Experimental and Theoretical Studies on Mechanical Properties of Composite Materials

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Abstract

Resistible composites have been suggested to be used instead of carbon steel pipes to overcome a number of common problems during commercial applications, especially the problem of fixing dead-beat carbon steel pipes within these systems. The new composites used are resistible materials of unsaturated polyester sponsored with glass fiber and aluminum honeycomb. Mechanical properties of resistible composites have been studied using ASTM in order to find the best conditions to create a system of pipes. It have been seen clearly that the best concentration of aluminum powder is 3٥ % of the composite mixture, which represent the most suitable mechanical properties. Also, it was found that aluminum honeycomb samples were a very good mechanical properties suitable for certain applications.

Key Words: Composite Material, Carbon Steel Pipes, Polyester, Mechanical Properties, ASTM.

الدراسة العملية والنظرية للخصائص الميكانيكية للمواد المركبة

المستخلص

تم اقتراح مواد مركبة بديلة لتصنيع الأنابيب الناقلة للتغلب على المشاكل الحاصلة في التطبيقات التجارية و خاصة مشاكل الاستهلاك في أنابيب الكاربون ستيل المستخدمة. المواد المركبة المستخدمة كبدائل هي مواد مقاومة تتكون من بولي استر غير المشبع مقوى بألياف الزجاج و خلايا الالمنيوم. تم دراسة الخواص الميكانيكية للمواد المركبة باستخدام الفحوصات القياسية ASTM لإيجاد افضل الظروف لإنشاء منظومة الأنابيب. وجد أن أكثر مواصفات ميكانيكية ملائمة تكون في تركيز% ٣٥ من مسحوق الالمنيوم في الخليط و كذلك وجد ان النماذج التي تحتوي على خلايا الالمنيوم تكون ذات مواصفات ميكانيكية جيدة و مفيدة للاستخدامات الخاصة.

1. Introduction

Composite materials were known to mankind in the Paleolithic age (also known as Old Stone Age). The 300 ft high ziggurat or temple tower built in the city center of Babylon was made with clay mixed with finely chopped straw [1]. In recent years, polymeric based composite materials are being used in many applications, such as automotive, sporting goods, marine, electrical, industrial, construction, household appliances, etc. Polymeric composites have high strength and stiffness, light weight, and high corrosion resistance [2].

Nowadays market challenges, based on economy and efficiency of the manufacturing process, as well as various customers' needs, resulted in the development of new and high quality materials, such as composites. Scientists have defined composite materials in many ways [3, 4], but, the common idea of all these definitions is that composites represent artificial materials, made of two basic, not-mixable, components represented by the *matrix* and the *reinforcing elements* [5]. Composite materials (or composites for short) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure. The physical properties of composite materials are generally not isotropic (independent of direction of applied force) in nature, but rather are typically orthotropic (different depending on the direction of the applied force or load) [6]. In contrast, isotropic materials (for example, aluminum or steel), in standard wrought forms, typically have the same stiffness regardless of the directional orientation of the applied forces and/or moments [7]. The relationship between forces/moments and strains/curvatures for an isotropic material can be described with the following material properties: Young's Modulus, the Shear Modulus and the Poisson's ratio, in relatively simple mathematical relationships. For the anisotropic material, it requires the mathematics of a second order tensor and up to 21 material property constants. For the special case of orthogonal isotropy, there are three different material property constants for each of Young's Modulus, Shear Modulus and Poisson's ratio—a total of 9 constants to describe the relationship between forces/moments and strains/curvatures [8].

A number of investigations have been conducted on several types of natural fibers such as kenaf, hemp, flax, bamboo, and jute to study the effect of these fibers on the mechanical properties of composite materials [9, 10, 11, 12]. Mansur and Aziz [1٠] studied bamboo-mesh reinforced cement composites, and found that this reinforcing material could enhance the ductility and toughness of the cement matrix, and increase significantly its tensile, flexural, and impact strengths. On the other hand, jute fabric-reinforced polyester composites were tested for the evaluation of mechanical properties and compared with wood composite [12]. A pulp fiber reinforced thermoplastic composite was investigated and found to have a combination of stiffness increased by a factor of 5.2 and strength increased by a factor of 2.3 relative to the virgin polymer [13]. In dynamic mechanical analysis, Laly et al., [13] have investigated banana fiber reinforced polyester composites and found that the optimum content of banana fiber is 40%. Mechanical properties of banana–fiber–cement composites were investigated physically and mechanically by Corbiere-Nicollier et al. [14]. It was reported that kraft pulped banana fiber composite has good flexural strength. Joseph et al. [15] tested banana fiber and glass fiber with varying fiber length and fiber content as well. The analysis of tensile, flexural, and impact properties of these composites revealed that composites with good strength could be successfully developed using banana fiber as the reinforcing agent. The source of banana fiber is the waste banana trunks or stems which are abundant in many places in the world. Therefore, composites of high–strength pseudo-stem banana woven fabric reinforcement polymer can be used in a broad range of applications. Wei Sun and Jerome in 2002 [16] developed model to predict the mechanical properties of the composite conductor based on two-level homogenization hierarchies. The developed model provides a theoretical basis and an accurate calculation for effective mechanical constants that are often difficult to be accurately determined through an experimental approach due to the structural heterogeneity and material anisotropy of the composite conductor. Wilson et al., in 2005 [17] developed Alumina-based composites in order to improve the mechanical properties of the monolithic matrix and to replace the WC-Co material for cutting tool applications. Al_2O_3

reinforced with refractory carbides improves hardness, fracture toughness and wear resistance to values suitable for metalworking applications. Al_2O_3-NbC composites were uniaxially hot-pressed at 1650 °C in an inert atmosphere and their mechanical properties and microstructures were analyzed. Maleque et al., 2007 [1] study the tensile, flexural, and impact properties of pseudo-stem banana fiber reinforced epoxy composites. They found that the tensile strength on the pseudo-stem banana woven fabric reinforced epoxy composite is increased by 90% compared to virgin epoxy. The results of the impact strength test showed that the pseudo-stem banana fiber improved the impact strength properties of the virgin epoxy material by approximately 40%. Higher impact strength value leads to higher toughness properties of the material. Maleque showed that the banana fiber composite exhibits a ductile appearance with minimum plastic deformation. Mihaiela et al., 2009 [5] represented experimental and theoretical studies for determining random reinforced glass fiber polymeric composite material mechanical characteristics, pointing out the importance of knowing real values of these characteristics in parts designing.

