the influence of load, and the elongation may reach five hundred percent in engineering applications.
ii. The stress-strain relation is noticeably non-linear.
iii. Exhibits substantial damping properties because of viscoelastic behaviors.
iv. Temperature and time-dependent behaviors.

v. Incompressible or incompressible, which indicates that its volume changes significantly under the action of stress, with the Poison's ratio being near or equal to 0.5.

The effects of high levels of vibration and noise are among the most common reasons that lead to the failure of the structures. As a result, rubber is used as a foundation for these structures in most applications to reduce these effects. In addition, Structure systems of a viscoelastic foundation are widely used in actual life for engineering applications such as decks of ships used as helipads for helicopters, runways of airports [14], railways vehicles, or any structure provided by the viscoelastic foundation. The viscoelastic foundation adds exterior damping to these structures, which is vital to the dynamic response. The viscoelastic foundation showed a time- time-frequency-dependent mechanical property. Therefore, the viscoelastic foundation is a mechanical component that is very important in the design process of the structure [15].

Relying on the above application's structure-foundation system can be represented as a thin plate sitting on the viscoelastic foundation. As a result, categorized the present works into two parts. Part one: studying the effects of adding the different percentages of ZnO and filler reinforcement (different percentages of MWCNT) to the natural rubber experimentally to obtain a suitable recipe characterized by good damping, good dynamic stiffness, and good fatigue life. Part two: Using the properties of the suitable recipe extracted from part one which recipe has good damping properties and good dynamic stiffness as a foundation for a thin plate to study the effects of various boundary conditions of plate edges, plate aspect ratio, and type of load on the dynamic response of a plate-foundation system analytically and numerically (by SOLIDWORKS software) [16].

Natural Rubber (NR)

Natural rubber is a fundamental elastomer and continues to play a vital role in the industry. It is one type of rubber from the heave tree as latex that grows in tropical regions and numerous countries. Indonesia, Malaysia, and Thailand are the largest producers, accounting for 80% of global consumption. Collect the latex in cups, then pour into containers before being transferred to the rubber factor. To generate technically specified, consistent viscosity grades of natural rubber, the latex is treated with stabilizers such as sodium sulfite, formaldehyde, and ammonia, as well as hydroxylamine, which may also add to enhance coagulation. Milled the rubber into sheets, cleaned, dried, smoked, and finally categorized to make smoked sheets [13].

Natural rubber is composed of carbon and hydrogen and has the empirical formula (CHs). The structure of natural rubber is a cis-1,4-polyisoprene (2-methyl-1,3-butadiene), as shown in Figure (1), and it has a glass transition temperature of about -70 °C [15,16]. It has a flexible nature, particularly if it has a high grade of (cis.) due to the existence of methyl groups following one of the chains that prevent the natural rubber from sufficiently arranging itself. As a result, gaps will arise between particles that dissipate the energy of the vibration wave. On the other hand, the uniformity of the molecular structure enables natural rubber to crystalline at low temperatures and increases hysteresis [17].

Furthermore, natural rubber has excellent low-temperature resistance, even down to -57 °C, where its stiffness can increase significantly [18]. Springs, bearings, vibration isolators, and heavy-duty tires are among the products made from natural rubber. It is utilized in seals, hoses, belts, conveyors, and other items for a specific function [19]. Table (1) lists the characteristics of Natural rubber.

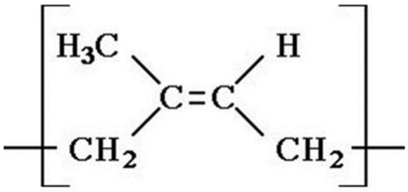

Fig. 1. - Natural Rubber Structure.

Table 1. Advantages and disadvantages of NR [20].

Advantages	Disadvantages
Tear Strength	Uniformly of Quality
Wear Resistance	Aging Resistance
Impact Resilience	Fatigue Resistance
Low Heat Generation	Ozone Resistance

Sodium Bicarbonate ($NaHCO_3$)

The structure of sodium bicarbonate $NaHCO_3$ or sodium hydrogen carbonate is represented by the monoclinic crystalline form. This salt is composed of sodium ions and bicarbonate ions, where ($NaHCO_3$) is its molecular formula. It is commonly called baking soda. It has a weak base and is used in cooking. The pH value is about 8.31. Figure (2) shows that structure.

