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Enhancing the Performance of Hybrid Composites through the Addition of Zinc Oxide and Carbon Fibers

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ABSTRACT

Hybrid composite materials combining polymers and reinforcements are gaining interest for enhanced engineering properties. The main goal of this study was to create the best hybrid composite using carbon fibers, zinc oxide micro- and nanoparticles, epoxy, phenol-formaldehyde resin, and more. Samples with varying ratios of epoxy resin (50–100%) and phenol-formaldehyde resin (0–50%) were fabricated. Mechanical and water absorption testing evaluated the effects of the zinc oxide particles and carbon fibers on tensile strength, elasticity, and liquid resistance. Results showed improved tensile strength and minimized water absorption at 10% phenol resin content. Further, zinc oxide nanoparticles offered better reinforcement than microparticles, attributed to higher surface area-to-volume ratios. However, carbon fiber addition increased water absorption despite improving tensile properties. In the end, the best composite was made up of carbon fibers, zinc oxide nanoparticles, 90% epoxy resin, and 10% phenol-formaldehyde resin. This affordable hybrid composite has potential applications in sewage system piping. Further work should focus on improved mixing methods to leverage synergies between the composite constituents. The study provides valuable insights into tuning hybrid composites with nanoparticles and fibers for advanced functionality.

1. Introduction

Hybrid composite materials are becoming more popular in many engineering applications due to their improved features and benefits over standard composite materials. Specifically, the hybridization of composite materials is commonly used to enhance mechanical properties and lower the cost of classic materials [1, 2]. Commonly, hybrid composites constitute two or more types of fillers, particularly fibers. Based on the utilized technology to synthesize the composites, hybrid composites can be classified into different types such as sandwich type, and reaction and mixed in sandwich hybrid. A common method of Fiber-Reinforced-Plastic (FRP) reinforcement is frequently used to introduce fibers into specific directional compounds to improve the mechanical properties [3]. FRP reinforcement can be used in different shapes or arrangements, depending on their application and manufacturing method as they are classified based on short, long or continuous fiber length [4]. According to the types of reinforcement used, composite materials are categorized into particulate composites, fiber reinforced composites, and structural composites as depicted in Figure 1. Also, the fillers can be placed in various orientations and shapes, as illustrated in Figure 2.

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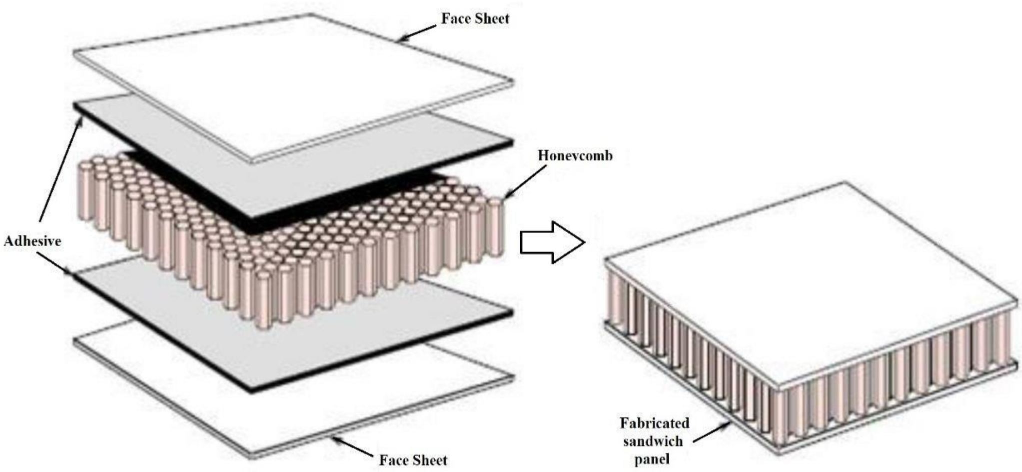


Figure 1. Sandwich panels [5]