In this work resistible composites are suggested to be used instead of carbon steel pipes to overcome a number of common problems during commercial applications, especially the problem of fixing dead-beat carbon steel pipes within these systems. This work also studies the mechanical properties of resistible composites using ASTM to find the best conditions to create a system of pipes.

2. Theory

The use of the composite material in the engineering applications depends greatly on its good mechanical properties, especially its high strength and low weight [18]. Generally the mechanical properties describe the behavior of the composite material under the influence of different forces [19].

2.1 Flexural Strength (F.S.) ASTM-D790

The flexural test measures the force required to bend a beam under three point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material’s stiffness when flexed. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, it is sometimes appropriate to test materials at temperatures that simulate the intended end user environment [20]. The capability of composite material to bend under centric stresses was located using the following equation:

$$F.S. = \frac{3pL}{2bd^2} \tag{1}$$

and

$$\tau = \frac{3p}{4bd} \tag{2}$$

2.2 Bending ASTM-D790

An **elastic modulus**, or **modulus of elasticity**, is the mathematical description of an object or substance's tendency to be deformed elastically (i.e., non-permanently) when a force is applied to it [21]. The elastic modulus of an object is defined as the slope of its stress-strain curve in the elastic deformation region:

$$\lambda \overset{\text{def}}{=} \frac{\text{stress}}{\text{strain}}$$

Where lambda (λ) is the elastic modulus; *stress* is the force causing the deformation divided by the area to which the force is applied; and *strain* is the ratio of the change caused by the stress to the original state of the object. If stress is measured in pascals, since strain is a unitless ratio, then the units of λ are pascals as well [22].

Since the denominator becomes unity if length is doubled, the elastic modulus becomes the stress needed to cause a sample of the material to double in length. While this endpoint is not realistic because most materials will fail before reaching it, it is practical, in that small fractions of the defining load will operate in exactly the same ratio. Thus for steel with an elastic modulus of 30 million pounds per square inch, a 30 thousand psi load will elongate a 1 inch bar by one-thousandths of an inch, and similarly for metric units, where a thousandth of the modulus in Giga Pascal will change a meter by a millimeter.

Specifying how stress and strain are to be measured, including directions, allows for many types of elastic module to be defined. The three primary ones are:

- *Young's modulus* (*E*) describes tensile elasticity, or the tendency of an object to deform along an axis when opposing forces are applied along that axis; it is defined as the ratio of tensile stress to tensilestrain. It is often referred to simply as the *elastic modulus*.
- The *shear modulus* or *modulus of rigidity* (*G* or μ) describes an object's tendency to shear (the deformation of shape at constant volume) when acted upon by opposing forces; it is defined as shear stress over shear strain. The shear modulus is part of the derivation of viscosity.
- The *bulk modulus* (*K*) describes volumetric elasticity, or the tendency of an object to deform in all directions when uniformly loaded in all directions; it is defined as volumetric stress over volumetric strain, and is the inverse of compressibility. The bulk modulus is an extension of Young's modulus to three dimensions.

From the change of deflection caused by variable masses, the specific modulus of elasticity (E) can be calculated from the following equation [21]:

$$E = \frac{mgL^3}{48fI} \tag{3}$$

(Mass/deflection is the slope of the curve)

(Which means load/ deflection is the slope of the curve)

I is the moment of inertia and:

$$I = {bt^3}/{12} \tag{4}$$

2.3 Impact Strength ISO-179

Because of the outer impacts on the composite materials in the industry, this test is important. The fracture means the separation or fragmentation of a solid body into two parts or more under the influence of a stress higher than it can bear, that means it consists of two stages, the first is crack initiation and the other is crack propagation [23]. The impact strength can be calculated from the following equation [22]

$$Impact\ strength = \frac{U}{A} \tag{5}$$

2.4 Brinell Hardness

The Brinell scale characterizes the indentation hardness of materials through the scale of penetration of an indenter, loaded on a material test-piece. It is one of several definitions of hardness in materials science. Johan August Brinell proposed the brinell scale in 1900; it was the first widely used and standardized hardness test in engineering and metallurgy. The large size of indentation and possible damage to test-piece limits its usefulness[24]. The typical test uses a 10 mm diametersteel ball as an indenter with a 3,000 kgf (29 KN) force. For softer materials, a smaller force is used; for harder materials, a tungsten carbide ball is substituted for the steel ball [26]. The Brinell hardness (Br. H.) is an important surface mechanical property and it’s known as a resistance of the material to deform [21]. The Brinell hardness can be calculated from the following equation:

