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Effect of Water Absorption on the Impact Behaviors of CFRE Composites

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Abstract- This paper is concerned with the effect of water absorption on the impact behavior of woven carbon fiber reinforced epoxy (CFRE) composites. The composite laminates were manufactured using the prepreg technique and then cut to the standard dimensions following the ASTM D 7136. The specimens were immersed in distilled water up to 368 h. The moist specimens were characterized by falling weight tester at different impact energies. The impact results are compared with the results obtained under dry testing conditions. The comparison shows that water-immersed plates absorb almost the same energy as the corresponding dry ones. However, the maximum force obtained with the water-immersed plates is 15%-20% lower than those of the corresponding dry plates. This can be interpreted in terms of the degradation effect the composite material by water absorption.

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1. INTRODUCTION

Fiber reinforced polymer (FRP) composite laminates are commonly used as light-weight materials in a wide variety of marine applications including sporting equipment as well as military structures. Low-velocity impacts in these applications cannot be avoided via falling tools and equipment, floating ice, struck submerged objects, grounding and collisions. Low-velocity impacts on composite structures can yield degradation of the composite material, which is sometimes hard to detect by external inspection. Impact damage is highly dependent upon the nature of the threat and conditions associated with the impact event. The impacted composite structures have 50%-75% less strength than undamaged structures [1].

Impact behavior of FRP composite structures have special attention by many researches [2-10]. However, few of them characterized the impact performance under water environments [8-10], which is the subject of the present study. FRP composites generally absorb energy through fracture mechanisms such as delamination, shear cracking, and fiber breakage; however some portion of the energy may

be absorbed through elastic-plastic deformation of the fiber and matrix. The mode of fracture and thus the energy absorbed are influenced by various test and material variables such as: fiber orientation, interface strength, specimen geometry, velocity of impact, and environmental conditions. Aymerich et al. [2-3] studied the impact-induced damage on stitched and unstitched graphite/epoxy laminates. Dau et al. [4] dealt with 3D-interlock composite materials. Kursun et al. [5] investigated the influence of the impactor shape on the post-impact strength of composite sandwich plates. Iqbal et al. [6] were interested in the impact damage resistance in nanoclay-filled CFRE. Arun et al. [8] investigated the effect of sea water on the impact properties of glass/textile fabric polymer hybrid composites using a pendulum type impact testing machine. The specimens were immersed in sea water for 8, 16 and 24 days.

Water absorption can exit in two distinct forms: free water that fills the microcavities of the network and bound water in strong interactions with polar segments [11]. The degradation of the impact strength of glass/polyester composites in water may be due to physical degradation such as matrix "swelling", degradation of matrix resin due to chemical reaction with water and degradation of interfaces bonding between fibers and matrix resin [9].

The present work is a continuation of a previous study [7] on the effect of temperature on the impact behaviors of CFRE composites. The impact tests were carried out using falling weight impact tester at room temperature (RT), 50°C and 75°C. Khashaba and Othman [7] reported that the reduction of stiffness and strength at room temperature and 50°C is comparable. The highest reduction in the stiffness and strength is observed at 75°C owing to softening of the epoxy matrix, plasticization of the matrix at the impacted zone, interfacial fiber/matrix debonding, degradation of the matrix properties and increases of the interfacial stress concentration of the re-solidified matrix.

Automotive and aircraft structures are always exposed to water from rains and condensation of atmospheric humidity. Applications, such as boats and marine industries, water pipes and tanks required more data about the effect of water as the main environment on their mechanical properties. Therefore, the main

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objective of the present work is to investigate the impact behavior of carbon fiber reinforced epoxy composites subjected to water environments. The experimental results of Gude et al. [11] showed that the saturation of epoxy (with and without carbon nanotubes) with water absorption is reached after about 265h. Therefore, in the present work the specimens were immersed in distilled water up to 386 h. Subsequently, they are subjected to impact tests using drop-weight machine in accordance with ASTM D 7136.

II. EXPERIMENTAL WORK

a) Materials

Carbon fiber reinforced epoxy (CFRE) composite laminates were manufacture dusing 25 layers

of T300-3k plain woven carbon fiber fabrics (200g/m²) and YPH-120-23A/B epoxy matrix by applying the prepreg method. The laminates are fabricated in 500x500x5 mm. The tensile and in-plane shear properties of CFRE composite were determined in some previous works, Khashaba et al. [12-13]. Moreover, the compressive properties are studied in Ref. [14] for non-impacted specimens. The tensile, compression and shear properties are illustrated in Table 1.