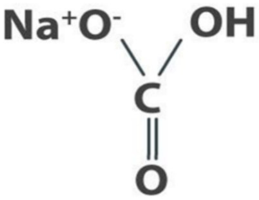

Fig. 2. - Carbon Nano-tubes (CNTs).

Ijimain Japan discovered CNTs in 1991 [21]. CNTs are among the most investigated nanomaterials owing to their unique features, for instance, high ratio of length to diameter, extraordinary strength, remarkable visuals, and conductivity experiences, making them attractive options for a diverse range of different applications [22]. A CNT is a graphene sheet (with carbon atoms arranged in a hexagonal pattern similar to the honeycomb) wrapped up to produce a hollow cylinder with diameters typically measured in a nanometere.

A nanometer is one-billionth of a meter, or around ten thousand times smaller than a human hair [23]. In other words, a graphene sheet shows a rolled-up chicken wire with a continued intact hexagonal lattice and carbon molecules at the vertexes of the hexagons [24,25].

Carbon nanotubes (CNTs) come in three types: MWCNTs, double-walled CNTs (DWCNTs), and Single-walled carbon nanotubes (SWCNTs). Because of the high aspect ratio (length-to-diameter ratio) and small diameter, the (SWCNTs) are 1D (meaning one-dimensional) substantial allotropes of carbon atoms. SWCNT has a hollow cylindrical shape produced by rolling a single layer of graphene sheets. Two or multiple rolling sheets of concentric graphene nano-tubes inside other nano-tubes give DWCNTs and MWCNTs respectively. Figure (3) shows the three types of CNTs mentioned earlier [26].

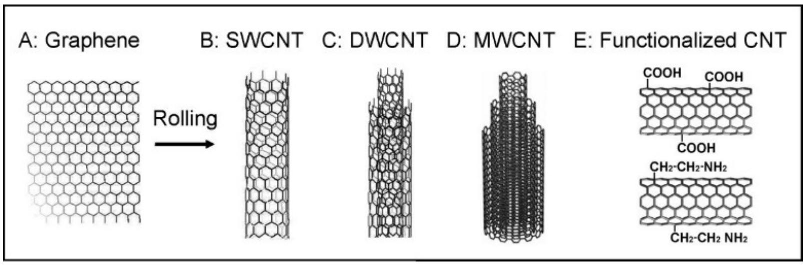

Fig. 3. - Types of CNTs.

Russian doll and Parchment structures are the two types of MWCNTs. In the Russian doll structure, numerous concentric CNTs that, the structure has a small and large diameter). Meanwhile, in the parchment structure, a single graphene sheet is wrapped around itself many times, similar to a rolled-up paper scroll, as seen in Figure (4) [27].

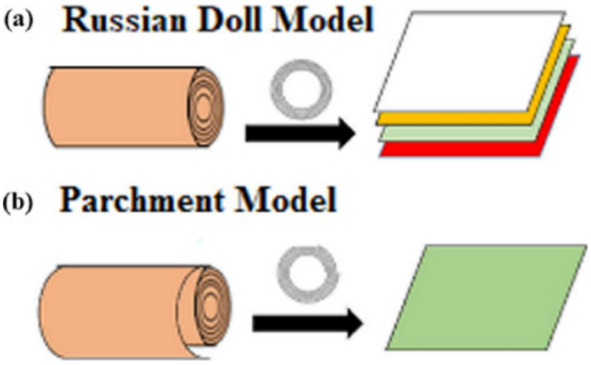

Fig.4. - Structures of MWCNTs.

Chemical vapor deposition are discharge, and laser ablation are three ways of producing CNTs. Most of these operations are carried out in emptiness or using gases for treatment. In chemical vapor deposition, the CNTs may be developed in airless or air pressure. All of these techniques can produce high-quality nanotubes in large amounts [28,29].

The arc discharge method generates CNTs by containing a chamber with two opposite electrodes (anode and cathode) constructed of graphite poles. These electrodes are placed in inactive gas (argon or Helium at 500 TORR), and a potential difference is used between them to produce an arc-resulted plasma. As a result, the carbon atoms are evaporated and deposited on the cathode pole, illustrated in Figure (5) [30,31].

