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Influence of Alkaline Solution Aging on Mechanical Properties of Natural Particle Reinforced Polymer Blend

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ABSTRACT

This paper aims at studying the degradation mechanism of the epoxy/unsaturated polyester (EP/UP) hybrid composites in alkaline aging. The secondary parameters are natural waste fillers that are employed to measure the resistance to alkaline attack. The weight percentages of date seed, olive seed and pistachio shell powder were added to the polymer blend in 0, 6, 8, 10 and 12 percentages to observe the influence of the additives on the initial mechanical performance and durability under alkaline conditions. Impact strength, hardness, compressive strength and flexural strength of the composites were also tested with an accelerated aging period in a solution of 10 weight percent of NaOH under different periods. Before aging, the filler addition to all mechanical properties; impact, compressive, and flexural strengths were at the highest point of 8 weight percent filler content whereas hardness rose to 12 weight percent. The degradation of all composites was gradual after being subjected to alkaline conditions, which was regulated by filler–matrix interfacial debonding, matrix softness and diffusion of solution into the polymer. Although flexural strength and hardness degraded at a slower rate, impact strength was the most sensitive to alkaline attack, with compressive strength being the next. The systems of interest exhibited greatest resistance to degradation by alkalis through pistachio shell-reinforced composites. The findings indicate the possibility of waste-based fillers in the preparation of cost-effective and durable polymer fillers in alkaline environments and verify that alkaline aging is the key factor that affects the long-term behavior.

1. INTRODUCTION

Polymer composites have become increasingly popular due to their low density and high-quality mechanical properties, making them ideal substitutes for conventional metals in various engineering applications [1, 2]. Their corrosion resistance and design flexibility are particularly beneficial in maritime and automotive sectors, where they confront harsh conditions. Unlike metals, polymer composites resist corrosion from moisture, saltwater, and chemicals, leading to their use in boats, offshore pipelines, and storage tanks [3, 4]. Additionally, they help the automobile industry create lightweight vehicles, thereby reducing fuel consumption and greenhouse gas emissions while providing improved design flexibility and noise reduction [5, 6]. Polymer blending offers a cost-effective method to enhance composite properties without complex chemical processes, achieving desirable traits like rigidity and toughness [7].

Researchers are increasingly exploring the combination of epoxy resin (EP) and unsaturated polyester resin (UPS) due to their complementary properties [1, 7]. EP, known for their strength and chemical resistance, are often brittle and costly, whereas unsaturated polyesters are more flexible and affordable but lack mechanical strength. A hybrid blend can enhance toughness and stress distribution, making it suitable for marine and automotive applications [8, 9]. Additionally, there is a growing interest in recycling agricultural waste materials like date seeds and pistachio shells as fillers in polymer composites [10, 11]. This sustainable method reduces costs and improves environmental properties. However, the performance of these composites in alkaline environments, common in various applications, necessitates further research, as alkaline exposure can degrade mechanical properties. While moisture absorption and thermal aging studies exist, comprehensive investigations into alkaline aging effects on agricultural waste-reinforced composites remain limited [12-15].

Epoxy/unsaturated polyester hybrid composites containing natural fillers obtained from waste materials, date seeds, olive seeds, and pistachio shells will be examined for their mechanical and alkaline-aged properties. The impact strength, hardness, compressive strength, and flexural strength of the samples before and after treatment with NaOH solution were calculated for different combinations of fillers and filler

content.

Most of the past studies have primarily focused on the initial mechanical performance, moisture absorption or thermal aging of hybrid polymer composite reinforced with natural fillers although the usage of these materials is becoming of growing interest. The fundamental degradation processes in alkaline conditions are not clearly comprehended. In real-world applications, polymer composites tend to be subjected to alkaline media (concrete, cleaning agents, and alkaline soils) in numerous applications, marine, infrastructure, and automotive components. Under such conditions, alkaline solutions can creep into the polymer matrix causing plasticization of the matrix, a weakening of the filler-matrix interface, the development of microcracks, and gradual deterioration in the performance of the mechanism. To ensure long-term wear and tear and reliable operation, it is important to have a detailed study that explains the mechanism of alkaline aging and how it interacts with the microstructure of the composite.