$$\mathrm{HBW} = 0.102\frac{2F}{\pi D(D - \sqrt{(D^2 - d^2)})} \tag{6}$$

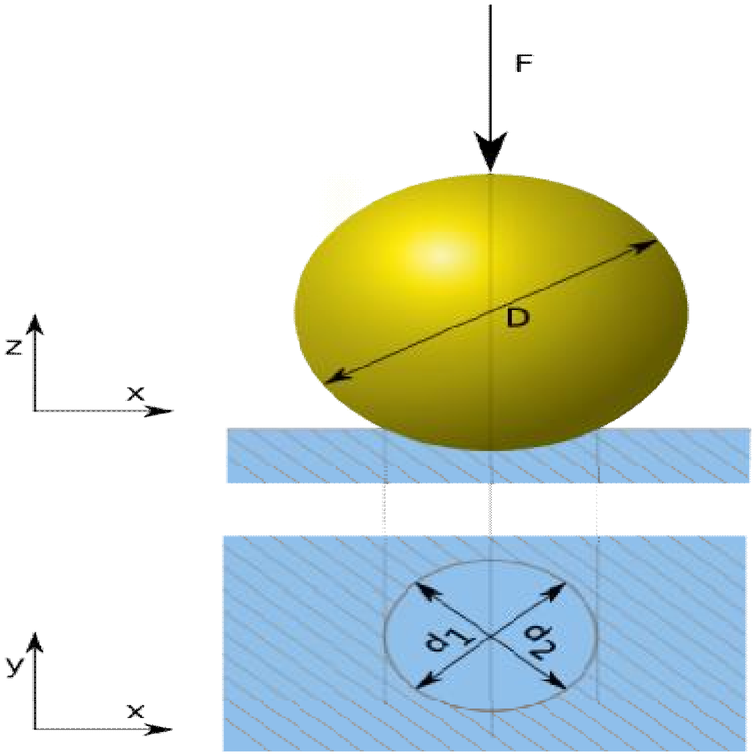

Figure (1). Force diagram.

3. Experimental work

Four mechanical tests were made to the composites and to the carbon steel specimens to make a good comparison between them:

3.1 Impact Strength (ISO-179)

The impact strength test was made by using Charpy impact device. The dimensions for the specimens used were 6*2*0.6 cm. The device consists of a pendulum hummer with an energy gage to measure the energy needed to break the specimen (breaking energy, j). Equation (5) was used to calculate the impact strength.

3.2 Bending Test (ASTM D-790)

The bending test device of Phywe Company was used to calculate the modulus of elasticity of the composite specimens 10*1*0.5 cm. The masses were hanged in the middle of the specimen using a holder. These masses will cause a deflection in the specimen, that measured by a deflection gage. Equations (3) and (4) were used to calculate the specific modulus of elasticity.

3.3 Flexural Strength (ASTM D-790)

Most commonly the specimen lies on a support span and the load is applied to the center by the loading nose producing three points bending at a specified rate [25]. The parameters for this test are the support span, the speed of the loading, and the maximum deflection for the test [26]. These parameters are based on the test specimen thickness and are defined differently by ASTM and ISO. For ASTM D790, the test is stopped when the specimen reaches 5% deflection or the specimen breaks before 5%. For ISO 178, the test is stopped when the specimen breaks. If the specimen does not break, the test is continued as far as possible and the stress at 3.5% (conventional deflection) is reported.

The test carried out made using a hydraulic compressor of Ley Bold Harris No.36110 type. The dimensions of the specimens were 10*1*0.5 cm. This test (three-point test) was carried out using the apparatus shown in figure (2) and with the gage in the hydraulic compressor; the load needed to break the specimen was read. Equations (1) and (2) were used to calculate the flexural strength and shear stress.

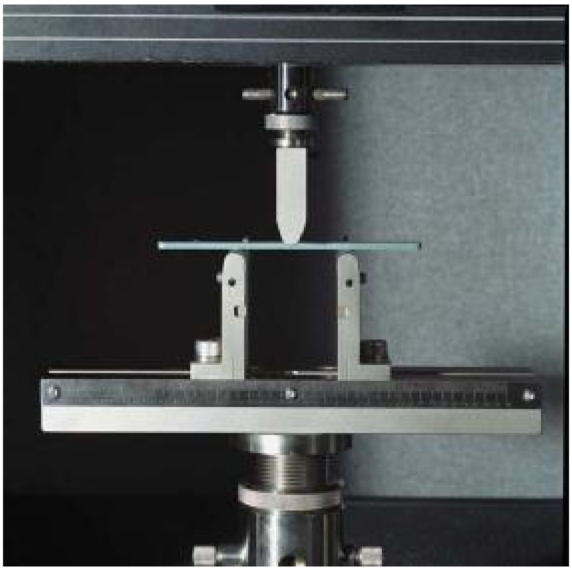

Figure (2). Flexural apparatus.

3.4 Brinell Hardness Test

Using a carbide ball penetrator, and applying loads of up to 3,000 kgf, Brinell hardness tester following ASTM E-10 is widely used on castings and forgings. This method requires optical reading of the diameter of ball indentation, and using a chart to convert the average measurement to Brinell hardness value.

The same hydraulic compressor was used with a stainless-steel semi-cone with diameters of the free end 5.0 and 2.5 mm, respectively. A specific load was put on the specimen for about 10-15 seconds, and then was appeared a hole on the specimen with specific diameter. Equation (6) was used to calculate Brinell hardness was found.

4. Results and discussion

4.1 Bending test

The important goal from this test is to see the Hookean behavior for the material under loading. Figures (3), (4) and (5) show that the deflection was increased proportionally with the load on the specimen and when the load disappears the specimen goes to its original state and it means that these specimens were under Hook’s law. Also the percentage between mass deflections is constant and represents the slope in all these figures by using equations (3) and (4) to calculate the specific modulus of elasticity (E) for all the specimens (8-spesimens).