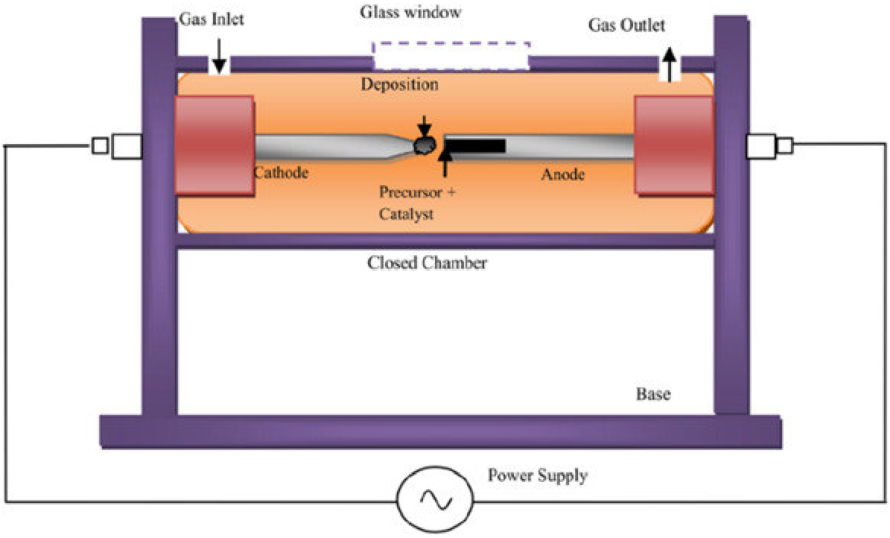

Fig. 5. - Arc discharge device.

In the laser ablation method, CNTs are produced by applying a laser beam to a solid graphite target instilled in a quartz tube within an inactive environment and subjected to a temperature of about 1200 °C, as seen in Figure (6). As a result, the graphite target evaporates, and then the carbon tubes are deposited on a copper collector that is cooled by water [32,33].

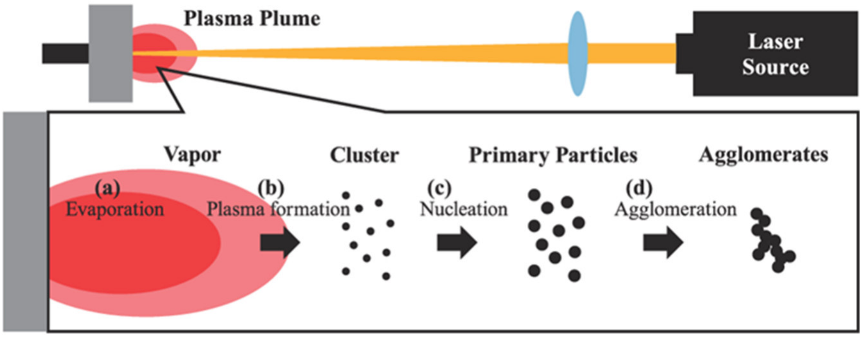

Fig.6. - Laser ablation method.

Injected the reaction compartment with a combination of hydrocarbons such as (ethylene ethanol, propylene, acetylene, CO, and methane), a metal catalyst such as (CO, Fe, and Ni), and inert gas, as shown in Figure (7). After injection, the reaction compartment is heated to temperatures between (500-1000 °C at the air pressure), and nano-tubes are formed on the device's base due to fractured hydrocarbon [34,35].

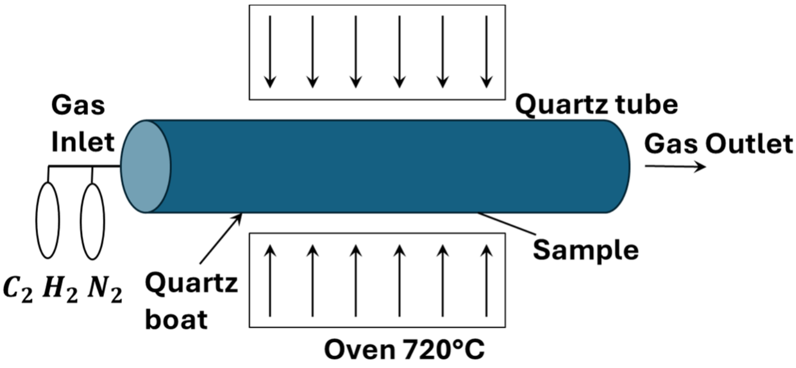

Fig. 7. - Chemical vapor deposition method.

Natural rubber is extensively used in many engineering applications because of its advantages, such as flexibility. However, some properties, like ozone resistance, oil resistance, damping, fatigue, and dynamic stiffness, are unsuitable for some applications. So, rubber blends, that is, natural rubber mixed with one or more types of synthetic rubber, are considered an appropriate way to change the efficiency of rubber materials to obtain the desired properties.