Table 1: Tensile, shear and compressive properties of CFRE composite

Tensile [12-13]			In-plane shear [121-13]		Compressive [14]	
Strength σ_t (MPa)	Modulus E_t (GPa)	Poisson's ratio ν	Strength τ (MPa)	Modulus G (GPa)	Strength σ_c (MPa)	Modulus E_c (GPa)
895.28	81.66	0.052	145.41	6.94	633.30	80.90

b) Specimens Preparation

The tested specimens were cut from the fabricated composite laminates to the standard dimensions of the falling mass impact tests according to ASTM D 7136. Three specimens were cut for each experimental condition using abrasive waterjet machine to dimensions of 101.6x152.4x5 $\pm$ 0.1 mm. The main advantage of this cutting technique is the elimination of heat generation, which is associated with the conventional machining processes. Heat generation is a main drawback as it can soften the fabricated materials that re-solidified after cooling. In the worst case, the heat generation can burn the matrix. Softening and solidifying of polymer composites is frequently associated with high stress concentration along the cutting path. In addition, the induced stress concentration can lead to premature failure of the specimens when subjected to the mechanical loads of the testing machines. A second advantage of abrasive waterjet machine is that it is dustless cutting technique. This is highly advantages mainly when cutting polymers and fiber-reinforced polymer composites (FRP). Consequently, this technique is environmentally friend and not hazardous.

To evaluate the effect of moisture environments on the impact response of CFRE composites, the specimens were immersed in a tank containing distilled water up to saturation, which is observed after about 368 h. The water in the tank was renewed every 3 days [9]. The moisture weight was measured at different time

intervals using high sensitivity (0.0001 g) digital balance of model A & D HR-200. The experimental results of Gude et al. [11] showed that the saturation of epoxy (with and without carbon nanotubes) with water absorption is reached after about 265h. Therefore, the selected immersion time (368 h $\approx$ 16 days) is enough for saturation of CFRE specimens with distilled water.

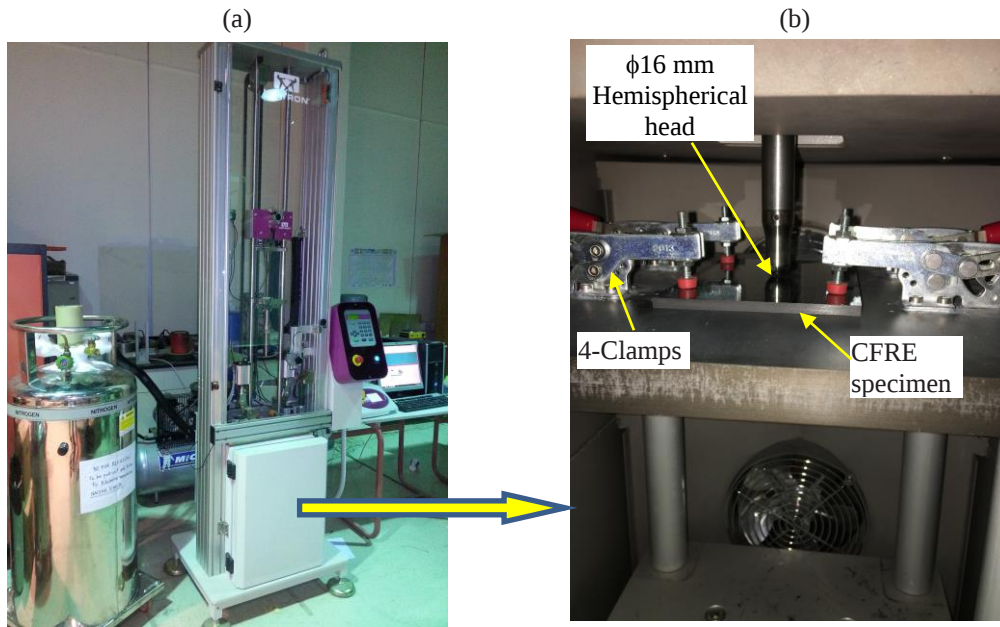


Fig. 1: (a) Falling weight impact tester model CEA9340, and (b) specimen clamped inside thermal conditioning chamber of impact tester