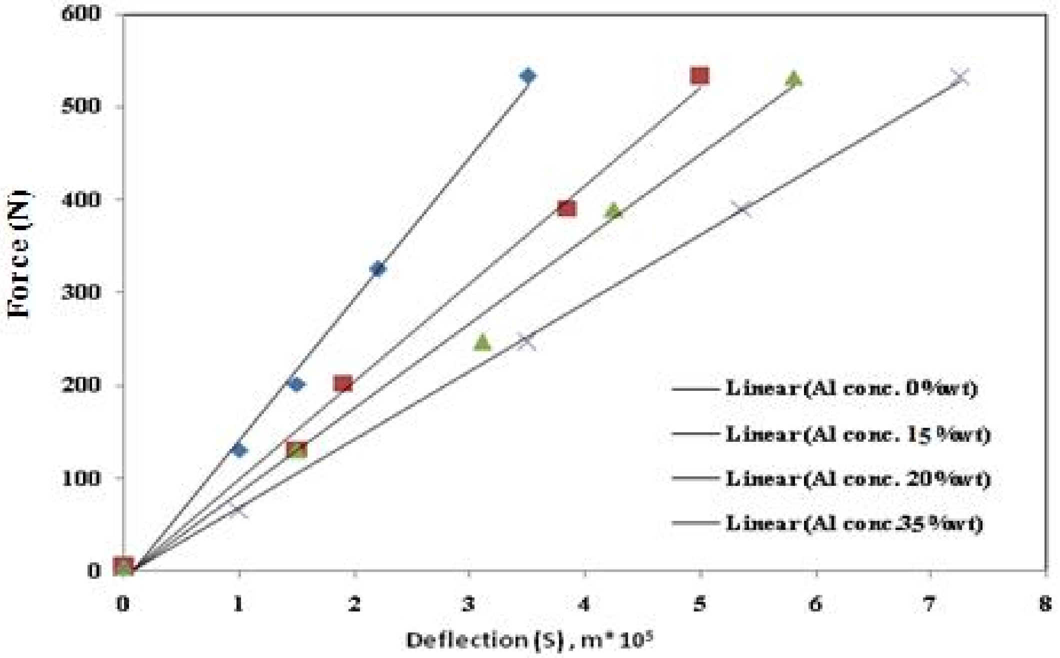

Figure (3) .Deflection against force of bending test.

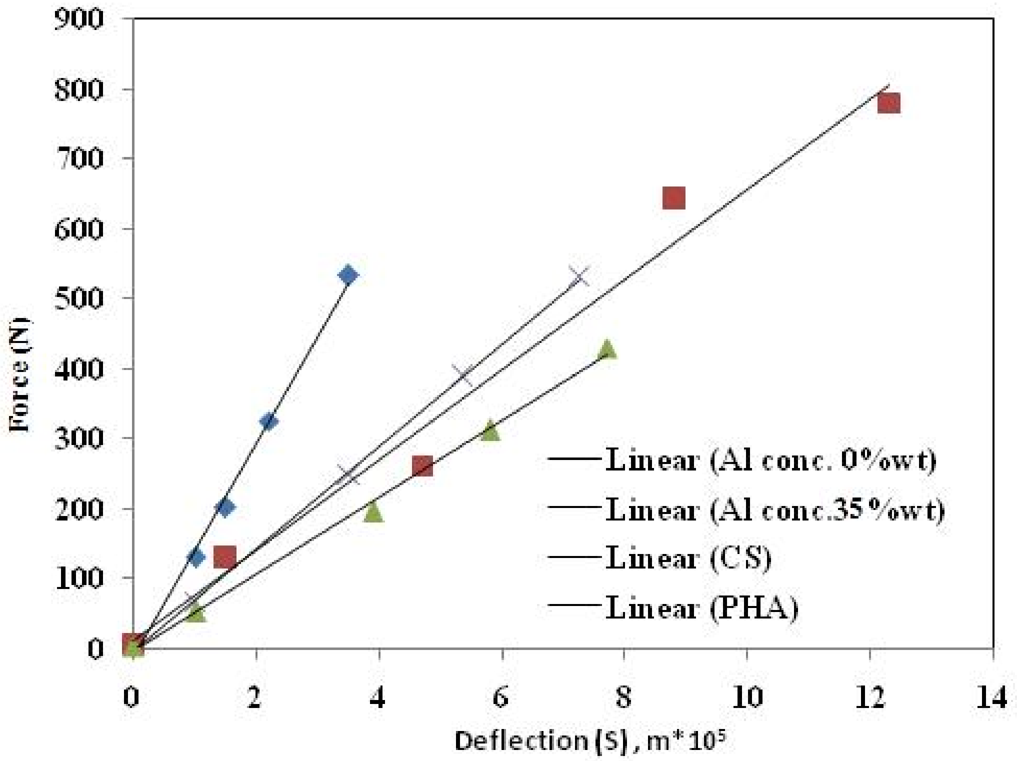

Figure (4). Deflection against force of bending test.