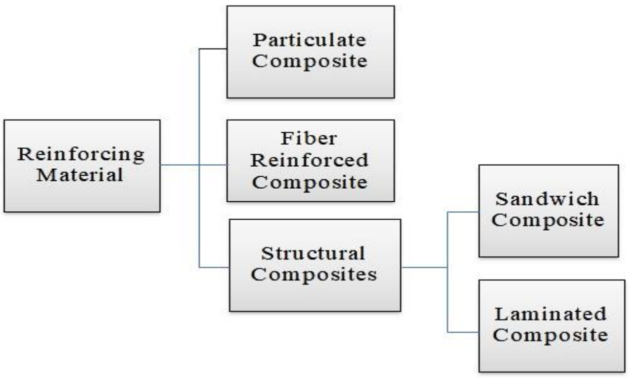


Figure 2. Classification of reinforcing materials [3]

These fillers are important to obtain the composite's prime thermal, electrical, and mechanical characteristics. Undoubtedly, the utilization of cheap polymer would intensively reduce the overall cost compared to the utilization of fiberglass [6]. More importantly, the mechanical, electrical, thermal, optical and electrochemical properties of the nanocomposites are greatly different from those of the constituent materials. In this regard, one of the most important mechanical properties of the nanocomposites is the ratio of specific surface areas of reinforced fibers and nanoparticles. Mostly, the nanocomposites have a significant interaction between the materials and nanostructures, in addition to a superior homogeneity [7, 8]. This in turn would interpret the progressive utilization of the nanocomposites as they introduce completely different and better mechanical properties than those of conventional materials [9]. However, natural fibers in nanocomposites, on the other hand, make the structure more cost-effective and environmentally friendly [10].

As a result of the growing desire for improved material qualities to meet market demands, nanoparticles have been integrated into composite materials. Several studies can be found in the open literature that focused on the reinforcement of the mechanical and physical properties of composites using nanoparticles [11-14]. Some successful examples of these studies are discussed below. Haribabu and Prasad [11] used a hand layup process to fabricate and investigate the mechanical characteristics of E-glass fibers /epoxy resin composites with variable weight percent of nano-$CaCO_3$. The hand layup process is employed in this study due to its simplicity to fabricate, low cost, and excellent surface polish. It is found that the addition of nano-$CaCO_3$ improves the reinforcing and toughening properties of E-glass epoxy hybrid composites. When the weight fraction was equal to 3%, Young's modulus, tensile strength, and tensile strain were seen to increase nonlinearly with the weight percent of nano-CaCO3 particles. The influence of adding $Al2O_3$, SiO_2 and TiO2 Nano-modifiers on the mechanical and physical characteristics of glass fiber/epoxy composites has been investigated by Abid et al [14]. The filler particles have raised the materials hardness and increased the material resistance against plastic deformation. However, SiO_2 has the highest positive effects on the hardness and flexural strength compared to other Nano-modifiers. This is attributed to its smaller particle size. Furthermore, it was found that the specimens of composite material filled with larger particles of TiO_2 have shown a higher water absorption and density compared to other specimens of composite material filled with smaller particles. [15, 16] evaluated the flexural properties and tensile strength of glass/epoxy fibers reinforced laminated composites after adding Nano-silica. When analyzing the original specimens with and without Nano-silica inclusion, the study found that specimens with Nano-silica particles significantly improved the tensile strength, flexural modulus, and flexural strength values. Study by Bulut et al. [17] investigated the mechanical properties of composites reinforced with carbon, glass, and Kevlar fibers and including microscale additions of silicon carbide (SiC) within an epoxy matrix.

Hybrid composite materials are getting popular in engineering due to its improved properties and numerous advantages; this section of the article gives an outline of these materials advantages. This study addresses a gap in the literature by investigating the efficiency of a hybrid composite material that enhances mechanical and sorption properties by combining carbon fibers with zinc oxide particles. The primary findings of this study are the improvement of mechanical properties and the reduction of absorption when reinforced with nanoparticles as opposed to microparticles of zinc oxide, as well as the significant increase in absorption property of the hybrid mixture due to the addition of carbon fibers. These findings could lead to the creation of a hybrid composite material that is inexpensive and environmentally friendly for use in industries such as sewage pipes.

2. Methodology

Hybrid mixtures of epoxy resin and phenol-formaldehyde resin (resole) in different proportions were prepared in this study as given in Table 1. Epoxy resin is a low-viscosity, solvent-free component while resole resin is the synthetic polymer obtained by reaction of phenol with formaldehyde with a mixing ratio of 2:1. The hybrid mixture was fortified with zinc oxide nanoparticles and zinc oxide micro particles. Furthermore, carbon fiber reinforcement is used for the hybrid structure. Table 2 presents the mechanical properties of the carbon fibers while Figure 3 shows the photograph of the carbon fibers used in this study.