c) Impact Tests

Drop weight impact tests were performed at room temperature on CFRE woven composites in accordance with ASTM D 7136 using CEA9340 falling weight impact machine shown in Figure 1(a). The specimen was clamped by four fixtures on a steel plate having a rectangular window of 125x75 mm². The specimen and the fixing frame are fixed inside the thermal conditioning chamber as shown in Figure 1(b). Six energy levels of 1.88J, 30J, 50J, 60J, 75J and 100J were selected to perform impact tests on CFRE composites. Three specimens were tested for each energy level and the average values are considered to evaluate the effect of water immersion on the impact behavior of CFRE composites at different impact energies.

The values of the falling height and impact velocity are automatically evaluated by the machine software. However, they can be determined from Eqs. (1) and (2), respectively, as follows:

$$H = \frac{E_i}{mg} \quad (1)$$

and

$$v_i = \sqrt{\frac{2E_i}{m}} = \sqrt{2gH} \quad (2)$$

where E_i is the impact energy, v_i is the impact velocity, H is the drop-height of the impactor, m is the total mass of the impactor and g is the gravity acceleration ($g =$

9.81 m/s²). Table 2 depicts the impact test parameters related to the investigated impact energies.

Table 2: Impact test parameters

Impact Energy (J)	Total Mass (kg)	Impact Height (m)	Impact Velocity (m/s)
1.88	3.632	0.053	1.02
30.13	7.632	0.402	2.81
50.00	12.632	0.403	2.81
60.00	12.632	0.484	3.08
75.00	7.632	1.002	4.43
100.05	12.632	0.807	3.98

The specimens were subjected to transverse impacts at low-velocities (1.02 – 4.43 m/s) with a hemispheric impactor of 16 mm in diameter. The impact testing machine is equipped with a pneumatic anti-rebound device to prevent a second impact on the tested specimen. Knowing the contact force and the impact velocity, the impactor acceleration $a(t)$, velocity $v(t)$, displacement/deformation $u(t)$, and energy $E(t)$, respectively, are calculated in terms of time, as follows [15]:

$$a(t) = -\frac{P(t)}{m}, \quad (3)$$

$$v(t) = v_i - \int_0^t a(\tau) d\tau = v_i - \int_0^t \frac{P(\tau)}{m} d\tau, \quad (4)$$

$$u(t) = \int_0^t v(\tau) d\tau, \quad (5)$$

and

$$E(t) = \int_0^t P(\tau) du = \int_0^t P(\tau) v(\tau) d\tau \quad (6)$$

The absorbed energy (E_a) is evaluated by subtracting the residual or rebound energy (E_r) from the impact energy ($E_i = \frac{1}{2}mv_i^2$) [16-17]. The residual energy is considered as the energy of the impactor when it rebounds and loses contact with impacted plate, i.e., when the force decreases back to zero. Hence, the absorbed energy (E_a) is evaluated as the asymptotic value of the energy $E(t)$ transferred from the impactor to

the composite plate. The absorbed energy ratio (ρ) is calculated as:

$$\rho = 100 \frac{E_i - E_r}{E_i} = 100 \frac{E_a}{E_i} \quad (7)$$

In addition, the peak force ($F_{max} = \max Ft$) is evaluated for each test.

III. RESULTS AND DISCUSSIONS

a) Water absorption and diffusion coefficient

The total moisture content (G) in composite materials that following Fickian behavior or Fick's diffusion laws can be described as follows [18]:

$$G = \frac{M - M_i}{M_m - M_i} = 1 - \frac{8}{\pi^2} \sum_{j=1}^{\infty} \frac{1}{(2j-1)^2} \exp \left[\frac{-(2j-1)^2 \pi^2 D t}{h^2} \right] \quad (8)$$

where M is the moisture content at time t , M_i is the initial weight of moisture in the specimen, M_m is the maximum (saturated) moisture content, h is the specimen thickness, and D is the mass diffusivity in the composite (diffusion coefficient).