Carbon black remains the most common and extensively used reinforcing filler. Furthermore, its properties, such as particle size, surface activity, structure, and surface area, influence the basic properties of polymers.

CNTs are used as reinforcing fillers added to rubber compounds to enhance their electrical, mechanical, and dynamic properties. The enhancement of these properties by adding CNTs in different proportions to the rubber compounds can be achieved when there is sufficiently better interaction between the rubber compounds and the CNT particles and when the CNT particles are well distributed within the polymer matrix. The viscoelastic foundations represent a part of the structure widely used in many engineering applications. This structure can be modeled as a plate, beam, or pipe sitting on viscoelastic foundations according to the application to be studied.

The mechanical, physical, and dynamical properties of elastomers have gained extensive attention from researchers. Those researchers are focused on the improvement of different properties of elastomers such as tensile strength, elongation, compression, curing characteristics, resilience, fatigue, dynamic stiffness, damping, and swelling under the effects of many factors like vulcanization agents, thermal agents, blends type, and type of reinforcement fillers.

The feasibility of making epoxidized natural rubber (ENR)-alumina nanoparticles composites (ENRAN) was studied using melt compounding followed by Sulphur curing. To examine the impact of filler loading on the cure characteristics and mechanical qualities, alumina nanoparticles were incorporated into the compounding recipes at concentrations of 10, 20, 30, 40, 50, and 60 parts per hundred rubbers (phr). SEM analysis was used to examine the distribution of alumina nanoparticles (SEM). Compared to empty ENRs, curing times were cut by as much as 40 percent when alumina nanoparticles were added to the matrix. As the cross-link density rose in the presence of alumina nanoparticles, so did the minimum torque (ML), the maximum torque (MH), and the torque difference (MH-ML). The ENR compound's tensile strength, elongation at break (EB), and impact strength dropped as the proportion of alumina nanoparticles to the total increased. However, the results showed better hardness and tensile modulus than unfilled ENRs. Increasing the ENRANs' MH, ML, tensile modulus, and hardness resulted from the matrix's evenly dispersed alumina particles [36].

The research was published concerning the creation of reinforced elastomer composite by adding reinforcing fillers Al_2O_3 and SiO_2 individually to the styrene butadiene rubber (SBR) with a range of loading stages (0-5-10-15-20 and 25 pp-hr). It has been demonstrated that mechanical properties, except for robustness, can be improved by adding reinforcing fillers and raising their loading level. In particular, silica fillers were superior to alumina fillers in terms of increasing these properties. In terms of ultimate strength tensile (67 MPa), with the elasticity of modulus at 100% elongation (13MPa) and percentage of elongation at break, the alloy SBR reinforced with silica fillers 25 pp-hr displayed the most significant values (172%). The silica reinforcement in the styrene-butadiene rubber decreased its minimum resilience to 65.59 percent. The figures for its hardness and abrasion resistance were also the highest and the lowest, respectively. The loading amount of reinforcing fillers had a notable impact on the physical characteristics, which meant that the liquid's action (swelling) was unique to that factor. By incorporating the strengthening of fillers and an increase in in terms of thermal conductivity, the filler loading was also improved. Fillers made of alumina rather than silica tend to significantly impact heat conductivity. Due to the increasing volume of reinforcing fillers, rubber composites' specific gravity must be increased [37].

The NR nano-composites were prepared using pure attapulgite (PAT) or modified attapulgite (MAT) in a double-roller plasticator mixer (PAT-450 and PAT-850, respectively), both of which were heated to 450 and 850 degrees Celsius for two hours. Modified attapulgite was distinguished by its immaculate crystal structures, which were clear by FTIR, TEM, XRD, and BET analysis. The findings suggested that the attapulgite's structure shifted when the temperature was raised. The mechanical characteristics of the NR nano composites were also studied to see how they were affected by the PAT treatment and composition. The data demonstrated that AT facilitated the natural rubber curing process. Nano composites containing various kinds of attapulgite outperformed pure NR samples in terms of tensile strength, wear ability, and solvent resistance. Scanning electron micrographs revealed that the filler was localized at the interface, which caused compatibilization with otherwise immiscible mixes. A thermo gravimetric study showed that the NR/PAT nanocomposites significantly increased thermal stability [38].

