



Synthesis of polymer matrix nanocomposite with carbon fibers and analysis of its strength properties

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Received 25 February 2023; Revised 15 March 2023; Accepted 10 May 2023

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Abstract

In polymer-based nanocomposites, carbon nanofibers have been used to improve mechanical properties in various applications. In this research, the tensile properties of carbon nanofibers have been used to create carbon-epoxy nanocomposite and improve the mechanical properties of epoxy nanocomposite, and the effect of the weight percentage of carbon nanofibers on the mechanical properties of epoxy nanocomposite has been investigated. Epoxy with weight percentages of 1.0, 5.0 and 1.5 carbon nanofibers were produced and their mechanical properties were investigated. The results showed that the use of even a small percentage of carbon nanofibers can lead to the improvement of mechanical properties.

Keywords: Polymer matrix nanocomposites, Carbon-epoxy nanocomposite, Carbon elasticity, Carbon nanofibers, strengthening, mechanical properties, Young's modulus,

1. Introduction

In addition to playing a very effective role as a matrix in composite materials, epoxy resins are one of the most important groups in thermoset polymers due to their excellent mechanical properties, excellent adhesion to other substrates, and appropriate chemical and thermal resistance [1-3]. However, due to its cross-linked structure, epoxy offers low stiffness and stiffness properties. Therefore, adding a small amount of inorganic nanoscale fillers to it can improve the mechanical properties of pure epoxy, including hardness and stiffness [4]. Various studies have pointed to the use of the properties created after adding ceramic particles on a micro and nano scale.

Zhang et al. strengthened the strength of epoxy composite by using carbon nanotube and carbon fiber. In the results, it is shown that the epoxy composite reinforced with CNT/CF. The main mechanisms of interstitial reinforcement are interpreted as wetted surface, mechanical bonding, chemical bonding and van der Waals bonding [5].

Also, nanocomposites with epoxy resin polymer base with reinforcing particles based on graphene nanomaterials have been investigated by many researchers due to their unique physical properties. On the other hand, these nano materials are usually used to achieve the desired characteristics; In order to improve the ionic bonds on the surface as well as the van der Waals interactions at the interface, they are used [6].

Carbon nanofibers are about a few micrometers in length, diameter in the range of 10 to 100 nm (50-200 nm), specific surface area of about 1877, and aspect ratio above 100. Cylindrical nanostructures of carbon nanofibers have different chemical structures of graphene sheets, which include stacked sheets, strips, spirals, hollow cores of amorphous nanofibers without graphene layers [7]. The relative improvement that these nanostructures can have in mechanical properties can depend on the shape, surface area, and homogeneous quality of the interface between the matrix and filler nanoparticles. Due to the high surface-to-volume ratio in these materials, their tendency to become lumpy is increased, and on the other hand, due to their chemically neutral nature, it can lead to weak interactions at the interface. Therefore, different techniques, including functionalization and dispersing strategies of these particles in the polymer matrix corresponding to the optimal loadings in nanocomposites can lead to different results in improved mechanical properties and other properties. Hence, it can be said that the amount of different loadings of carbon filler nanoparticles can bring different levels of tensile strength and hardness [8]. Since hybrid composites reinforced with carbon fibers have good mechanical and thermal resistance, their use has been made possible for many complex space and air missions. The purpose of the present research work is to investigate the effect of the

presence of carbon nanofibers on the mechanical properties of epoxy resin with different loading levels.

2. Materials and methods

Araldite epoxy resin with low viscosity, brand name LY 5052/Aradur 5052 (Huntsman Company of America - prepared from Shimi Afson Company - Iran) was used as a polymer base for making nanocomposites. Among the interesting features of this resin are the easy saturation of reinforcing materials in it, long life (2 hours for 100 ml in the environment), high temperature resistance after curing in the environment, excellent mechanical and dynamic properties after curing in The medium indicated the potential for even higher properties after curing at high temperatures. It should be noted that the hardener used for the mentioned resin was HY 5052. The specifications of this item are presented in Table 1-2.

Table 1-2: Specifications of LY 5052 epoxy resin used in this research

Appearance characteristics	Colorless
density	1.17 ()
viscosity	cP 3000-1000
Thermal bending temperature	140>

Carbon nanofibers as fillers for the preparation of nanocomposite parts were obtained from Pishgaman Nano Materials Iranian Company. The physical characteristics of the aforementioned nanofibers are presented in Table 2-2.

