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Experimental investigation of the effect of nanomaterial reinforcement on the mechanical properties of rubber structures used in crank pulleys

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Automotive technology is constantly evolving with the desire to make engines light and to reach strong torques. The viscoelastic rubber material is seen as the most damaged material in crank pulleys structure used to dampen torsional vibrations. For this reason, the manufacturers' efforts to increase this structure's strength without departing from the design parameters of the rubber material are continuing today. In this study, nanosized alumina and zeolite reinforcements were introduced into natural and EPDM rubbers, which are non-linear materials, using spraying and homogeneous mixing methods. Tensile tests were carried out on reinforced and non-reinforced rubber samples. A graph was created with torque data corresponding to four different samples. The torsional stiffness was found from the slope of the graph. Experimental modal analysis results using a hammer were compared with torsional stiffness. A deviation close to 10% was observed between these two methods. Motor simulation and noise tests were performed on the sample pulleys and it was found that the most suitable pulley is the nanozeolite-reinforced crank pulley with the homogeneous mixing method (HMM).

Keywords: Rubber, nanoalumina, nanozeolite, torsional vibration damper, vibration, noise.

INTRODUCTİON

Crank pulleys are front parts of the engine that are attached to the crankshaft on the engine assembly. The movement from the crank is integrated with the other pulleys (alternator, air conditioner, water pump, oil pump, idler) on the engine with the help of the v-belt.

Crankshafts are subjected to torsional vibrations in a regular regime. The tensile strengths and fatigue strengths in critical regions of the crankshaft must be determined precisely by modern calculation methods for these vibrations. Today, due to technical, commercial, and environmental requirements, internal combustion engines must operate with high cylinder pressures, and components must be optimized for best performance. Therefore, the crank pulley plays an important role.

Elements that make up the crank pulley are:

1. *Pulley:* It is responsible for moving the engine elements such as the water pump, alternator, and air conditioner through the Poly V belt with the movement taken from the crank.
2. *Hub:* This is where the crank pulley is mounted on the crankshaft. A crank speed and position sensor is connected between the crankshaft and the hub joint. This sensor is responsible for reporting the angular position of the crankshaft and the engine speed to the ECU.
3. *Vibration rubber:* It is responsible for damping torsional vibration amplitudes.

Ramzan *et al*., in their study, obtained a material whose elastomers are composite with nanomaterials. The damping capabilities of natural rubber by adding nanoparticles into it were investigated, and as a result, design parameters in different variations were determined [1]. In another study, Ramzan and Kumar prepared a test setup and demonstrated that this test method increased the damping ability of nanomaterials [2].

Ziraki *et al.* added silica nanoparticles and polypropylene fibers to the silicone rubber matrix. The viscoelastic behavior and mechanical properties of the samples of this nanoparticle reinforced rubber were investigated. The results proved that silica particles increase the elastic modulus of rubber and impart high hardness [3].

Huang and Tsai characterized the vibration damping response of composite layers containing silica nanoparticles and rubber particles. The experimental results were compared with the finite element method. From these results it was concluded that the bending stiffness of fiber composites decreased, and the damping properties of the layers improved, especially for (90/10) layers [4].

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Muhammad *et al.* have designed a new nanocomposite vibration damper. They used NR and alumina zirconium as test samples. In addition, they made a comparison with the analytical and finite element method with the modal analysis [5].

Nagar *et al.* designed a damper for a multi-cylinder engine and compared two different rubbers such as EPDM and AEM, and found that it provides better damping, oil resistance, and durability. The currently produced EPDM rubber sample has proven that it absorbs torsional vibrations better by 50% at critical speeds in a multi-cylinder diesel engine by measuring torsional vibrations in the engine test device and then subjecting it to the same tests on AEM rubber [6].

Qiu *et al.* have prepared a series of maleic anhydride-grafted ethylene-propylene-diene rubbers (EPDM-g-MAHs) with different inoculation grades by rotary evaporation assisted melt grafting, which can achieve a higher inoculation rate and smaller gel content. Morphological observation, thermal analysis, and rheological measurements confirmed that the interfacial compatibility of core-shell dispersed phases is enhanced by increasing the inoculation degree. In this study, a new understanding of the hardening mechanism of core-shell particles was presented [7].