The diffusion coefficient is an important parameter in Fick's law, which can be determined by solving the diffusion Eq. (8) for the weight of moisture, and rearranging in terms of the percent moisture content, the following relationship is obtained [18-19]:

$$D = \pi \left(\frac{kh}{4M_m} \right)^2 \quad (9)$$

where, k is the initial slope of a plot of $M(t)$ versus $t^{1/2}$ as shown in Fig. 2. This figure indicates that the difference between the last two subsequent weight readings approaches zero, which means that the maximum (saturated) moisture content of CFRE specimens is ($M_m = 0.066$ g) reached after 336 h immersion time. The estimated diffusion coefficient using the above equation is $4.145 \times 10^{-6} \text{ mm}^2/\text{s}$.

Since the sample was initially dry, the weight of moisture in the materials is $M_i = 0$. Thus, the Eq. (8) is reduced to the ratio $G = M/M_m$. Fig. 3 shows comparison between the predicted, Eq. (8), and the measured moisture absorption of T300-3k plain woven carbon fiber/epoxy composite. Because of the series of Eq. (8) is rapid convergence, the first four terms are enough for prediction the ratio (G) of the weight of moisture (M) at time t to the moisture in the fully saturated equilibrium condition (M_m) [20]. It is obvious from Fig. 3 that water absorption of T300-3k plain woven carbon fiber/epoxy composite has good agreement with Fick's law.

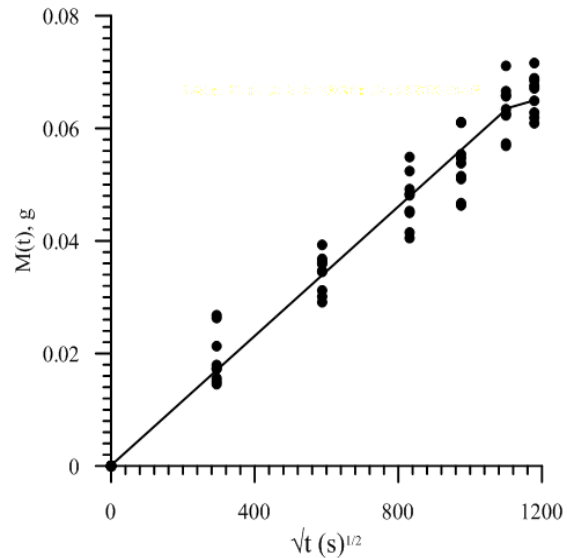


Fig. 2: Water absorption behavior of CFRE composites

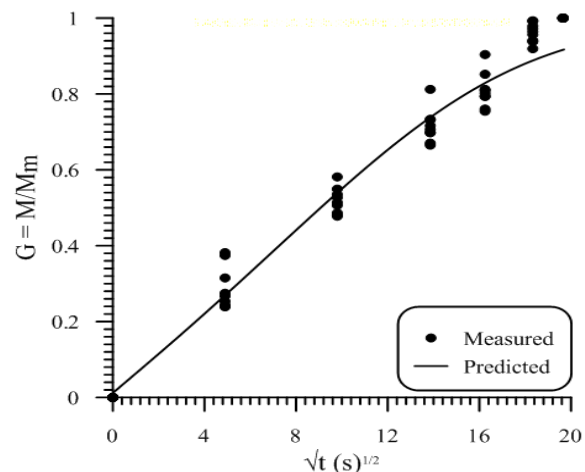


Fig. 3: Comparison of predicted and measured moisture absorption of CFRE composite

b) Low-velocity impact tests

Fig. 4 shows a typical force-time curve of the water-immersed CFRE composite plates at impact energy of 30J. First, the force increases almost linearly till about 600 micro-seconds. The sharp increase in the force is interpreted in terms of the composite's undamaged elastic behavior. Second, the elastic deformation is followed by sharp drop in the force due to damage initiation. The peak force observed in this elastic range defines the threshold force that initiates a change in the material stiffness it is also named delamination threshold[21]. Third, the sharp drop in the force is followed by a second nonlinear increase, which describes the damaged elastic behavior of the composite material. This occurs after redistribution of the load on the undamaged composite layers. Fourth, a peak force associated with non-linear plastic behavior was observed due to collapse of CFRE specimen. Finally, the force drops gradually to zero as the impactor rebounds off the composite plate.

The energy transferred from the impactor to the composite specimen of Fig. 4 is indicated in terms of displacement as shown in Fig. 5. It increases almost in a parabolic way till a maximum value corresponding to the kinetic energy of the impactor or the impact energy. Thus decreases as the impactor goes upwards. The impactor loses contact with the composite plate as the displacement decreases back to zero. The value of the energy at this time is absorbed energy by CFRE plate.