Table 2-2: Physical characteristics of carbon nanofibers used in this research

particle size	100-100 nm
Purity	%90 by weight
Specific surface area	2 square meters per gram
Color	Black
External diameter	100-100 nm
the length	50-50 micrometers
Electrical conductivity	100 Siemens/cm

Bulk density	1.17 grams per cubic centimeter
true density	1.17 gram per cubic centimeter
Construction method	chemical vapor deposition (CVD)

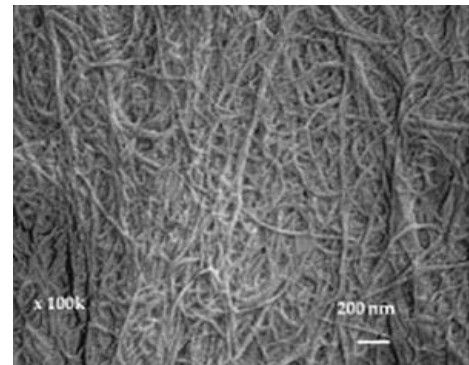


Fig. 1-2. SEM image of commercial carbon nanofibers used

Table 2-3: The equipment used in the current research

Manufacturer	Application	Equipment
Sartorius, BSA124S-CW	Weighing materials	Digital scale with 3 decimal places
NUVE (Turkey)	Resin curing and drying of composite parts	Digital atmospheric oven
AutoMixII	Uniform distribution of particles in the solvent	Mechanical stirrer under vacuum

The goal is to prepare nanocomposite parts with a combination of 0.5%, 1%, and 1.5% by weight of carbon nanofiber filler. At first, a steel mold was prepared and a fireproof cloth was placed on its bottom, and it was covered with a non-stick wax. After preparing the mold and greasing it and placing a fireproof cloth in its lower part to prevent the material from leaking from under the mold, it was sealed all around using aquarium glue.

In order to cure the resin used in this experiment, it was placed at room temperature for 24 hours and then placed in an oven at 120 degrees Celsius for 4 hours. A digital

scale with an accuracy of 3 decimal places was used to weigh the materials, including the amount of resin and the number of nano fibers. It should be noted that the amount of resin was kept almost constant and the amount of carbon nano fibers was added to the epoxy resin according to the mentioned amounts. The determined amount of epoxy resin was cured and then carbon nano fibers were added to it, and in the last step, the determined amount of hardener was added to this solution and in the next step, it was stirred using a mechanical stirrer under vacuum for 45 seconds.

It should be noted that after curing the resin using the prepared mold, a piece of pure resin was prepared. In relation to composite parts including carbon fibers, after complete mixing, the solution was slowly poured into the mold and it was placed at ambient temperature for 24 hours and then placed in the oven, and the temperature gradually increased after placing the mold inside. It was increased from the ambient temperature to 120 degrees Celsius and after 4 hours, we allowed the temperature to gradually decrease to the ambient temperature. Then it was separated from the mold.

It is worth mentioning that due to the use of fireproof fabric in the bottom layer of the mold, a series of waves and unevenness were formed in small parts of the manufactured sample. To remove these unevenness, soft sanding was used. The surface is also completely smooth. At first, the thickness of all prepared samples was in the range of 3.4-4.6 micrometers and with a length of 20 cm. Then the manufactured samples were cut with a size of (2x2) cm to perform the tensile test. It should be noted that due to the polished nature of the samples, the edges of the 2.5 cm length were roughened using a file to prevent the samples from sliding during the tensile test. It should also be said that the mentioned issue was resolved in all prepared samples and this problem was observed only in the sample containing pure epoxy resin.

In order to check the tensile strength and tensile modulus of molded nano composite parts including pure epoxy resin and containing fillers with different weight percentages according to the standard ASTM D-638 [10,9] were cut and subjected to a tensile test with a force loading speed of 1 mm/min. Tensile tests were performed using Centim model STM-150 manufactured by Centim-Iran.