Thus, explaining the alkaline aging degradation mechanism of epoxy unsaturated polyester hybrid composites; polymer blending and use of natural waste filler are the second parameters and are deemed secondary in revealing the extent of their influence on the resistance to alkaline attack. The strategy bridges a major gap in the literature and provides valuable information regarding the development of sustainable polymer composites that are durable enough and can be used in various automotive and marine environments.

2. MATERIALS AND METHODS

2.1 Materials

The study explores the use of date seeds (DS), pistachio shells (PS), and olive seeds (OS) as fillers made from waste materials. Fresh seeds were chemically treated with 50% sulfuric acid for 5 hours, washed with distilled water, air-dried for 24 hours, and then oven-dried at 70°C for 8 hours to remove moisture. The dried materials were milled and sieved to achieve a particle size of 75 µm [16, 17]. The characteristics of the fillers are presented in Tables 1-3. Additionally, Quickmast 105 EP was utilized, noted for its structural suitability and favorable mechanical properties. An UPS, hardened with methyl ethyl ketone peroxide, was also included in the study. Tables 4 and 5 show the properties of epoxy and unsaturated polyester.

Table 1. Chemical composition of date palm seeds

Materials	Date Seeds
Carbohydrate	2.4-4.7
Moisture	8.6-12.5
Dietary fiber	67.6-74.2
Protein	4.8-6.9
Fat	5.7-8.8
Ash	0.8-1.1

2.2 Experimental work

2.2.1 Preparation of composite materials

The composite samples were prepared by hand. To prepare the polymer blend, EP and UPS were first combined. The two resins were combined in an 80/20 (EP/UPs) volume ratio and stirred with a magnetic stirrer to ensure that both were thoroughly mixed and to prevent the formation of air pores.

Table 2. Chemical composition and physical properties of PS powder

Parameters	Value
Cellulose (%)	42
Moisture content (%)	4.92
Density (g/cm^3)	1.4
Ash content (%)	0.8
Lignin (%)	13.5

Table 3. Chemical composition and physical properties of the OS powder

Parameters	Value
Cellulose (%)	26.9
Hemicellulose (%)	34.8
Soluble (%)	5.4
Ash content (%)	0.8
Lignin (%)	32.1

Table 4. The typical characteristics of epoxy according to the product company

Parameters	Value
Application temp.	5°C to 30°C
Compressive strength (C.S)	35MPa approx.
Density	Approx. 1.1 kg/liter
Flexural strength (F.S)	14MPa approx.
Service temp.	< 70°C
Shrinkage	Negligible

Table 5. The properties of UPS according to the product company

Parameters	Value
Fracture toughness (MPa)	1 - 3 at [25°C]
Thermal conductivity (W/m. K)	< 2.6
Density (g/cm^3)	0.6

After reaching a homogenous polymer blend, filler particles (pistachio shell powder, date seed powder, and olive seed powder) were gradually added at 6, 8, 10, and 12 percent of the polymer blend mass. The fillers were gradually added, and the mixing process was carried out for a further 20 min to ensure that the particles were well dispersed and not fused to each other.

The fillers were blended thoroughly, after which the hardeners of the epoxy and polyester resins were added in quantities recommended by the manufacturers as the most appropriate. The mixture was then gently stirred to ensure that no bubbles were formed and poured immediately into silicone rubber moulds that were then prepared to the ASTM standard size required for each mechanical test.

The moulds were then left to dry at room temperature for 24 h. The specimens were allowed to cure and then carefully removed from their moulds and subjected to post-curing at 50°C for 2 h to enhance the structure of the polymer network. All samples were stored at room temperature prior to aging and testing.

2.2.2 Aging in basic solution

This aging procedure was designed not only to estimate the amount of property loss, but also to simulate the alkaline degradation process, which involves solution diffusion into the

polymer, a reduction in the interface, and a degradation of the microstructure.

A 10 wt% solution of sodium hydroxide (NaOH) was used as an aging agent to determine how the composites would decompose in an alkaline environment. To prepare the solution, the required number of NaOH pellets was dissolved in distilled water and mixed continuously until all pellets were dissolved. The solution was allowed to cool to room temperature.