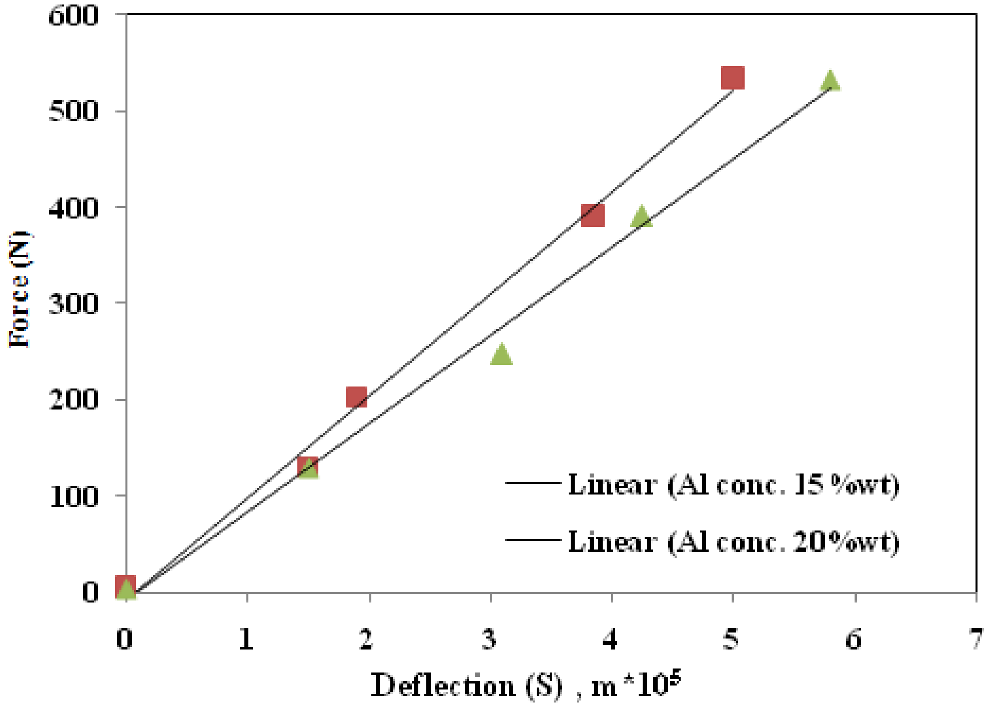

Figure (5). Deflection against force of bending test.

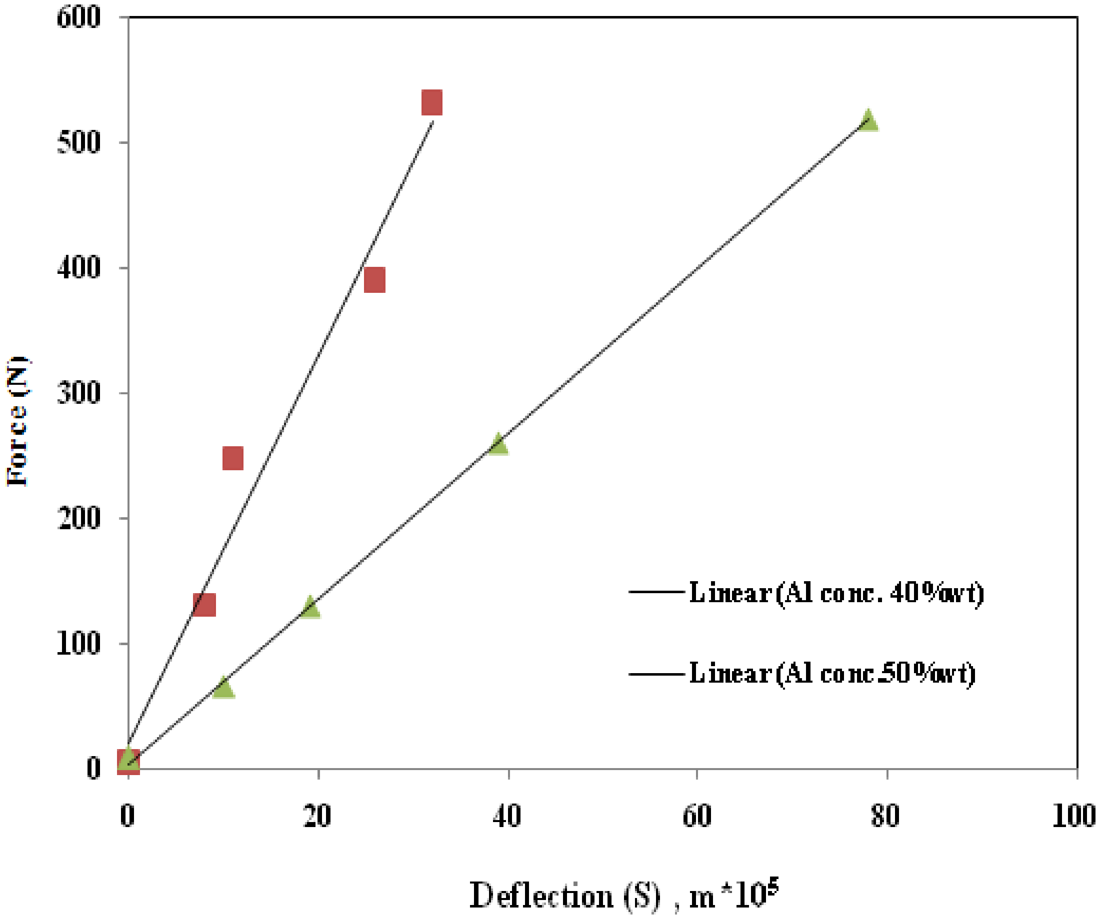

Figure (6) .Deflection against force of bending test.

Figure (6) shows that the samples of 40 and 50 wt % aluminum powder show a high influence of deflection than the other samples.

Figure (7) below shows that the specific modulus inversely proportional with the aluminum powder concentration, it decreases when the aluminum powder concentration in the specimens' increases and that means the cross-link density between the unsaturated polyester molecules decreases with increasing the aluminum powder concentration. It can be seen that the specific modulus of the aluminum honeycomb was low compared with the other specimens; this means that the glass fiber departs loads more than the aluminum honeycomb.