3. Discussion

Chen et al investigated electro spun carbon nanofibers with diameter and length of 200 nanometers and 15 micrometers and prepared nano-epoxy resins. The resins

prepared for making multi-scale hybrid composites using common woven carbon fibers were investigated through resin transfer molding technique under vacuum. For a comparative study, carbon nanofibers made by steam growth method and graphite carbon nanofibers were investigated for making nano-epoxy resins and multi-scale hybrid composites. Unlike carbon nanofibers obtained by steam and graphite growth methods, which are prepared by bottom-up methods, electro spun carbon nanofibers are obtained using top-down techniques; Therefore, these nanofibers will have high economic efficiency compared to the other two types. The results of this research showed that the placement of even a small amount of these electro spun nanofibers inside the epoxy resin matrix can significantly improve the absorption energy as well as the interlayer shear strength and bending properties in both cases of nano-epoxy resins and multi-scale composites. be made Therefore, the type of preparation method of carbon nano fibers can also play a very important and key role in the mechanical performance of hybrid composites [11].

mechanical properties

The mechanical properties of molded composite parts containing pure epoxy resin and combined with carbon nanofibers with weight percentages of 0.5, 1, and 1.5% were investigated using the aforementioned tensile device in accordance with the ASTM D-638 standard and the results It is presented in Figures 1-3, 3-2, 3-3, and 3-4. Considering the graphs presented, it can be said that the amount of stress in composite parts depends on the amount of loading of carbon nano fibers; Thus, with the addition of carbon nanofibers, the maximum amount created in a sample containing a high percentage of carbon nanofibers will be higher. According to the stress/strain diagram corresponding to the piece containing pure epoxy, it can be mentioned that the maximum stress created in the tensile test was equal to 52 MPa, which occurred at a strain of 17%. In Figure 2-3, it can be seen that the maximum stress created is about 53.5 MPa and it occurred at a strain of 18.2%, so it can be said that the maximum stress created has increased by about 3% and at a higher strain, this maximum has been Examining the stress/strain diagram of the sample containing 1% by weight of carbon nanofibers (Figure 3-3) also shows a slight increase in the maximum stress created in the strain of about 19.5%. Finally, according to the diagram presented in Figure 4-3, it can be said that the maximum stress created has a significant increase compared to the sample containing 1% (33.2%) at a strain of 28%, and in addition, compared to the piece Pure epoxy composite has increased by 38.3%.

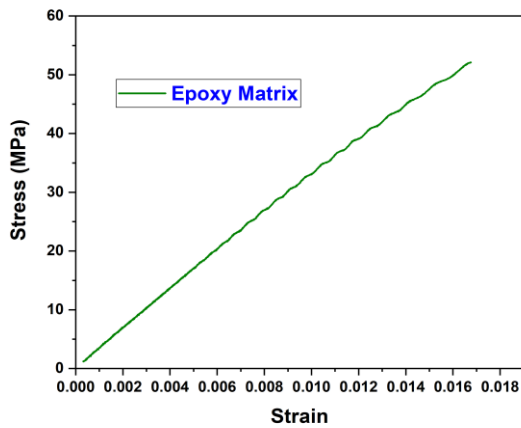


Fig. 1-3. Stress/strain diagram for pure epoxy resin sample

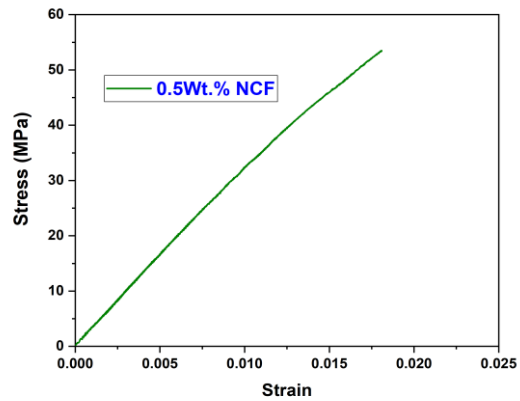


Fig. 2-3. Stress/strain diagram for the sample containing 0.5% by weight of carbon nanofibers

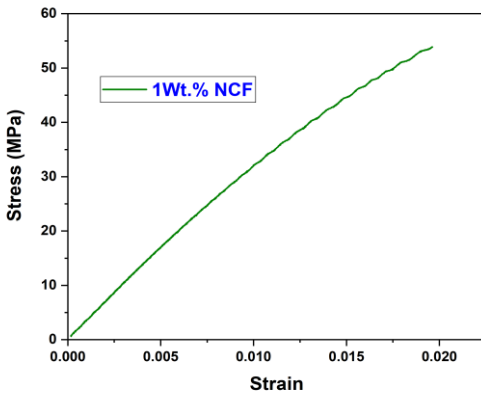


Fig. 3-3 .Stress/strain diagram for the sample containing 1% by weight of carbon nanofibers