Enew *et al.* investigated the effect of aramid fiber in the form of vlar (KP), carbon mono fiber (CMF), and nanocarbon black (NCB) pulp as filler for Trilene liquid polymers on the mechanical properties of the EPDM rubber. They found that EPDM rubber improved its mechanical properties such as thermal insulation, tensile strength, elongation, and hardness [8].

Ravindran *et al.* investigated the mechanical properties and solvent absorption properties of the nanocomposites they produced by TEM analysis. They found 243% as the maximum increase in tensile strength of nanocomposites. The value and percent elongation of the pure mixture increased by 67%. They observed significant differences in mechanical and absorption properties as the filler content changed [9].

Fig. 1 shows the failure of the damping ability of the crankshaft to resonate and its rupture from the elastomer area. In this case, nanoparticle reinforcement improves the mechanical properties of the elastomer part and increases the damping ability, thus eliminating these problems.

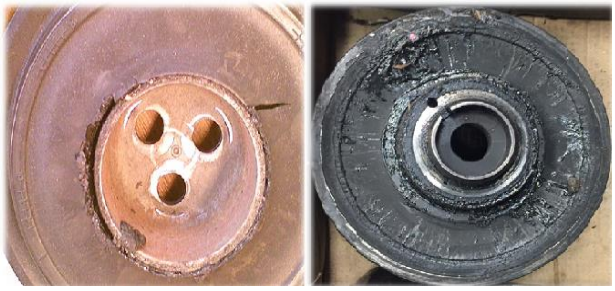

Fig. 1. Defects in the crank pulley

MATERİAL AND METHODS

Nanoalumina (0.5%) and nanozeolite (1.1%) reinforcement particles were added to NR and EPDM rubbers as matrix elements of the test samples using homogeneous mixing (HM) and spraying method. Sample crank pulleys were vulcanized in a hot press at 150 °C for 15 minutes. For the uniaxial tensile test, samples conforming to ASTM D412 – C standards were cured at the same temperature and time.

In the homogeneous mixing method, the raw materials in Table 1 were mixed. A 100% pure polymer NR and EPDM rubber was used. Nanoalumina 0.5% and nanozeolite 1.1% were reinforced in the mixture. Carbon black was used to increase the hardness of the sample and other raw materials to increase the efficient workability of the mixture. It was applied to natural rubber and EPDM rubber by spraying alumina and zeolite particles on rubber with a spray gun at 3 – 4 bar air pressure. In this method, a special solution (methyl ethyl ketone + nanomaterial) was made and absorbed into the rubber. A physical mixture was provided with 40 mg of nanomaterial and 20 ccs of MEK into the mixture.

According to Hooke's law, both tensile and compressive behaviors of metals show the same properties in the elastic region. Features such as Poisson's ratio and modulus of elasticity can be found easily. However, the same statements are not true for elastic materials such as rubber [10]. Due to the different behavior of rubber in the tensile and compression regions, it is insufficient to determine only the mechanical properties. Due to the accumulation of knowledge on this subject, standards such as ASTM D412, DIN 53 504, and ISO 37 have emerged [11-13].

Test samples were made according to ASTM D412 – C sample and subjected to the uniaxial tensile test under a constant load of 45 kN without preload. (LLOYD LR50KPlus).

Table 1. Ratios of nanoalumina and nanozeolite-reinforced rubbers produced by HMM

Raw Materials	%	phr
NR Rubber/ EPDM Rubber	100	51.7
Nanoalumina	0.5	0.25
N330	76	39.29
Oil	4	2.06
Other	14.6	7.53
Total	193.39	100

Raw Materials	%	phr
NR Rubber/ EPDM Rubber	100	33.82
Nanozeolite	1.1	0.37
N550	120	40.5
Oil	45	15.22
Other	29.5	9.95
Total	295.6	100