Table 1: Blind Epoxy-Resin and resole resin hybrid mixing ratio

No.	Epoxy resin	Resole resin
1	100 %	0 %
2	95 %	5 %
3	90 %	10 %
4	85 %	15 %
5	80 %	20 %
6	70 %	30 %
7	60 %	40 %
8	50 %	50 %

Table 2: The properties of the carbon fibers employed in this work

Density (g/cm^3)	Elastic modulus	Compressive strength	Tensile strength
1.75–2.20	(200–935 GPa)	(1–3 GPa)	(3–7 GPa)

The samples of this study were prepared by pouring the mixture into a mold consisting of glass plates measuring 200 x 200 x 6 mm, and nylon sheets (placed before the casting process). The edges are then scraped after all samples have been formed. In the beginning, epoxy resin is selected, then phenol and zinc oxide nanoparticles and microparticles are added. The results obtained for samples containing zinc oxide nanoparticles showed a significant improvement in tensile strength compared to the original samples without reinforcement with zinc oxide nanoparticles and microparticles. The absorbance properties of the hybrid mixture reinforced with zinc oxide nanoparticles and microparticles and carbon fibers were also studied.

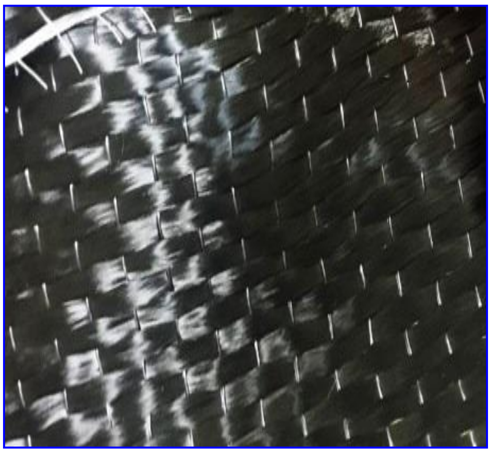
Formaldehyde is added according to the specified proportions shown in Table 1. Carbon fiber reinforcement was done first to demonstrate the effect of the fibers on the mechanical properties, followed by the use of zinc oxide microparticles and nanoparticles to strengthen the samples made of epoxy resin and phenol formaldehyde. Air bubbles in the sample were removed and high homogeneity between the hybrid composition of the resin and the ZnO micro- and nanoparticles was obtained by combining 90% epoxy resin and 10% phenol-formaldehyde resin in a magnetic mixing machine. Figure 3.

The hybrid mixture was reinforced using mats of supporting fibers and nanoparticle fillings through the following steps: To make the first layer of the mats, a part of the hybrid mixture reinforced with zinc oxide micro particles was poured first and zinc oxide nanoparticles second, then the fibers in the mixture were evenly placed over hybrid resin, followed by another layer of hybrid resin. The mixture layer was then uniformly thickened using a notched steel roller before being poured at room temperature and allowed to dry for 24 hours. The hybrid mixture was obtained from the mold to produce a sheet of epoxy and phenol formaldehyde, which was then cut, involving the cutting of several solid materials, using a computer numerical control (CNC) machine equipped with a rotary head and a drill.

3. Results and discussion

3.1. Tensile properties

Epoxy resin is a thermosetting polymer with high stiffness and strength but low tensile strength due to its relative brittleness and lack of toughness. It is susceptible to breaking or cracking when subjected to tensile forces. Therefore, it must be reinforced with additional materials such as carbon fibers and zinc oxide particles to improve its mechanical properties. [16]. Tensile strength is significantly increased when reinforced with carbon fibres, although elasticity is low (Figure 4). When cemented with zinc oxide particles, it will gradually thicken, occupying more space inside the resin and enabling better load distribution.