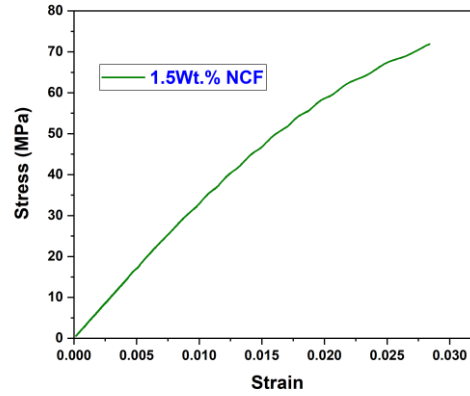


Fig. 4-3. Stress/strain diagram for the sample containing 1.5% by weight of carbon nanofibers

The results presented in past researches indicate that the way nano materials are dispersed is a key and determining factor in achieving acceptable mechanical properties [12,13]. The good dispersion of nanomaterials can have more available surface area of filler particles on one hand, and on the other hand, it leads to preventing the accumulation of particles that can lead to the role of stress concentration and also slippage of nanotubes during loading of composites. . The mentioned cases will ultimately lead to a significant decrease in performance and mechanical properties of composites.

On the other hand, in diagram 5-3, the mechanical behavior of the prepared parts can be seen in comparison with each other with different loading levels. According to the graph, it is clear that the percentage of strain has increased with the increase in the loading of carbon nanofibers. It should be noted that the amount of tensile

strength in the sample containing the highest loading of carbon nanofibers (1.5% by weight) has experienced a significant increase in comparison with the pure epoxy matrix.

The observed increase in the mechanical properties of nanocomposites containing the highest amount of loading of nanofibers can be related to the very good adhesion between the two polymer phases and nanofibers, although the acceptable dispersion of nanofibers can also play an effective role in providing this performance and can be ignored. It is not [14].

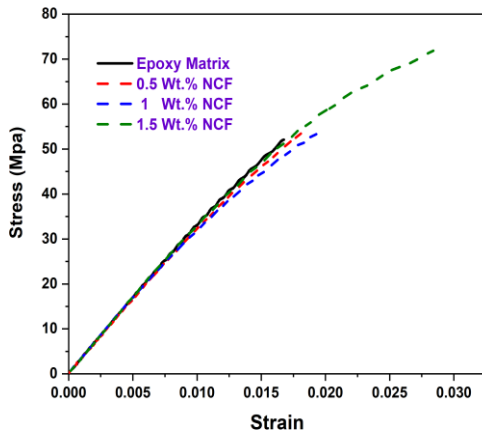


Fig. 5-3 Stress/strain diagrams of composite parts compared to each other

Young's modulus, which shows the stiffness of the sample as well as its resistance to deformation, has also been investigated. Young's modulus values were also calculated according to equation 1-3.

$$(1-3) \quad E = \frac{\sigma}{\epsilon} = \frac{F/A}{dl/l}$$

In this relationship, E is Young's modulus, σ is the amount of stress, ϵ is the amount of strain, F is the force applied to the part, A is the surface area of the part, l is the length of the part, and dl is the change in length of the part in response to the force applied to it. A comparison of Young's modulus values for prepared composite parts is shown in Figure 6-3. As can be seen, the value of Young's modulus is increasing with the increase in the content of carbon nanofibers in composite parts, so that in the sample containing 1.5% by weight of carbon nanofibers, the value of Young's modulus has been improved by about 4.5%.

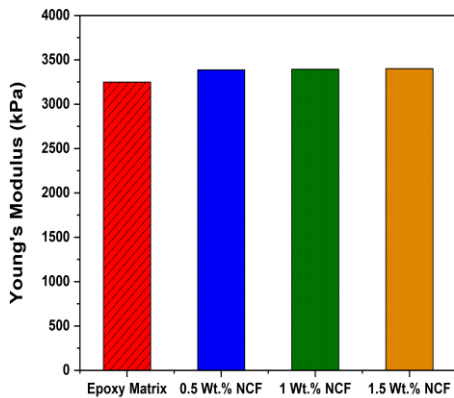


Fig. 6-3. Comparison of Young's modulus values related to composite parts with different percentages of carbon nanofibers

The details and parameters related to the mechanical test are presented in Table 1-3.