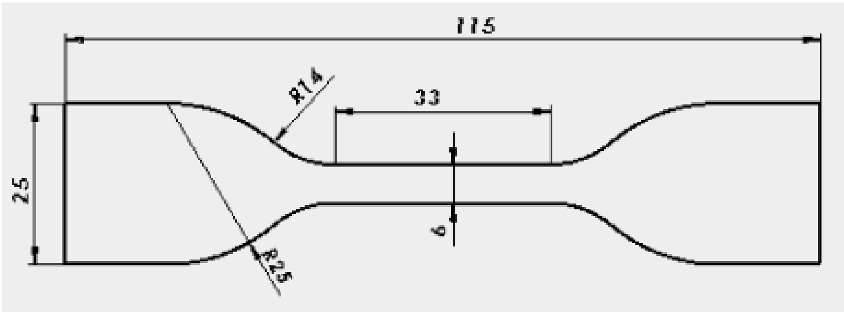

Fig. 2. ASTM D412 – C sample type

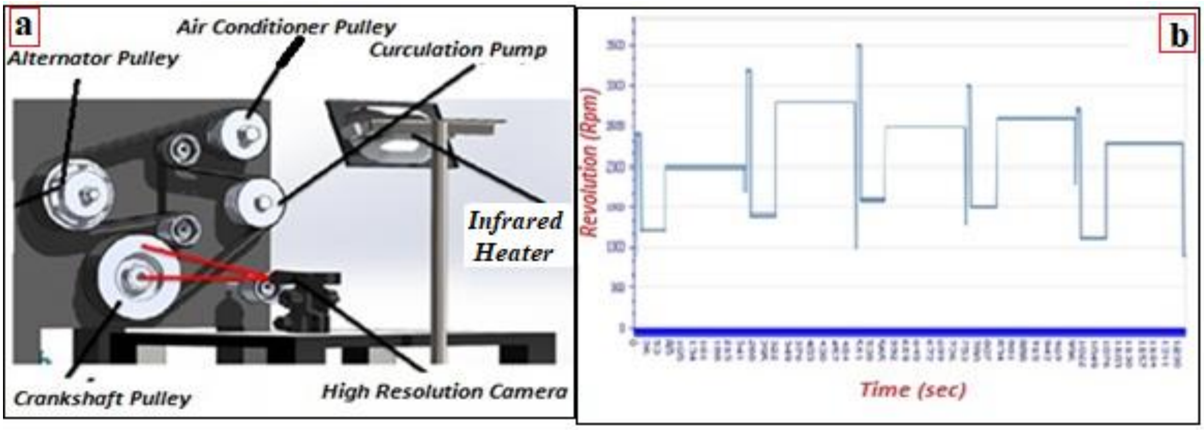

Fig. 3. Engine simulation test setup (a) and cycle-time graph (b).

Elastomer materials such as rubber have similar characteristic properties as a metal spring and a viscous liquid. This visco-elastic behavior is defined as deformation and energy-absorbing. Rubber consists of an infinite number of patterns with a wide spectrum of spring constants and viscosities. Torsional stiffness test specimens were made in the DEVOTRANS Torque Life Test device at room temperature, providing angles of 1 º – 30 º.

Many researchers have developed test methods for natural frequency and vibration measurements. For crank pulleys, the natural frequency of torsion is an important design parameter. Natural frequency measurements are generally performed with the hammer method because it is cheap and easy. The vibration frequency distribution of the force is found in the hammer test in the modal test setup [14]. For the natural frequency test, the frequency values and amplitudes of the pulley were measured by performing FFT (Fast Fourier Transform) analysis with the DEWESoft Sirius program for the vibrations against the force coming from the accelerometer, which was attached to the damper on the test samples, and the hammer.

Vibration data were found in terms of mm/s by applying a radial load of 700 N. Torsional vibration data were obtained using a sampling time of 1 second at a constant temperature of 90 °C in the test setup given in Fig. 3 (a) and variable revolutions between 900 rpm and 3000 rpm given in Fig. 3 (b).

RESULTS AND DISCUSSION

Tensile test result graphs of sample rubbers extracted in ASTM D412 – C dimensions are given in Fig. 4. Maximum strengths were examined by giving the graphs in Load (N) – Time (seconds).