The nano fillers reinforced natural/synthetic rubber were studied, and the production of synthetic composites with micro and nano-$CaCO_3$ as filler material was also studied for comparison purposes. It has been discussed how fillers may change rubber's mechanical strength, thermal conductivity, and permittivity, among other qualities. However, the nanoparticles' high surface energy makes them prone to climbing together, which has proven to be a challenge. Nano-sized calcium carbonate ($CaCO_3$) is used as a reinforcing agent in various sports equipment compositions (laminated sheets for inflated balls, for example). $CaCO_3$ particles are impermeable; therefore, the permeability to gases and vapors becomes lower when added to flexible polymeric membranes. Permeation values were reduced because the nano-$CaCO_3$ filler in NBR formed a more convoluted route against gas penetration than traditional fillers [39].

Work on the fabrication of Matrix composites was achieved Using curauá fiber and a nanoparticulate mineral (montmorillonite clay - MMT) as reinforcing agents were, made from Styrene-Butadiene-Styrene (SBS) (SBS). Composites with 5, 10, and 20 percent cure Fiber and a maleic anhydride grafted styrene (ethylenic butylene)-styrene triblock copolymer underwent testing for tensile strength, grip strength, rebound resilience, flex fatigue life, abrasion loss, hardness, and water absorption (MA-g-SEBS) coupling agent. The best mechanical properties were found in the hybrid SBS composite containing 2% MMT and 5% curauá fiber. Increases in All mechanical parameters were negatively affected by fiber content up to 20 wt.%, and tensile strength was negatively affected by the addition of 5 wt.% MMT. The poor mechanical performance of composites with increasing concentrations of curauá fiber and MMT nanoparticles may be due to poorly distributed clay agglomerates (tactoids) in the hybrid composites. Using plasticizer further decreased the tensile strength of all SBS composites, whereas incorporating MMT nanoparticles decreased their water absorption [40].

Researchers worked on the calendaring procedure for reinforcing synthetic compounds of styrene-butadiene rubber (SBR) and natural rubber (NR) with Al_2O_3 and SiO_2 fillers. Adding alumina and silica particles at different ratios has changed the tensile characteristics of both styrene butadiene rubber (SBR) and natural rubber (NR) (5, 10, 15, 20, and 25 pphr). Increasing the loading amount of both reinforcing particles improved the tensile properties. Natural rubber's tensile qualities were superior to styrene-butadiene rubber's, and silica particles were more efficient in reinforcing the material than alumina ones. Maximum tensile strength at break (70MPa), modulus of elasticity (18 MPa), and elongation percentage at break (350%) were measured for natural rubber reinforced with (25 pphr) of Silicon dioxide [41].

Natural rubber vulcanizates with varying concentrations of titanium dioxide particles were produced and characterized. Rubber samples were vulcanized in a hydraulic press after being processed in a two-roll mill used in the lab. Our prior research served as the basis for creating the rubber combination and the rubber-processing technology. Titanium dioxide loadings of 15, 25, 45, and Vulcanizates with a range of TiO_2 particle sizes were found to perform well across the board. A study using Fourier transform infrared spectroscopy revealed that the chemical structure of the resulting natural-based composites was unaffected by the addition of titanium dioxide particles85 wt % per 100 wt % of natural rubber were used to obtain the samples. This research aimed to identify the effects of varying titanium oxide particle loadings on the chemical composition and morphological, mechanical, and thermo-mechanical characteristics of natural rubber-based composites. It was clear from the SEM micrographs that the TiO_2 particles were evenly distributed throughout the natural rubber matrix. At more significant concentrations of TiO_2 in the matrix, the filler began to aggregate. The resulting natural rubber composites exhibited somewhat varied thermal stability, as determined by thermo gravimetric analysis. A dynamic mechanical and thermal examination found that the glass transition temperatures of the produced materials are close to one another. However, more significant energy loss occurred during mechanical work on the materials, and higher cross-link density was achieved by increasing titanium dioxide concentration in the produced materials [42].

It was found that nitrile rubber (NBR) enhanced with hybridized Graphene oxide (GO) and silicon dioxide (SiO_2) nanoparticles increased mechanical and dynamic mechanical capabilities. The newly produced hybrid nanoparticles (GO/SiO_2) were more thermally stable than GO due to the uniform dispersion of SiO_2 nanoparticles on the surface and between GO layers. Soluble blending and mechanical solution procedures were used to generate GO/SiO_2/NBR nano-composites, which were then tested for their mechanical characteristics. It was found that the tensile strength of GO/SiO_2/NBR nano-composites grew more gradually than that of GO/NBR and SiO_2 nano-composites. In contrast, the elongation at break varied only gradually. In addition, dynamical tests revealed that incorporating GO/SiO_2 hybrid nanoparticles into NBR improved the material's elasticity. Morphological studies of GO/SiO_2/NBR and GO/NBR nanocomposites led researchers to infer that the hybridization of the GO/SiO_2 was the crucial factor in reinforcing the mechanical characteristics and elasticity of the NBR [43].