Throughput rate Carbon nano fibers	Tensile strength (megapascal)	Young's modulus (Kilopascal)	Strain at yield point (%)
0% by weight	52	3248	17
0.5 percent by weight	5/53	3387	18
1 percent by weight	54	2/3392	20
1.5 percent by weight	9/71	2/3399	28

Table 3-1: Tensile test properties in nanocomposites including epoxy and carbon nanofibers

It can be seen that with the increase in the weight percentage of carbon nano fibers in the reinforced composites, the strain at the yield point has gone to higher percentages and on the other hand, the Young's modulus has also experienced a significant increase.

By investigating the mechanical properties of nanocomposites containing functionalized multi-walled carbon nanotubes, Wanger et al. concluded that by adding 1% by weight of these materials to the Epon 828/D-2000 rubber epoxy matrix, the Young's modulus value is about 28%. has been upgraded and on the other hand, the tensile stress has also been upgraded from 480 kilopascals to 980. This was despite the fact that this amount in the nanocomposite including resin and Epon 828/T-403 and 1% by weight of the same nanotube has had an insignificant change compared to epoxy resin [14].

Zhang et al investigated the effect of carbon nanotube surface treatment on the mechanical behavior of composites. Their results showed that CNTs-NH₂ functionalized nanotubes have negative effects on the interface, as well as CNTs-COOH functionalized nanotubes can lead to the improvement of mechanical behavior and properties at the interface of these two phases. According to the analysis, modified CNTs-COOH nanotubes on the surface of carbon fibers created strong bonds with epoxy and provided more effective charge transfer between the matrix and fibers, while the aggregation of CNTs-NH₂ nanotubes was clumped and the bonding energy At the interface between the nanotubes and the epoxy resin, it is reduced and the ester barrier created by the amine functional groups in these

nanotubes can hardly lead to the inhibition of crack growth in the matrix under stress [15].

It should be noted that the direct distribution of carbon nanofibers with epoxy primary building materials creates very non-uniform compositions and forms lumps with a size larger than 20 micrometers in the longitudinal direction. The use of solvents improves the distribution of nanofibers by reducing the viscosity of the composition. In the test conditions, chloroform and THF solvents have been proposed as two very practical options. It should be said that compared to THF, due to its high polarity, chloroform can be a more suitable option as a medium for the distribution of graphite nanofibers. Using a sonicator in the preparation stages of the resin solution filled with carbon nanofibers at relatively high frequencies can improve the level of uniform distribution of carbon nanofibers. However, it should be said that it has been observed that sonication is not enough to achieve optimal distribution and the use of a high-speed shear stirrer is considered as a necessary condition. Utilizing the combination of sonication techniques and mechanical stirrer with high shear speed seems to have a very good potential in separating possible clumps. It should be noted that even with the mentioned cases, there is still a possibility of lumps with a length of 1 micrometer and absolute uniformity cannot be expected. The small non-uniform clumps created can be related to the high concentration of nano fibers and their long length. On the other hand, the non-implementation of any chemical modification on the surface of nanofibers should be considered in the creation of non-uniform clumps [16].

Prolongo et al. found the optimal conditions for the preparation of epoxy/carbon nano fiber composite parts, including initial functionalization of the nano fiber surface using an amine binding agent, using chloroform as a solvent, and using multiple distribution techniques that include magnetic stirring at 60 degrees Celsius, sonication at high frequencies, mechanical stirring with high shear, they reported. Therefore, it can be concluded that the various factors mentioned can be involved in the uniform distribution of carbon nanofibers in the epoxy matrix and on the other hand have a significant effect on their physical and mechanical properties [17].