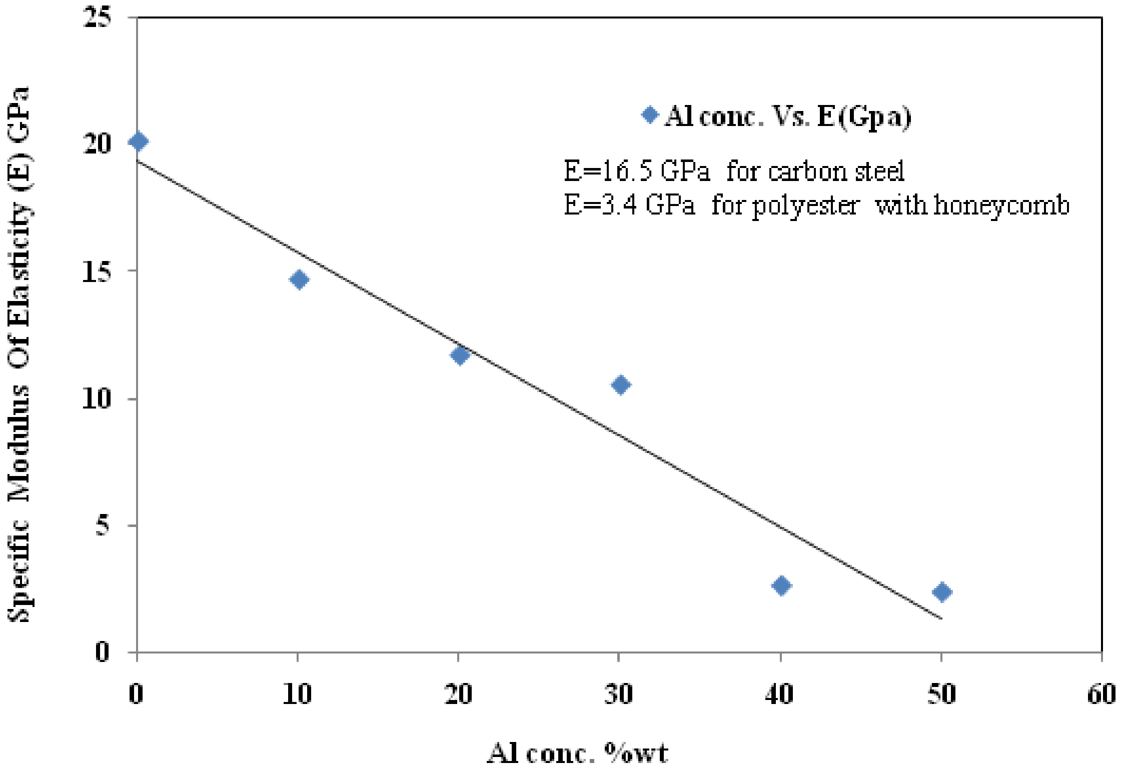

Figure (7). Effect of Aluminum powder concentration on the specific modulus.

4.2 Flexural strength test

This test was used to specify the highest twisting stress that the specimens can afford. There are three kinds of failure happened at different places in the same time and its [26]:

1. The tensile stresses failure:

This will cause matrix chapping and will load the fibers to be on the surface and when the load increases this chapping will grow faster from fiber to another in the transverse direction.

2. Compressive stresses failure:

   At usual the primary failure of the specimens in this test will happen on the other surface of these specimens. This compression will cause a micro-buckling phenomenon to the fiber and when the loading increases the fibers will breakout.

3. Shear stresses failure:

   The generated shear chapping could grow both in transverse and longitudinal directions. When the cross-link density between the fibers and the polymer and the polymer itself increases, the shear strength will increase too. There are many factors that influence these failure kinds such as: the fiber type, the fiber length and diameter, the fiber direction and the volume fraction of the fiber [23].

Figure (8) represents the failure happened on the prepared samples by the flexural strength test.

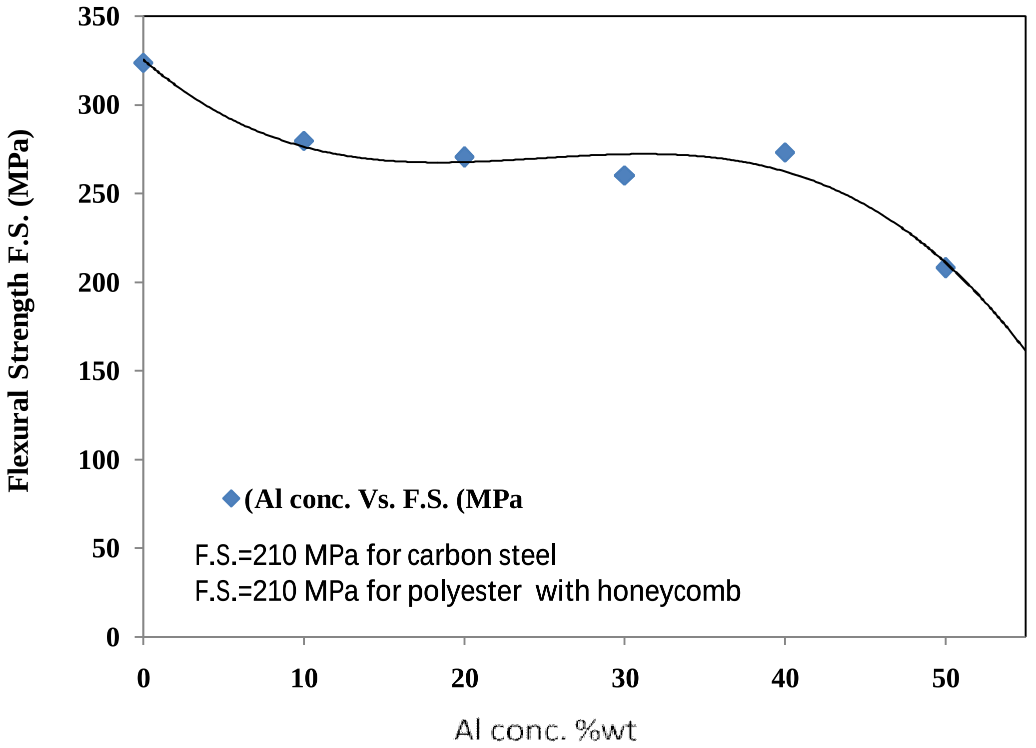

Figure (8) .Effect of Aluminum powder concentration on the flexural strength.