The traditional ZnO was replaced with nano-ZnO as an activator, and its impact on the tensile characteristics of natural rubber composites was studied. Traditional ZnO was used as the activator in one compound at a concentration of 8 p hr (part per hundred rubber), whereas Nano-ZnO was used in eight other compounds at values of (0.2), (0.6), (1.0), (1.4), (1.8), (2.2), (2.6), and 4% phr. We used a Monsanto T10 Tensometer to conduct the tensile test. The results indicated that at 1.8 phr, Nano zinc strength under tension and modulus of elasticity were higher for oxide, at 300%. The cost of the compounds was reduced by 77.5% when traditional ZnO was replaced with Nano ZnO. Moreover, its tensile strength was increased by 38.14%, and its impact on the environment was diminished by 62% [44].

Preparation methods, characterization methods, and developed nano-composites mechanical and thermal characteristics and their most recent applications were all presented. Rubber nano-composites (RNCs) have found commercial homes in the tire and sports sectors thanks to their benefits in terms of product weight, energy loss, and air retention [45].

Investigation was carried out on how using a novel reinforcing material differs from using carbon black or other traditional reinforcement materials in various applications. This research demonstrates the use of white cement as a carbon black substitute in construction applications, adding a new material, sediment dust, to recipes that traditionally call for carbon black as a reinforcement, all to examine the materials' mechanical properties. Samples were tested for properties, including tensile strength, tear resistance, hardness, and compressibility, and the reinforcement formulas that included carbon black came out on top in every case. The practical test also showed that using white cement and Nanoparticles of sediment dust (new reinforcing material) produced acceptable results in comparison to the traditional recipes reinforced by carbon black, particularly when using percentages between (2-8%) [46].

Detailed processes involved in making nano-scale carbonaceous reinforcements in rubber nano-composites include graphene, expanded graphite, SWCNTs and MWCNTs, graphite oxide, graphene oxide, and hybrid fillers made up of combinations of individual fillers. After that, we looked at the thermomechanical characteristics (glass transition temperature, crystallization temperature, and melting point) and static mechanical parameters (parameters for fracture toughness, tensile strength, elongation at break, and Young modulus) of these nanocomposites of rubber. Finally, the results found by Payne and Mullin in rubber-containing carbon nanofillers were discussed [47].

Some investigators looked at how rubber's mechanical characteristics and creep behavior may be altered by reinforcement using carbon multi-wall Nanoparticle composites. The mechanical characteristics (rubber's strength) and mechanical creep behavior weight fraction impacts of Nanoparticle materials are being evaluated as part of the study. Experimental methods created many rubber samples with varying concentrations of Nanoparticles. The mechanical characteristics and behavior of the materials were then evaluated using tensile and creep testing equipment. Nanoparticles were utilized at 0%, 2%, 4%, 6%, 8%, and 1% by weight, respectively. The creep behavior is also studied numerically, employing the finite element method within the ANSYS software, and the findings are compared to those obtained by experimental calculations. The comparison indicates that the inaccuracy is less than or equal to (8.36%). The research concluded that rubber's mechanical characteristics and creep behavior were influenced by roughly (65%) with reinforcement by (1%wt) for multi-wall carbon Nanomaterial [48].

Comprehensive research was presented on nanofillers in natural rubber, including carbon nanostructures, clays, and spherical silica particles made using the sol-gel technique. It was shown that various parameters, including processing conditions, filler dispersion state, polymer-filler interactions, and filler morphological characteristics, influence the mechanical response of NR. Mechanical reinforcement using rod-shaped particles, such as those found in clay, carbon fibers, or CNTs, is much more effective owing to the particles' anisotropic nature and ability to align themselves in the direction of stretch, even if the sol-gel technique is used. vulcanized rubber yields almost ideal distributions. Distribution (exfoliation) in the rubber is crucial for performing multilayer fillers like clays and graphitic structures. Still, peeling off an entire layer of clay or graphite is difficult, limiting the huge nano-reinforcement that could otherwise be achieved. Due to strain amplification effects, crystallization always began at a lower strain value than in the empty matrix [49].