The maximum torsional strength of 30° (0.6 rad) of the sample pulley, which is produced with nanoalumina-reinforced NR rubber (a) angle-torque graph, produced by the spraying method given in Fig. 5, was found to be 290.172 Nm, and the torsional stiffness from the inclination was found to be 561.37 Nm/rad. In the angle-torque graph (b) of nanozeolite-reinforced NR rubber produced by the spraying method, the torsional stiffness is 584.55 Nm/rad.

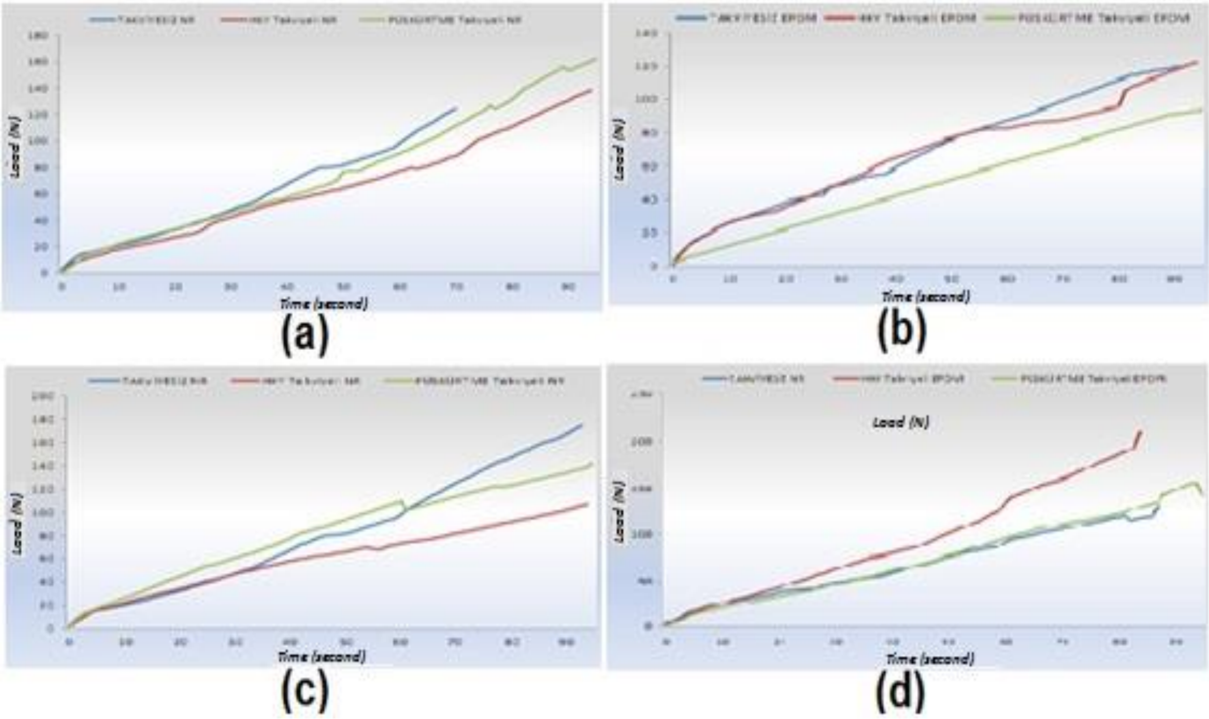

Fig. 4. Uniaxial tensile test results of sample rubbers

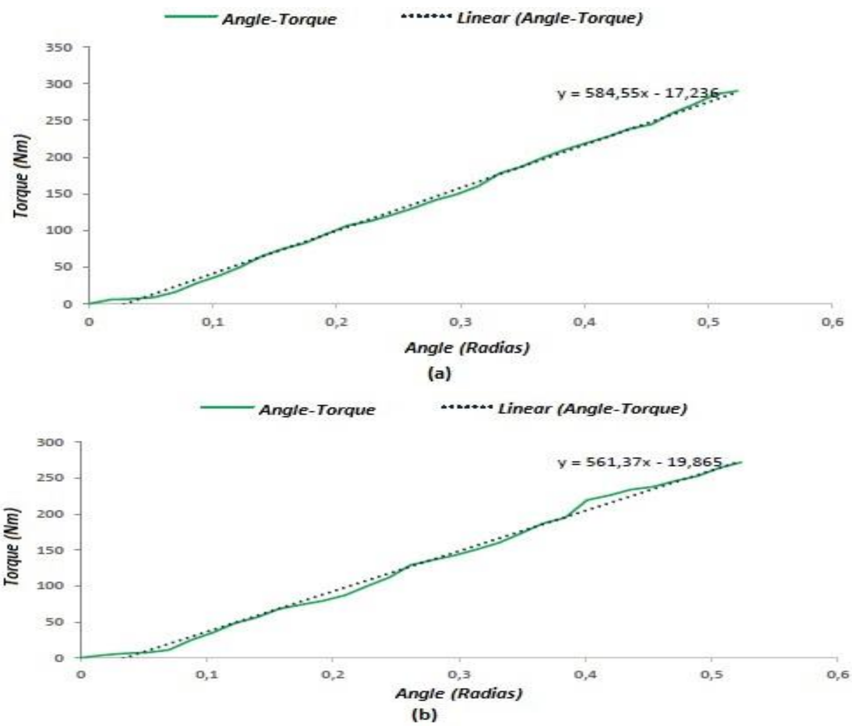

Fig. 5. Angle-torque graph of a) nanoalumina-reinforced b) nanozeolite-reinforced NR rubber crank pulley by spraying method

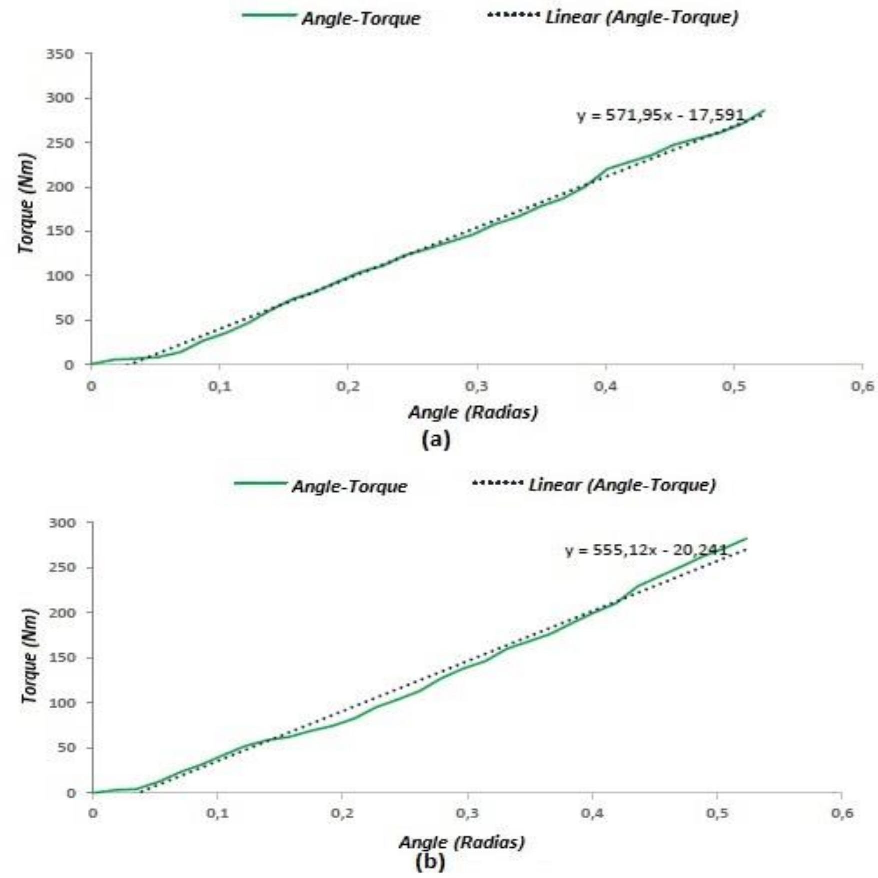

Fig. 6. HMM of EPDM rubber a) reinforced with nanozeolite and b) reinforced with nanoalumina by spraying method. Angle-torque graph of the crank pulley