The test samples were placed in chemically resistant containers and fully immersed in a NaOH solution. The samples remained suspended in air and did not touch the container walls to ensure that there was no localized effect of the chemicals. One, two, four, and six weeks of aging were performed at room temperature in the laboratory (approximately 25°C) under both short-term and long-term alkaline conditions.

The samples were removed from the solution at the end of every aging period and washed several times with distilled water to eliminate any remaining NaOH. The rinsing was continued until the final rinse water attained a neutral pH. The samples were then dried using lint-free laboratory tissue and allowed to air dry at room temperature (24 h). To ensure that no traces of absorbed moisture remained, they were placed in an oven at 50°C over a period of 2 h, as was common to all samples.

The final mass and size of the aged samples were measured when the samples were dry, and the preparation for mechanical testing was completed. The aging technique allowed us to observe the effect of alkaline degradation on the physical and mechanical behavior of the EP/UP hybrid composites reinforced with natural particulate fillers. The codes and compositions of the samples are listed in Table 6.

Table 6. Mix ratios for the production of composite materials

Samples	Composition
X	80%EP + 20% UPS
C1	74%EP + 20% UPS + 6% DS
C2	72%EP + 20% UPS + 8% DS
C3	70%EP + 20% UPS + 10% DS
C4	68%EP + 20% UPS +12% DS
B1	74%EP + 20% UPS + 6% OS
B2	72%EP + 20% UPS +8% OS
B3	70%EP + 20% UPS+10% OS
B4	68%EP + 20% UPS+12% OS
M1	74%EP + 20% UPS+6% PS
M2	72%EP + 20% UPS+8% PS
M3	70%EP + 20% UPS+10% PS
M4	68%EP + 20% UPS+12% PS

3. TEST

The mechanical tests involved three specimens (n = 3) for each composition/percentage, with the results reported as the mean ± standard deviation (SD).

3.1 Impact test

The HSM41 Pendulum Impact Tester, a German-made pendulum impact testing machine, was used to calculate the Charpy impact test on unnotched specimens, the test was conducted in compliance with ISO-179 [18]. The sample dimensions were 55 mm × 10 mm × 5 mm, as shown in Figure 1. The specimen was fixed at both ends, and the hammer was lifted to its maximum potential energy. Upon release, the hammer strikes the specimen, converting the potential energy into kinetic energy. The instrument measures the energy required to fracture the specimen. For each composition/condition, three specimens (n = 3) were tested, and the reported values represent the mean ± SD. All tests were performed at room temperature (25°C). The impact strength indicates the energy absorbed by a material during fracture and is calculated by dividing the fracture energy by the cross-sectional area of the specimen.

$$I.S = Uc / A \quad (1)$$

where, Uc, A, and $I.S$ are the fracture energy (joule), cross-sectional area (mm), and impact strength (kJ/m^2), respectively.

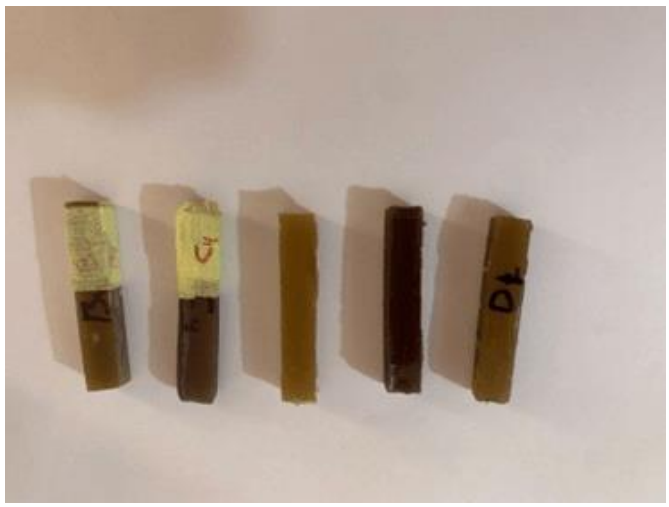


Figure 1. Impact strength specimens

3.2 Hardness test

A Shore D hardness tester (Qualitest HPE) was used at room temperature to determine the relative hardness of the composite samples. This was performed in accordance with ASTM D2240 [19]. The Shore D instrument consists of a needle with a 30° conical point and 1.4 mm diameter, which measures the depth of penetration into polymeric materials on a scale from 0 to 100.