The investigation of how nano ZnO differed from traditional ZnO was carried out in its effects on natural rubber composites' curing characteristics and mechanical qualities. Nano ZnO (particle size = 10-30 nm, surface area = 30-60 m^2/g), added at concentrations of 0, 0.4, 0.8, 1.2, 1.6, and 2 pphr, was used to create six different rubber composites. ZnO was mixed with rubber at the standard concentrations of 0, 2, 4, 5, 6, and 8 parts per million to create six different compounds. The torque differential increased by 4.77 percent, while the cure rate index increased by 48.29 percent. There was a 7.37 percent increase in tensile strength, a 3.27 percent increase in modulus at 300%, and a 5.73 percent drop in hardness. There was a 75% decrease in ZnO content in rubber composites when nano ZnO was used instead of regular ZnO [50].

It was shown that nanomaterials and particles have been found to positively affect how composite materials act in context, which has been investigated. This influence was found to extend to factors such as the material's size, shape, dispersal method, adherence, and compatibility with other phases taken into account throughout the production process. So, they looked at how various nanomaterials performed depending on loading circumstances and adhesion sizes in the designated fillers class. Moreover, it demonstrated the optimum filler quantity for increasing mechanical characteristics and fracture toughness from interlaminar and intralaminar viewpoints. In addition, a system was developed to categorize the impacts of soft, complex, and hybrid fillers, demonstrating how some fillers had spectacular benefits for improving specific properties. In addition, the optimal nanomaterial application in terms of loading circumstances was elucidated. The review concluded with hints about how nanofillers and particles impact the beginning of damage and the behavior of fiber-reinforced plastic composites [44].

The reinforced polymer mix (silicone rubber: 5% PMMA) with two distinct types of natural nano-powders is used to create nanocomposite composites. Loading levels (0%, 0.1%, 0.2%, 0.3%, and 0.4%) of Pomegranate peel powder (PPP) and seed powder of dates ajwa (SPDA) were tested. Mechanical parameters, including tensile strength, hardness, compressive strength, and surface roughness, were evaluated, and FTIR, DSC, and SEM analyses were performed on the produced sample. Based on the data, a combination of 2% PPP and 3% Ajwa Seed Powder yields the best possible qualities [51].

To restore the functionality and enhance the aesthetics of maxillofacial prostheses, looked at the enhanced characteristics of hybrid nanocomposite materials. 95% styrene-butadiene-methacrylate (SR)/5% poly(methyl methacrylate (PMMA) and (PPP) polymer mix composite was modified by adding ultra-high-molecular-weight polyethylene (UHMWPE) fiber of varying lengths (0%, 2%, and 1%) to improve the characteristics of silicone rubber for maxillofacial prosthesis applications. Based on the findings, the ideal component ratio of the hybrid composite sample is 95% SR, 5% PMMA, PPP at 0.2%, and UHMWPE at 0.5% in a continuous state fiber added. Consequently, the mixture may be a contender for reaching the qualities needed for the applications of maxillofacial prostheses [52].

Some researchers have investigated how combining SiO_2 nanoparticles into a styrene-butadiene rubber and natural rubber (NR) affects the latter's mechanical and physical properties (SBR). Nanoparticles were added at concentrations of 0, 0.2, 0.4, 0.8, 1, 1.5, 2, 2.5, and 3 pp hr to the rubber blend (30% NR/ 70% SBR) in an experimental two-roll mill with molds and a thermal piston; the pressure, temperature, and time difference test conditions were standard; and the rubber blend was prepared with vulcanization factors, accelerators, and activators. Mechanical properties (hardness, fatigue, and compression set) improved in the lab with increasing percentage load (pphr) up to 0.8 pphr, when a little decrease occurred. Increases in SiO_2 concentration in the rubber formula increase viscosity and decrease torque, scorch, and cure times [53].

Some investigators did a look at how nano-silica particles affected the properties of SiO_2-doped ethylene propylene diene monomer (EPDM) and styrene butadiene rubber (SBR). The composite EPDM/SBR was processed with and without a silane coupling agent in an open mill mixer. The composites' curing behavior, mechanical properties, hardness, rebound resilience, swelling resistance, abrasion resistance, and compression set were all studied. Components were tested for various characteristics, including curing speed, hardness, rebound resilience, swelling resistance, abrasion resistance, and compression collection. Mechanical characteristics, including swelling resistance, hardness, abrasion, and compression set, were enhanced in EPDM/SBR rubber composites when introducing nano silica particles [54].