Table 2. Hardness values and % changes of sample rubbers

Sample Type		*Hardness (Shore A)*
Non-reinforced NR		54
NR + Nanoalumina	*Homogeneous Mixing*	51
	Spraying	54
NR + Nanozeolite	*Homogeneous Mixing*	62
	Spraying	65
Non-reinforced EPDM		54
EPDM+Nanoalumina	*Homogeneous Mixing*	51
	Spraying	54
EPDM + Nanozeolite	*Homogeneous Mixing*	62
	Spraying	65

The torsional stiffness (a) of the crank pulley sample with nanozeolite-reinforced EPDM rubber produced by HMM is shown in Fig. 6 as 1000.05 Nm/rad. The maximum torsion of the crank pulley is 282.097 Nm. Again, the maximum torsion of the nanoalumina-reinforced EPDM rubber pulley (b) produced by the spraying method given in Fig. 6 is 286.01 Nm, while the torsional stiffness is 900.12 Nm/rad.

The changes in the hardness value of nanomaterial reinforcements to NR rubber and EPDM rubber are given in Table 2. As can be seen in the table, the hardness of NR rubber decreased when it was produced with HMM in nanoalumina reinforcement. In nanozeolite reinforcement, a direct effect on the hardness of NR rubber is seen, especially in the spraying method, with an effect of 16.09%. To examine the effect of hardness on torsional stiffness, torsional stiffness graphs of nanoalumina- and nanozeolite-reinforced NR rubber, zeolite-reinforced EPDM rubber produced with HMM, and alumina-reinforced EPDM rubber produced by spraying method were obtained for the samples.

In the experimental modal analysis test performed on the sample pulleys, natural frequencies were found using a hammer. These values are based on the peak of the pulley, and the frequency amplitudes of the crankshaft and pulleys are given in Fig. 7.

While the natural frequency value for nanoalumina-reinforced NR by spraying method was 333.5 Hz, it was 339.4 Hz for nanozeolite-reinforced NR. Although EPDM reinforced with nanoalumina by spraying method was in the maximum frequency range of 465.8 Hz, the closest natural frequency result to the crankshaft with 418.9 Hz was nanozeolite reinforcement with HMM.

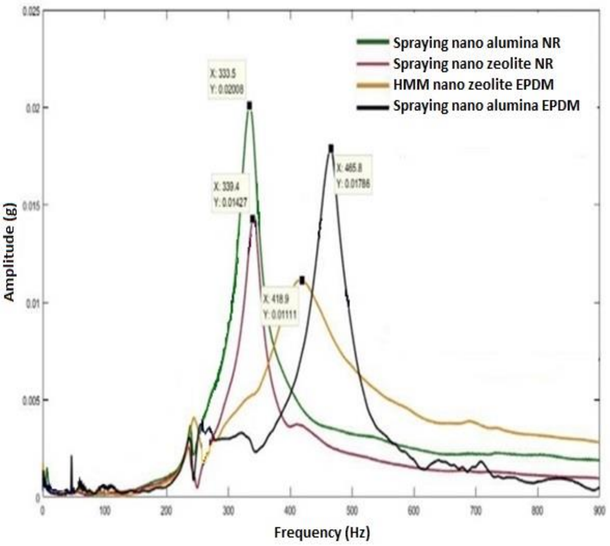

Fig. 7. Natural frequency test results of sample pulleys

In this case, the results from the torsional stiffness and the natural frequency results comparison are given in Table 3. As seen in the table, the analytical modal analysis and experimental modal analysis error rates resulting from torsional stiffness are around 10%. The closest result was for the crank pulley with nanozeolite reinforced EPDM rubber produced with HMM. Engine simulation tests on sample pulleys performed at a constant temperature with the cycles given in Fig. 3(b) are given in Fig. 8 below.

According to the engine simulation test results, the most vibrating pulley was the nanozeolite-reinforced NR rubber pulley produced with the spraying method, while the least vibrating pulley was the nanozeolite-reinforced EPDM rubber pulley produced with HMM.

Acoustic control tests were carried out on the crank pulleys at certain speeds with the help of a microphone. These test results are shown in Fig. 9, and the sound intensities of the pulleys are given in dB (A).