Figure 2. Hardness standard specimens

For each specimen, the device was placed vertically on the surface to allow the needle to penetrate the material. The reading was taken after a dwell time of 3 s. Five measurements were taken at different locations on each specimen, and the mean ± SD was reported. Three specimens (n = 3) were tested for each composition/condition. Figure 2 illustrates the standard sizes of the samples subjected to the hardness test.

3.3 Flexural strength test

Flexural tests were performed using an Instron Universal Machine (Tinius Olsen UK, model HKT 50KN) at the Materials Engineering Department of the University of Technology. Rectangular specimens with dimensions of 100 × 10 × 5 mm³ were tested according to ASTM D790 [20]. Figure 3 shows the standardized sizes of the test samples. The samples were placed on two supporting pins with a span of 80 mm, and the third loading pin was lowered at a constant speed of 2 mm/min until failure. For each composition/condition, three specimens (n = 3) were tested, and the reported values represent the mean ± SD. All tests were conducted at room temperature (25°C). Using Eq. (2), the value of the flexural strength was determined using the maximum load that caused failure

$$F.S = 3PL/2bd^2 \quad (2)$$

F.S. stands for flexural strength (MPa), *P* for load (N), *L* for distance between 2 cushions (mm), *d* for sample thickness (mm), and *b* for sample width (mm).

Figure 3. Flexural strength standard specimens

3.4 Compressive strength test

Compressive tests were performed on specimens according to the ASTM D695-15 [21] at room temperature using a universal testing machine (Tinius Olsen RH15DZ). The tests were conducted at a crosshead speed of 1 mm/min. For each composition/condition, three specimens (n = 3) were tested, and the reported values represent the mean ± SD. Figure 4 shows the standard sizes of the compression specimens. Using Eq. (3), the maximum compressive load applied to the specimen was used to determine the compressive strength.

$$\sigma = \frac{P}{A} \quad (3)$$

where, P = applied load (N), A = cross section area (m^2).

Figure 4. Compressive strength standard specimens

4. RESULT AND DISCUSSION

4.1 Mechanical test

The mechanical properties of the polymer composites filled with waste resources were evaluated using impact, hardness, compression, and bending tests. It is evident that the use of pistachio shells, olive seeds, and date seeds significantly affects the mechanical properties of the composite, which depends on the type of waste material as well as the amount of fillers.

4.1.1 Impact strength

Figure 5 shows the behavior of the polymer composites filled with natural waste fillers after being struck. The findings are quite clear that the incorporation of the powders of pistachio shell, olive seed, and date seed in the polymer blend renders it highly resistant to impacts compared to the unfilled matrix. This improvement is made possible by the fact that lignocellulosic fillers can absorb and distribute impact energy through various energy-dissipation mechanisms. In the case of impact loading, the rigid particles in the polymer matrix cause cracks to bend, pin, and branch out, and they slow down crack propagation and become more difficult to fracture [22, 23].

In the case of a filler that is not too abundant, it is evenly distributed in the polymer matrix. This allows the redistribution of stress in the case of a dynamic load. This increases the strength of the impact because some of the energy utilized is absorbed during interface debonding, particle exfoliation, and the localized plastic deformation of the surrounding polymer. Other analogous methods of strengthening things have been discovered in natural particle-reinforced polymer composites, in which the correct concentration of filler causes them to be harder and more resistant to impact [22].

However, the higher the filler content, the lower the impact strength. The primary causes of this decrease include filler agglomeration and insufficient particle wetting by the polymer matrix, which increases the difficulty of impact energy absorption of the composite. In high-strain-rate loading, agglomerated particles are regarded as stress concentration points, and cracks begin more easily and spread faster [22]. The optimal impact strength was attained at 8 wt. % of the filler with 6.5 ± 0.155 kJ/m² in pistachio shell composites

(M2), 5.7 ± 0.150 kJ/m² in date seed composites (C2), and 5.3 ± 0.152 kJ/m² in olive seed composites (B2). This indicates that there is an optimal filler loading that balances toughness and structural integrity.