A thorough analysis was provided for plant-based filler rubber biocomposites. The matrix (natural or synthetic rubber) and lignocellulosic fillers (cellulose from plants) determined the structure's divisions (natural fiber, microcrystalline cellulose, lignin, and nitrocellulose) [55]. Curing behavior and static and dynamic mechanical properties of the resultant rubber bio-composites were investigated. In addition, a comparison was made of the attributes of these rubber bio-composites after taking into account the impact of hybrid filler systems, surface modification of lignocellulosic filler, and the rubber matrix [56].

The qualities of the Nanotube rubber material were investigated using inverse FE modeling and indentation tensile testing. NR rubber's mechanical properties were improved by adding nano-tubes of carbon varying ratios of multiple-walled CNTs subjected to high tensile stress. All- Recently, CNTs have begun to appear in natural rubber. To generate nano-composites, a solvent casting method, toluene, was employed. 0.2%, 0.4%, 0.6%, 0.8%, and 1%. The mechanical characteristics of NR CNTs have been investigated. Parametric FE models were used to simulate and validate indentation tensile tests on rubber samples. The rubber samples' hyperelastic properties under uniaxial tension were identified using an inverse materials parameter identification strategy. The data on material properties and force-displacement relationships may be automatically updated and extracted. with ABAQUS FE software. We will use these curve-fitting parameters and display equations to draw a mathematical connection between and. curve coefficients. Material attributes were shown to streamline the inverse FE modeling process [20].

A study of recycled rubber composites was produced with different reinforcements in the literature through toughening methods, mechanical and physical qualities, and microstructural and fracture surface research. Microscale reinforcements (glass bubbles and alumina fiber) and nano-scale reinforcements (nano-silica and graphene nano-platelets) exploited as reinforcements in rubber composites were comprehensively examined. Most research into recycled rubber composites has found that using micro-scale particles to strengthen the material improves the structural, physical, and mechanical qualities while making the composites cheap and lightweight. High toughness and impact resistance are two qualities that may make composites made from recycled rubber a good fit for specific uses [57].

The epoxy and epoxy-based carbon fiber-reinforced polymer tensile characteristics were investigated to determine the fracture toughness and glass transition temperature (CFRP). The experiment included three CSR nanoparticle-containing additives, with the filler fraction in the epoxy resin ranging from 2% to 6% by weight. The maximum filler percentage of CSR nanoparticles resulted in a decrease in tensile strength and elastic modulus of 10–20% and an increase in fracture toughness of 60–108%, as shown by experimental data. A maximum of 53% increase in CFRP interlaminar fracture toughness was recorded for ACE MX 960 at 4 wt.% CSR content. The glass transition temperature of the epoxy increased by 10–20 degrees Celsius for every doubling of the number of CSR nanoparticles in each addition. In some cases, a combination of stiff and soft particles may be preferable to employing only one kind of particle to provide the desired tensile properties and fracture toughness [58].

Conclusion

This review has critically examined the enhancement of mechanical and dynamic properties of elastomeric materials - particularly natural rubber - through the incorporation of nanostructured reinforcements such as ZnO, MWCNTs, and $NaHCO_3$. The integration of these fillers has demonstrated significant improvements in tensile strength, elongation at break, tear resistance, dynamic stiffness, and damping behavior, thereby extending the functional performance of elastomers under complex loading conditions.

The literature reveals that the performance enhancement is primarily governed by filler morphology, dispersion quality, interfacial bonding with the polymer matrix, and the cross-linking density achieved during vulcanization. MWCNTs exhibit exceptional reinforcing efficiency among the reviewed nanofillers due to their high aspect ratio and mechanical robustness, while ZnO and $NaHCO_3$ contribute to curing kinetics and microstructural stability.

Furthermore, applying these optimized elastomeric formulations as viscoelastic foundations in structural systems, such as thin plates subjected to free and transient vibrations, has shown promise in controlling structural dynamics and mitigating vibration-induced stresses. Finite element modeling has proven to be an essential tool for predicting the behavior of such systems and validating experimental findings.

The convergence of material innovation and structural dynamics modeling underscores the strategic role of nano-composite rubber in next-generation vibration isolation and damping systems. Future research should focus on optimizing filler content, improving dispersion techniques, and exploring multifunctional filler systems to further advance the capabilities of elastomeric composites in mechanical and civil engineering applications.

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