According to the test results given in Fig. 9, the same results were obtained as the vibration data. The crank pulley that made the most noise was the nanoalumina-reinforced NR rubber produced by the spraying method, while the nanozeolite-reinforced EPDM rubber crank pulley produced with HMM made the least noise.

CONCLUSİON

Crank pulleys are some of the front parts of the engine that absorb the torsional vibrations coming from the crankshaft and transmit the movement from the crank to other parts. Light and powerful engine technology is constantly developing, and the importance of the type of material used is growing day by day. Especially the field of nanotechnology shows continuous development.

In this study, a nanocomposite material was formed by adding nanoalumina and nanozeolite to natural and EPDM rubber, which is a non-linear material used in crank pulleys, using homogeneous and spraying methods. Nanocomposite specimens were subjected to a uniaxial tensile test, and a positive effect on tensile strength and elongation was observed in the homogeneous mixing method of nanoalumina reinforcement of natural rubber. It was found that zeolite supplementation has negative results in both production methods. It was observed, however, that the zeolite reinforcement made to EPDM rubber increased the breaking strength by 61% compared to the unreinforced rubber.

Table 3. Analytical and experimental modal analysis % error rates of sample pulleys

Rubber Type	Reinforcement Material	Mixing Method	Analytical Modal Analysis (Hz)	Experimental Modal Analysis (Hz)	% Error
NR	Nanoalumina	Spraying	307.74	339.4	9.33%
	Nanozeolite	Spraying	301.58	333.5	9.57%
EPDM	Nanoalumina	Spraying	402.52	465.8	13.59%
	Nanozeolite	Homogeneous Mixing	381.88	418.9	8.84%