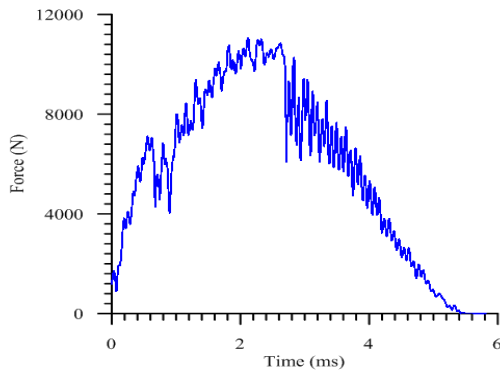


Fig. 4: Force-time variation ($E_i = 30J$)

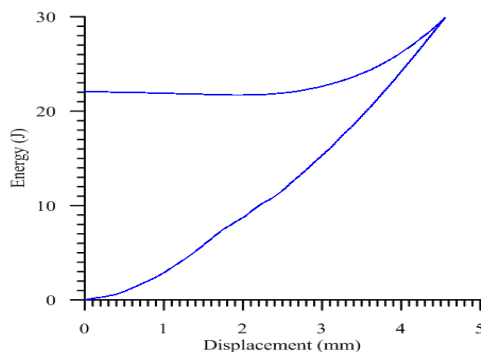


Fig. 5: Energy-displacement relationship ($E_i = 30J$)

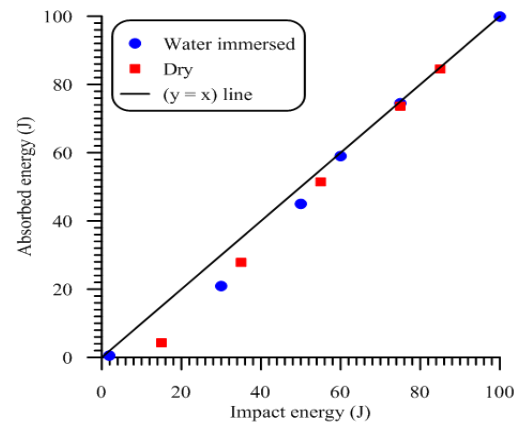


Fig. 6: Absorbed energy vs. impact energy

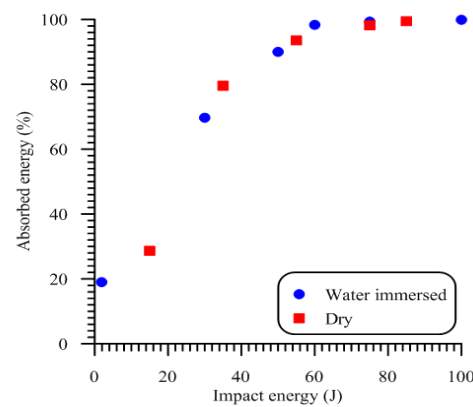


Fig. 7: Absorbed energy ratio vs. impact energy

Fig. 6 shows the absorbed energy for the water-immersed plates at different values of impact energy. At impact energies higher than 60J, the absorbed energy matches the equality line ($y=x$), which means that the composite plates absorb the total impact energy. On the other hand, at lower impact energies, the absorbed energy comes lies below the equality line ($y=x$), which means that the composite plates absorb, in this range, only a part of the impact energy. Fig. 7 shows the absorbed energy-to-impact energy ratio for water-immersed and dry plates. The absorbed energies of the saturated CFRE specimens with distilled water have insignificant differences compared with those corresponding to the dry samples, as shown in Figs. 6 and 7. Similar behavior was observed by Imielińska and Guillaumat [22]. They reported that the absorbed energy of woven aramid-glass fiber/epoxy composite was not affected with water immersion ageing.