a. Carbon fibers **b.** Tensile stress measurements **c.** Tensile test sample

Figure 3. The carbon fibers used in this study

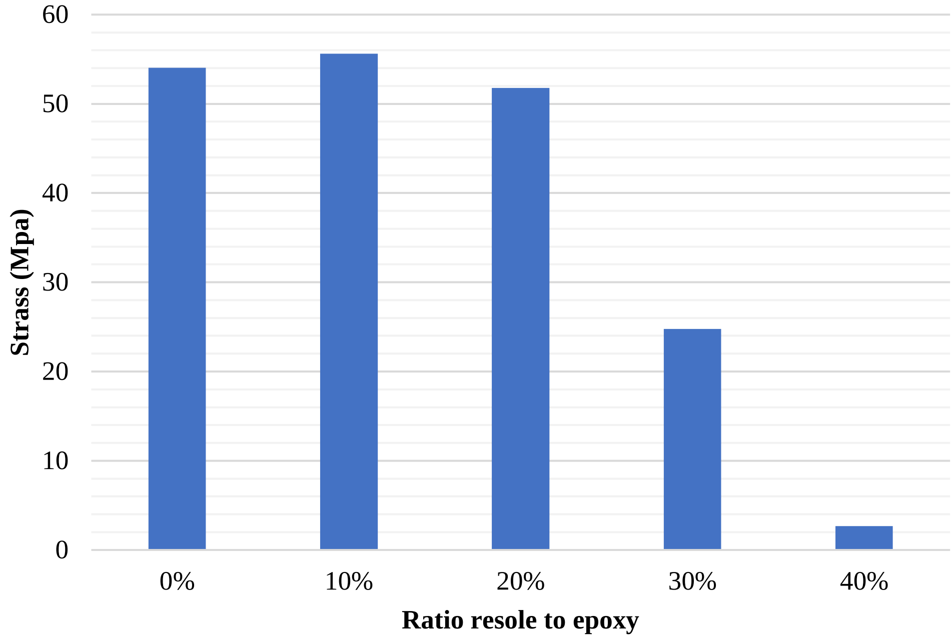


Figure 4. Tensile stress measurements of the hybrid mixture with various mixing ratios after being reinforced with carbon fibers

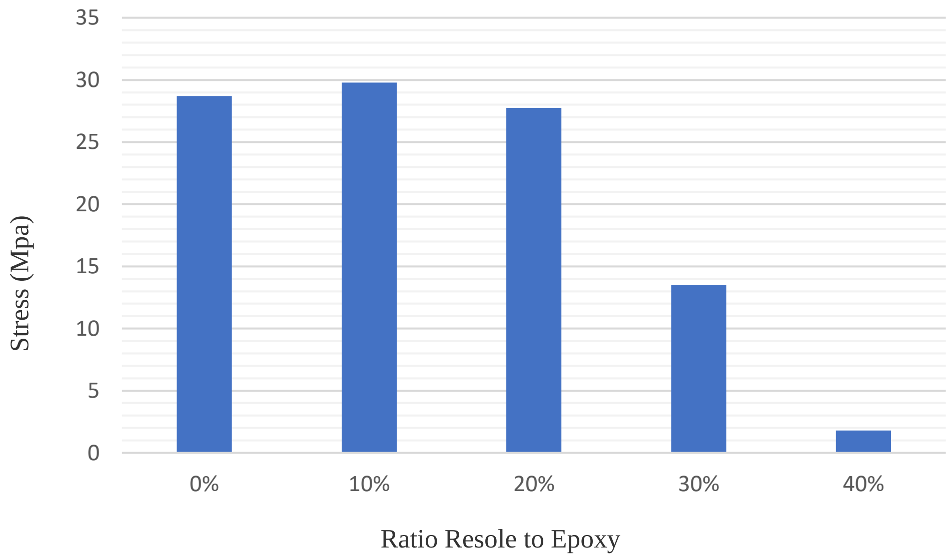


Figure 5. The hybrid mixture's tensile stress values after being reinforced with zinc oxide microparticles at various mixing ratios

Particle-reinforced hybrid composites are becoming more and more popular in many engineering applications due to their improved features and benefits in engineering applications. Where the hybridization of composite materials is commonly used to enhance the mechanical properties and reduce the cost of classical materials [17]. A significant improvement was also observed in the adhesion of ZnO nanoparticles compared to ZnO microparticles (Figures 5 and 6) due to the increase in the area/volume ratio.