Figures (8) and (9) show the effect of the aluminum powder concentration in the specimens, on the flexural strength and shear stress it can be seen that when the concentration of the aluminum powder increases the flexural strength and shear stress decreases because of the particles of the aluminum powder decreases the cross-link density of the polymer with the glass fiber and with each other. Also it can be seen from that shear stress values are very much less than the flexural strength because it is only a surface stresses, not for all the body.

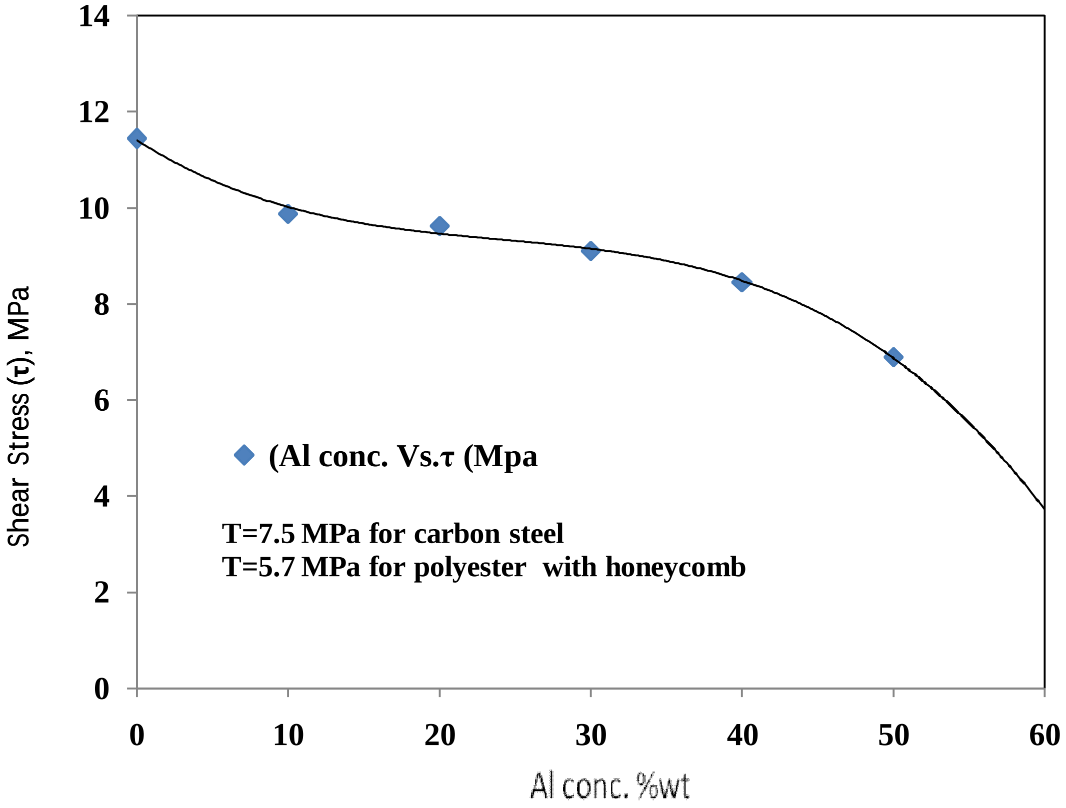

Figure (9). Effect of Aluminum powder concentration on the shear strength .

4.3 Impact test

The failure caused by fast stresses is one of the most mechanical properties that get attention lately, because sometimes the polymeric material is flexible under static stresses, but it looks like a shooing one under fast stresses [21].

Equation (5) has been used to calculate the impact strength for all the specimens. From Figure (10) below it can be seen clearly that when the aluminum powder concentration increases, the impact strength decreases, while the carbon-steel specimens have the highest value of impact strength because it’s a flexible material.