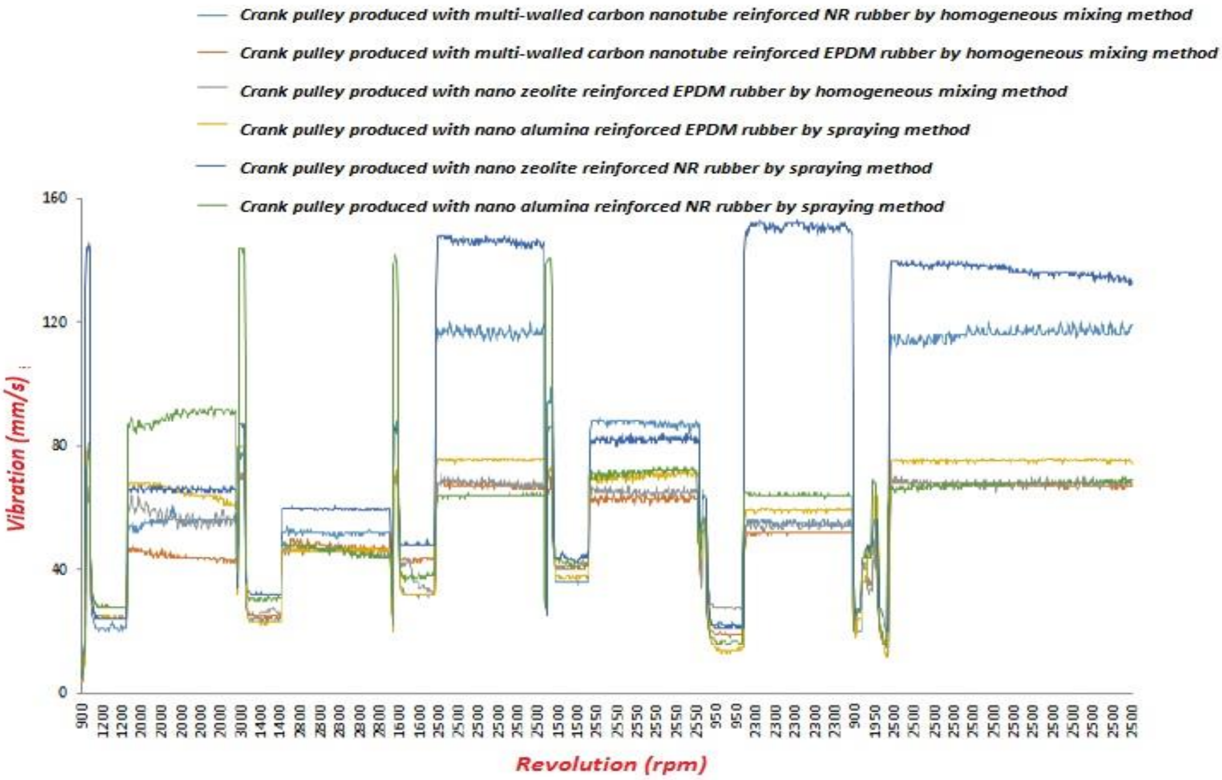

Fig. 8. Speed – vibration test results of sample pulleys

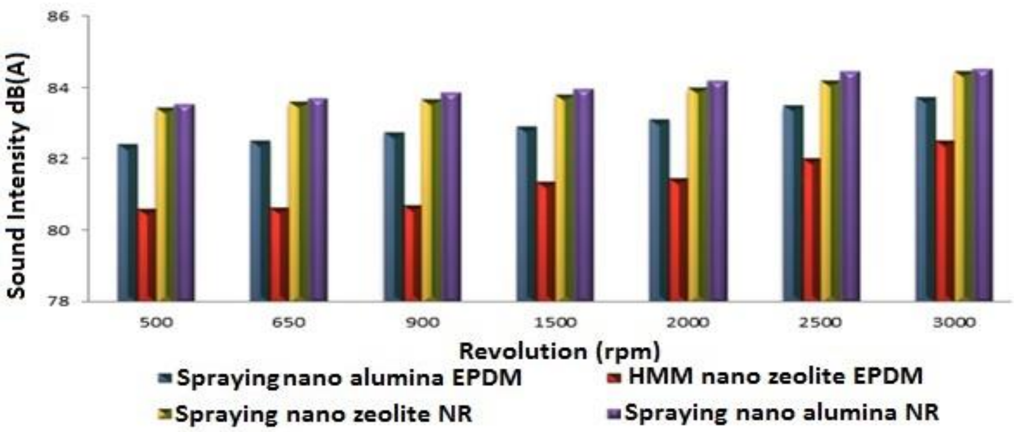

Fig. 9. Sound intensities of sample pulleys

It was found that the nanoalumina reinforcement of NR rubber did not change the hardness value, while the nanozeolite reinforcement increased the hardness. Especially in the spraying method, it was observed that the hardness changes at a rate of 16%. When the effect of the hardness value on the torsional stiffness was examined, it was found that the hard material had a lower torsional stiffness. Since the ratio of torsional stiffness and inertial mass gives the square of the natural frequency, it is compared with the modal analysis results.

Modal analysis was performed using the hammer method, and the natural frequency of the sample pulleys and crankshaft was found. In this experiment, it was seen that the nanozeolite-reinforced EPDM rubber crank pulley produced with HMM has the closest resonance frequency to the crankshaft. This situation is interpreted as a contribution to the durability of the crankshaft as the pulley is at the same resonance frequency without the shaft resonating during the torsional vibrations coming from the crankshaft. In the natural frequency results calculated by the analytical method and found by the experimental method, it was found that the results of the HMM and nanozeolite-reinforced EPDM rubber pulley with an error rate of 8.84% approach the experimental results, therefore the natural frequency can be found from the torsional stiffness and torsional inertia mass.

As regards the vibration and noise data, it was concluded that the noise intensity of the pulley that vibrates the most is higher than that of the other samples. Due to this situation, it was determined that a correlation can be established with the acoustic control test instead of the engine simulation test in terms of time and cost. As it is known that the noise levels of the crank pulleys will be at the engine idling speed (900 rpm), it was seen that the crank pulley with nanozeolite-reinforced EPDM rubber produced with HMM had the least noise level of 80.07 dB (A). In the light of these data, it was found by the test results that the nanozeolite-reinforced EPDM rubber crank pulley produced with HMM, taking into account the parameters that dampen the vibrations coming from the crankshaft and the rubber structure, shows the best strength.

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