Interface model in carbon fiber reinforced composites

For the continuous elements in the interface used in the new interface model, the elastic region is defined as an isotropic material with absolute stiffness (P). Progressive damage is also considered as a condition that begins at the maximum amount of normal or tangential stress. Since the stress that initiates the destruction basically determines the behavior of the elements, the amount of elastic stiffness of the elements is less important [18,19]. In order to be able to accurately model the tangential and normal

stress of the continuous elements at the interface at the yield point, two separate models of destruction are modeled simultaneously. The normal degradation behavior of the interface elements is modeled according to the progressive strength degradation model, which determines the normal separation of the interface. After the initiation of degradation occurs, since the normal strain increases, the elastic modulus of the elements at the interface decreases according to the following relationship.

$$(2-3) \quad E_{d=}(1-d)E$$

that in this regard E_d is the degraded elastic modulus, E is the elastic modulus before degradation, and d is the degraded modulus. A material equalizes when it changes, at which point the stiffness of the material becomes zero. Changes are calculated according to the following equation.

$$(3-3) \quad d = \exp\left(-\frac{\int_0^{u^{pl}} \sigma_y L_e \varepsilon^{pl}}{G_f}\right)$$

In the mentioned relationship, ε^{pl} is the rate of plastic strain, σ_y is the yield stress, L_e is the characteristic length of the material, G_f is the fracture energy of the material, and u^{pl} can be calculated according to the relationship 4-3.

$$(4-3) \quad u^{pl} = \frac{G_f}{\sigma_y}$$

It should be noted that the parameter for normal and tangential fracture energies is calculated according to relations (5-3) and (6-3) respectively.

$$(5-3) \quad G_n = \int_0^{\varepsilon_f} \sigma d\varepsilon$$

$$(6-3) \quad G_t = \int_{-Y_f}^{Y_f} \tau dY$$

In the mentioned relationships, ε_f and Y_f are shear and normal failure strains, respectively. Similarly, shear failure of interface elements is modeled by progressive failure method to calculate failure in negative and positive shear strains. After the destruction starts, the progress of the shear destruction according to the equation (4-3) is exponential until the elements are assumed to yield in the strains corresponding to $\pm Y$ and when the destruction variable becomes equal to one. General stress-strain relations for normal and tangential behaviors of interface

elements can be defined for general normal and tangential behaviors according to relations (7-3) and (8-3), respectively.

$$\sigma(\varepsilon) = \begin{cases} P\varepsilon & : \varepsilon \leq \varepsilon_d \\ (1-D)P\varepsilon & : \varepsilon_d < \varepsilon < \varepsilon_f \\ 0 & : \varepsilon \geq \varepsilon_f \end{cases} \quad (7-3)$$

$$\tau(Y) = \begin{cases} (1-D)P_Y & P_Y & : -Y_d \geq Y \geq Y_d \\ & : -Y_d > Y < -Y_f; Y_d < Y < Y_f \\ 0 & : Y \leq -Y_f; Y \geq Y_f \end{cases} \quad (8-3)$$

In the above relationship, ε_d and Y_d are the initial normal and tangential strains, respectively.

4. Conclusion

Epoxy resins play a very important and key role as a polymer matrix in composite materials, on the other hand, as one of the most important groups of thermoset polymers due to having excellent mechanical properties, acceptable adhesion to other materials, and thermal and chemical resistance. are mentioned above. However, due to the structure including transverse joints, epoxies have low strength, compressive and hardness properties. Therefore, adding a small amount of inorganic nano fillers in the epoxy matrix can improve its properties, especially its stiffness and compressive properties. The relative improvement in mechanical properties mainly depends on the shape, specific surface area, as well as the quality of the interface between the polymer matrix and the carbon nanofillers. Polymer nanocomposites generally have high strength, low weight, high thermal stability, high electrical conductivity and high chemical resistance. By adding a small percentage of nano materials to a pure polymer, tensile strength, yield strength and Young's modulus increase significantly. According to the results obtained in the current research, it can be said that the use of even a small percentage of carbon nanofibers can lead to the improvement of mechanical properties, so that the mechanical behavior of composites based on nanostructures is due to their high flexibility and their high surface-to-volume ratio. It can be different from other types based on micrometer size. On the other hand, the method of distribution and dispersion of the aforementioned nanofibers is also of great importance. Considering the fact that the non-uniform distribution of these nano-fibers in the epoxy matrix on the one hand and also the lack of acceptable adhesion between these two phases are critical issues that lead to the formation of lumps in the matrix and finally the loss of mechanical properties in will find.

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