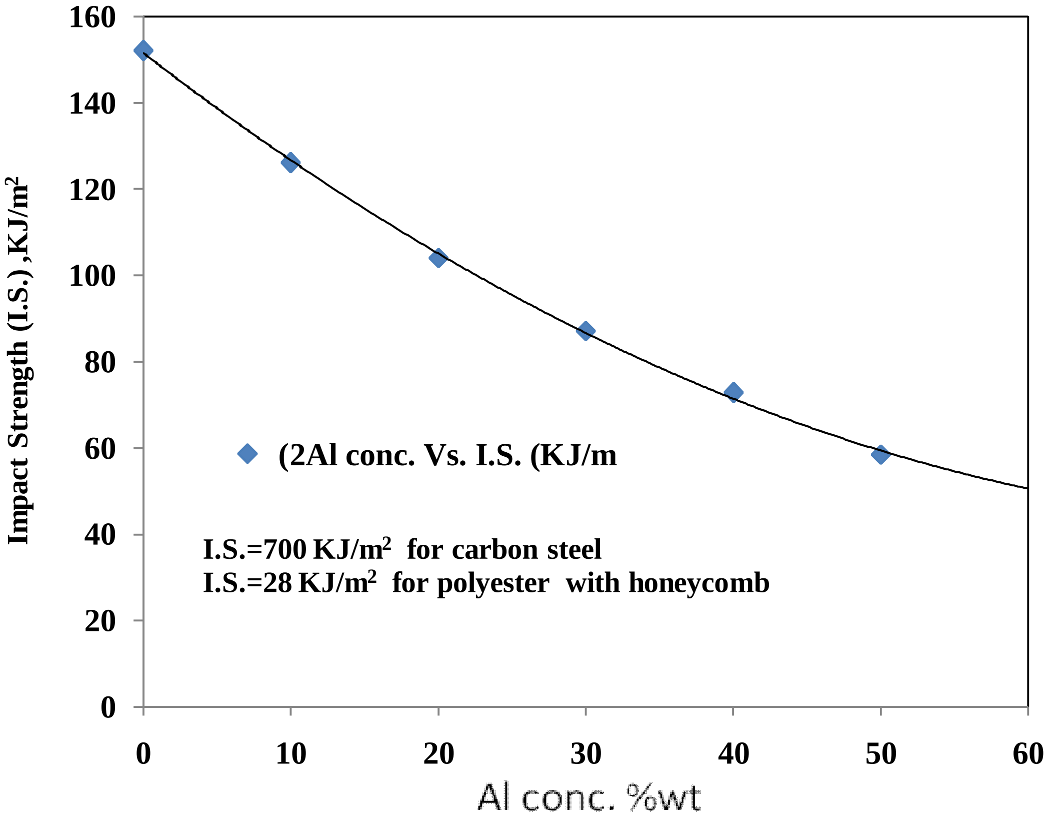

Figure (10). Effect of Aluminum powder concentration on the impact stress.

4.4 Brinell Hardness Test

Brinell hardness (Br. H.) test is used to measure the resistance of the material to plastic deformation on the surface.

Figure (11) shows the values of Br. H. calculated from equation (6), it can been seen that when the aluminum powder concentration increasing, the Br. H. decreasing and this means that the particulate filler minimizing the mechanical properties values specially when adding a 40-50 wt% of aluminum powder. While at 0, 15, 20 and 3٥wt% samples the mechanical properties values were close to of carbon-steel specimen, while the aluminum honeycomb has a different mechanical property.

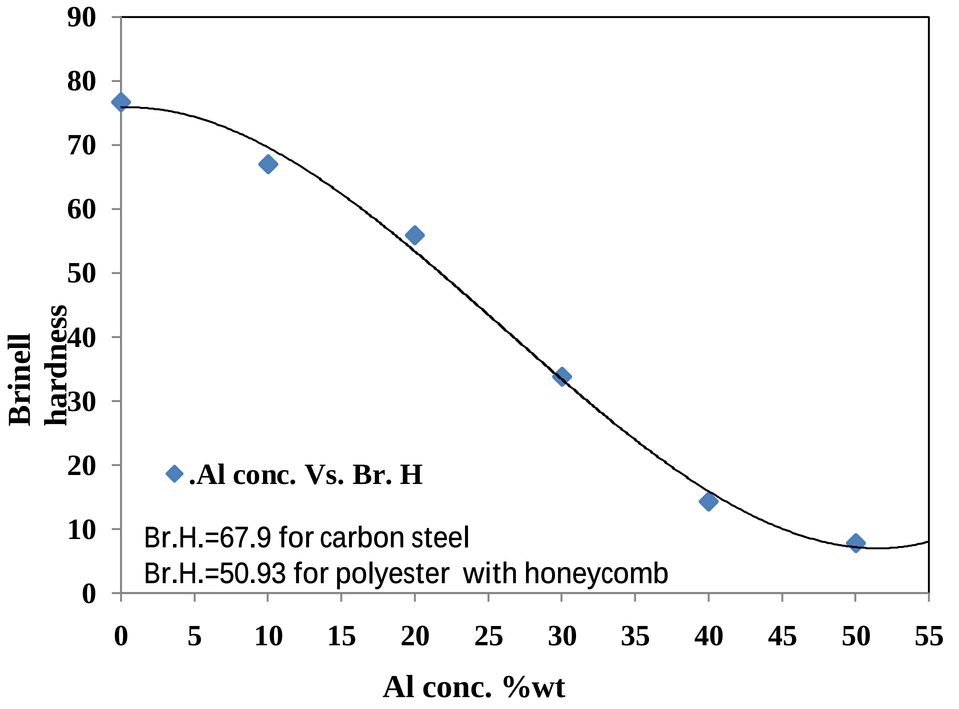

Figure (11) .Effect of Aluminum powder concentration on the Brinell hardness.

5. Conclusions

In this work, the specimens were under Hook's law this is because the proportionally increasing of the deflection with the load on the specimen, as well as when the load disappears the specimen goes to its original state.

The cross-link density between the unsaturated polyester molecules decreases with increasing aluminum powder concentration. The mechanical properties decrease with the increasing of aluminum powder concentrations.

The glass fiber departs loads more than the aluminum honeycomb, this is due to the fact that the specific modulus of the aluminum honeycomb was low compared with the other specimen.

Increasing the aluminum powder concentration led to a decrease in the impact strength, while the carbon-steel specimens have the highest value of impact strength because it's a flexible material.

The most suitable weight percent of the aluminum powder is 3٥wt% which gives mechanical properties values close to the mechanical properties of carbon-steel. Aluminum honeycomb samples were very good mechanical properties suitable for certain applications such as aircraft engine parts, spacecraft parts, assemblies,air/light directionalization, energy absorption, etc..

6. References

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7. Nomenclature

A	Cross-sectional area of the sample (m^2)
.b	Width of the specimen (m)
D	Stainless-steel semi-cone diameter (mm)
.d	Diameter of the hall on the specimen (mm)
F	Loaded force (KN)
f	Deflection
F.S.	Flexural strength (MPa)
g	Acceleration 9.81 m/s^2
L	Length of the specimen (m)
m	Mass (kg)
.τ	Shear stress (MPa)
p	Load (N)
.t	Thickness of the specimen (m)
U	Breaking energy (J)