The increase in initial resistance as the percentage of epoxy additive increases is due to the fact that the addition of epoxy resin to the mixture increases the amount of cross-linking between the molecules, resulting in an increase in the material's strength and stiffness. However, as the additive percentage increases, the material becomes more brittle, and the additional cross-linking between the molecules becomes more restrictive, preventing the molecules from moving and reducing the material's flexibility and toughness. As a result, the material's resistance begins to decrease once a certain threshold is reached, which in this case is typically around 10% epoxy additive. It is essential to determine the optimal amount of additives to achieve the desired mechanical properties without compromising the material's overall performance, as this is a common occurrence in composite materials.

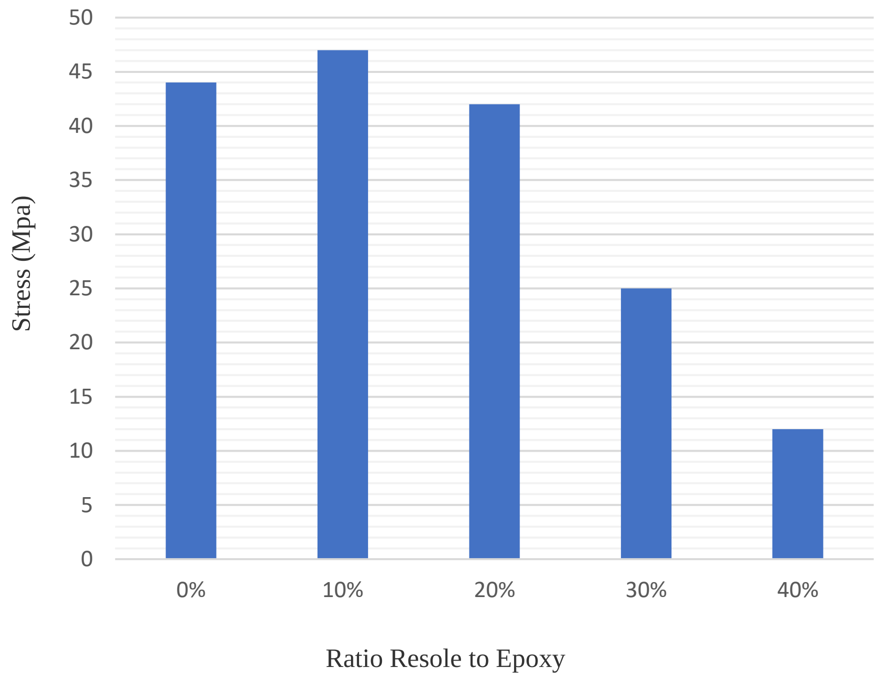


Figure 6. The hybrid mixture's tensile stress values after being reinforced with zinc oxide nanoparticles at various mixing ratios

3.2. Absorption test

The absorbed water content of a carbon-fiber-reinforced hybrid mixed with zinc oxide micro- or nanoparticles was determined by immersing the sample in distilled water at room temperature and weighing it. Samples were consistently weighed at various periods. The absorbed water was calculated by the weight difference and then the weight gain of the samples was measured at different time intervals. In Figures 7 and 8, the results showed that the absorption property reduces as the phenol formaldehyde proportion rises up to 10%, after which point it starts to rise as the phenol formaldehyde percentage rises, as the absorption increases dramatically when strengthening with fibers because these fibers cannot bridge the gaps between the components of hybrid compounds, but when strengthening it with zinc oxide micro and nanoparticles, the results showed a significant improvement in the material's resistance to adsorption, and it increased more when it was reinforced with nanoparticles compared to micro particles. As seen in Figure 7, the carbon fiber reinforcement gave the highest value of absorbance due to the high proportion of voids it contains. when compared to the hybrid mixture without reinforcement. Thus, the changes are almost insignificant in dimensions as shown in figure.