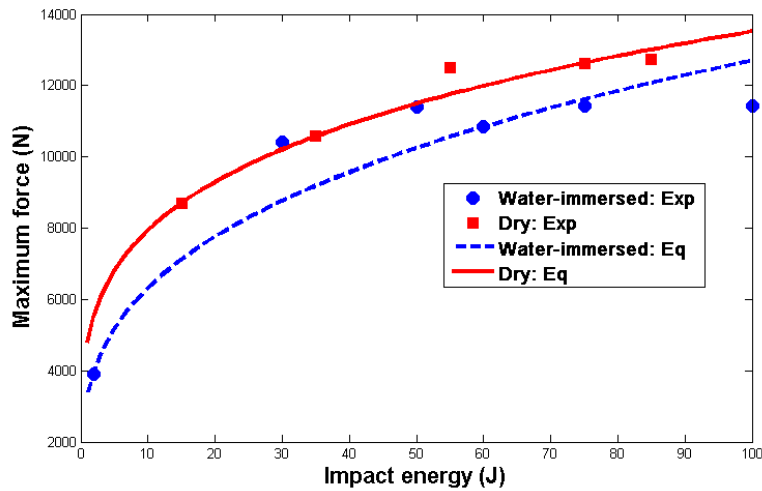


Fig. 8: Maximum force vs. impact energy



Fig. 9: Images of post-impact damage of moist CFRE specimens with 75J: (a) front side, and (b) back side

The maximum force was calculated for different impact energies of dry as well as moist CFRE specimens and the results are illustrated in Fig. 8. The results in this figure showed that the maximum forces of both dry and moist specimens were sharply increases at low impact energies. In this range no perforation of the plates is observed. The maximum force recorded with the water-saturated CFRE plates is comparable to the maximum force measured with the dry CFRE plates in the low impact energy range. Only cross-shaped surface cracks are noticed. On the opposite, the maximum force is almost constant at high impact energy (higher than 50 J). At these impact energies, the composite plates are completely perforated as shown in Fig. 9. In the front side, the impactor leaves a larger printed circular shape, Fig. 9a, on the CFRE specimens with a diameter that is directly proportional with the impact energy. The excessive delaminations on the back side accompanied with long cross-cracks have constructed a 3-D pyramidal shape as shown in Fig. 9b.

The four ends of the cross-crack of the back side were connected together to form the base of the

pyramids, while the specimen center represent its vertex.

The maximum forces recorded for the saturated CFRE specimens with distilled water are in the range of 15 to 20% lower than those corresponding to the dry ones. This can be explained by the fact that water absorption degrades the mechanical strength of composite materials in general [23-24] and more particularly CFRE composite materials [25]. Imielińska and Guillaumat [22] attributes this behavior to chemical degradation of resin matrix and fiber matrix interphase region. Water degradation will cause swelling and plasticization of the polyester matrix and debonding at the fiber/matrix interface that may reduce the impact force.

The maximum/peak force measured with the water-immersed or the dry composite plates can be interpolated using the following equation [7, 26-27]:

$$P_{Peak} = -\frac{c}{2} \left(\frac{2E_i}{m} \right)^{\frac{n}{2}} + \sqrt{2K_0 E_i + 2^{n-2} c^2 \left(\frac{E_i}{m} \right)^n} \quad (10)$$

where P_{peak} , K_0 , c and n are the maximum force, global plate stiffness, the damping coefficient and a constant to include non-linear effects. The constants obtained by curve fitting and root mean squared error (RMSE) are reported in Table 3.

Table 3: Constants of Eq. (10)

Constants	Water-immersed CFRE	Dry CFRE
K_0 (N/m)	0.2049	0.141
c (N/(m/s) ⁿ)	4866.9	6493.1
n	0.3803	0.294
RMSE error (%)	6.4	1.7

IV. CONCLUSIONS

In this work, the effect of water absorption on the low-velocity impact behavior of CFRE composite plates was investigated. To this aim, falling weight testing machine was used to impact water-saturated CFRE plates at different values of impact energies. Several conclusions can be drawn:

- For impact energies higher than 60J, 100% of the impact energy is absorbed by the CFRE plate and a perforation is observed.
- The maximum force increases rapidly at low impact energies and tends to an asymptotic/constant value at high impact energies.
- The absorbed energies of the saturated CFRE specimens with distilled water have insignificant differences compared with those corresponding to the dry samples
- The maximum force recorded with the water-saturated CFRE plates is comparable to the maximum force measured with the dry CFRE plates in the low impact energy range.
- The maximum force recorded with the water-saturated plates is 15 to 20% lower than the maximum force measured with the dry plates in the high impact energy range. This is explained in terms of the chemical degradation of resin matrix and fiber matrix interphase region owing to water absorption.

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