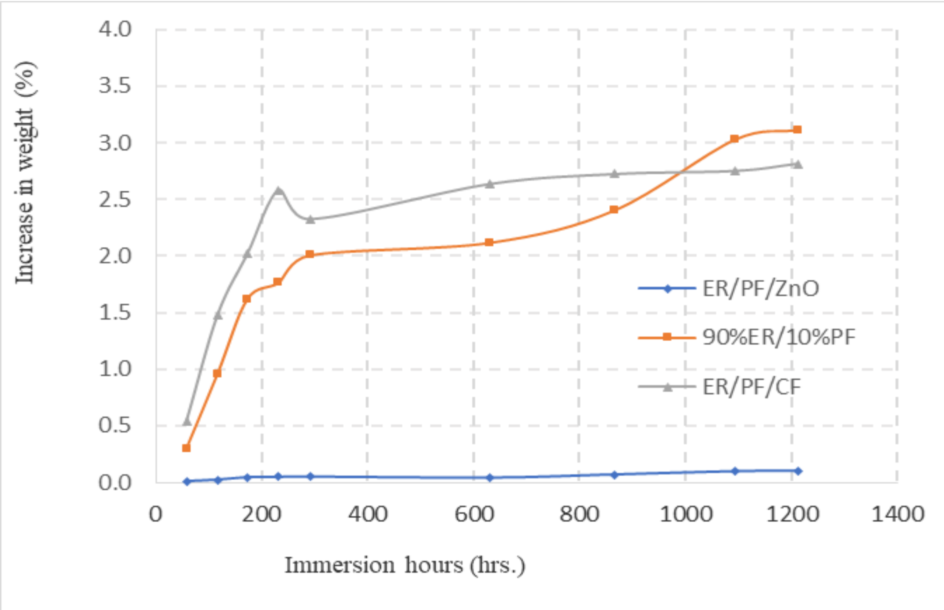


Figure 7. Water absorption tests of Nano-ZnO with ER/PF Mix

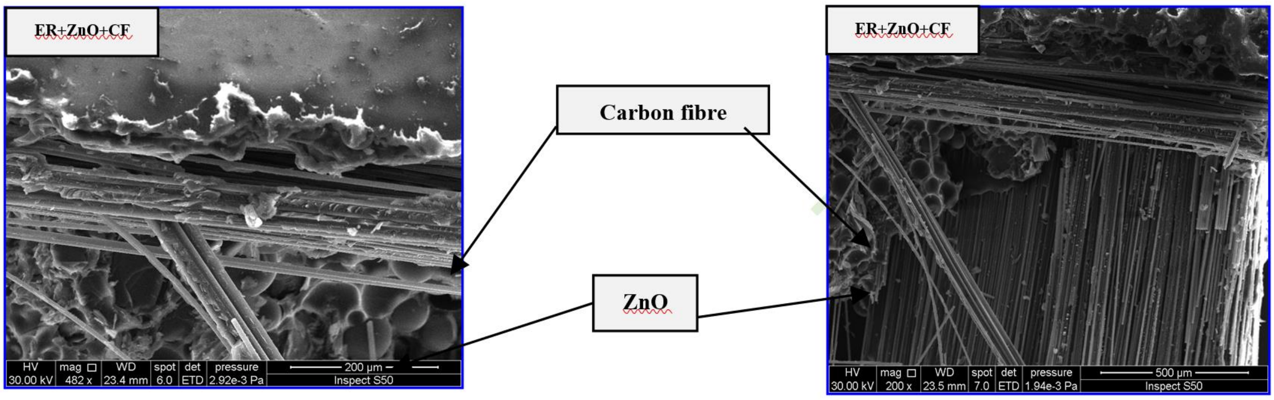


Figure 8. Surface morphology of the composite blends

4. Conclusions

1- The tensile property increases to some extent and then the property decreases with the increase of the percentage of phenol formaldehyde in the presence of 90% epoxy resin and 10% phenol formaldehyde.

2- The carbon fiber reinforcement of the hybrid mixture increases the tensile strength, when compared to the hybrid mixture which is not reinforced with carbon fibers.

3- Improvement in tensile strength upon strengthening with zinc oxide nanoparticles compared to materials reinforced with zinc oxide micro particles.

4- We propose to use the hybrid mixture used in the current study in the manufacture of sewage pipes, as it is suitable for this, consisting of 10% phenol formaldehyde and 90% epoxy resin.

5- When reinforced with carbon fibers, the absorption property rises, giving carbon fibers a high absorption capacity when used to enhance the hybrid mixture.

6- The absorbance property increases when it is strengthened with zinc oxide micro particles compared to nanoparticles.

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