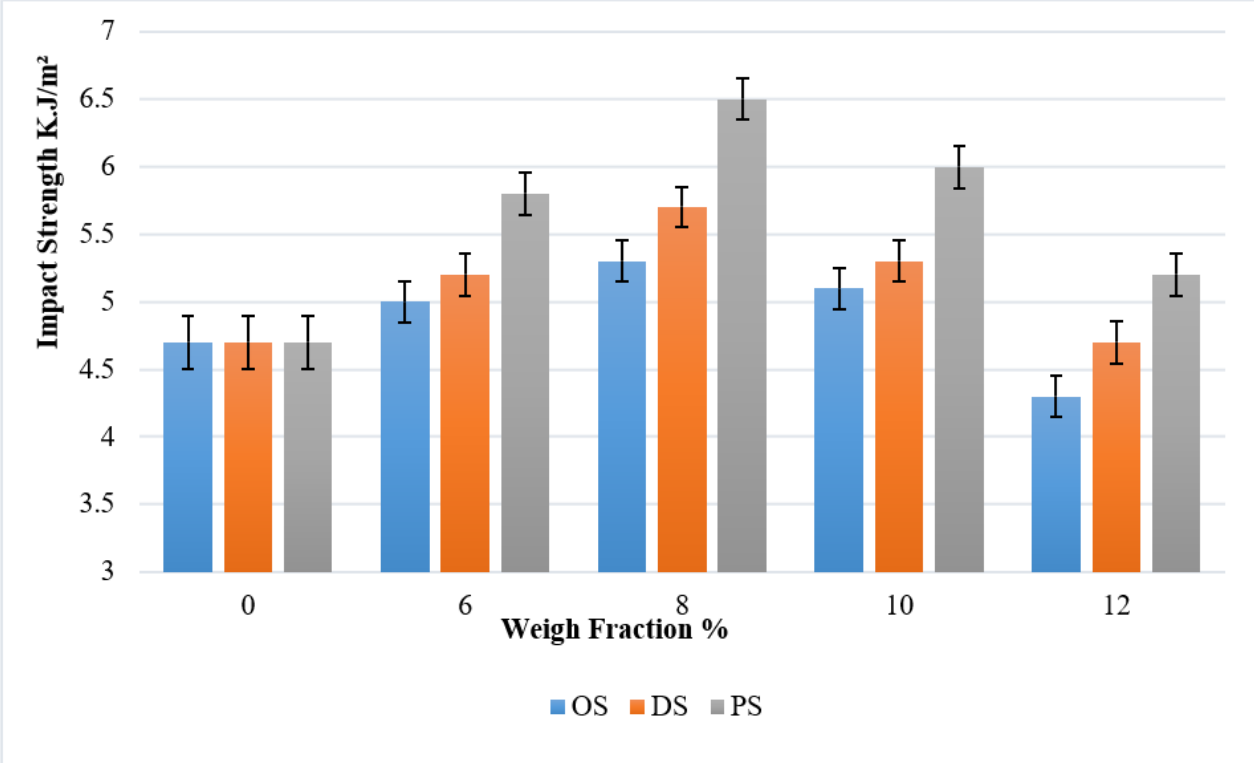


Figure 5. Result of impact strength (I.S)

4.1.2 Hardness test

The results for the hardness of Shore D are shown in Figure 6. They demonstrated that all the composite systems became harder with an increase in the filler content compared to the neat polymer blend. The optimal hardness at maximum filler loading was 12 wt. % with 87 ± 1.54 in pistachio shell composite (M4), 81 ± 2 in date seed composite (C4), and 85 ± 2 in olive seed composite (B4). This behavior is facilitated by the inflexible structure of lignocellulosic fillers.

This causes the polymer chains to move more slowly and causes localized surface deformation to occur more slowly.

The introduction of waste particles into the compound seals the micropores that develop during the process of manual molding, resulting in a more compact composite structure that is more effective for packing. This enhanced contact between the filler, and the matrix renders the material resistant to indentation, as the polymer chains do not rearrange and flow once a load is applied to them [24, 25]. Filler agglomeration has less impact on hardness than on impact and strength properties, owing to the fact that hardness largely depends on the surface resistance rather than the efficiency of load transfer in bulk. Therefore, although the other mechanical properties deteriorate, the hardness continues to increase despite the increased amount of filler.

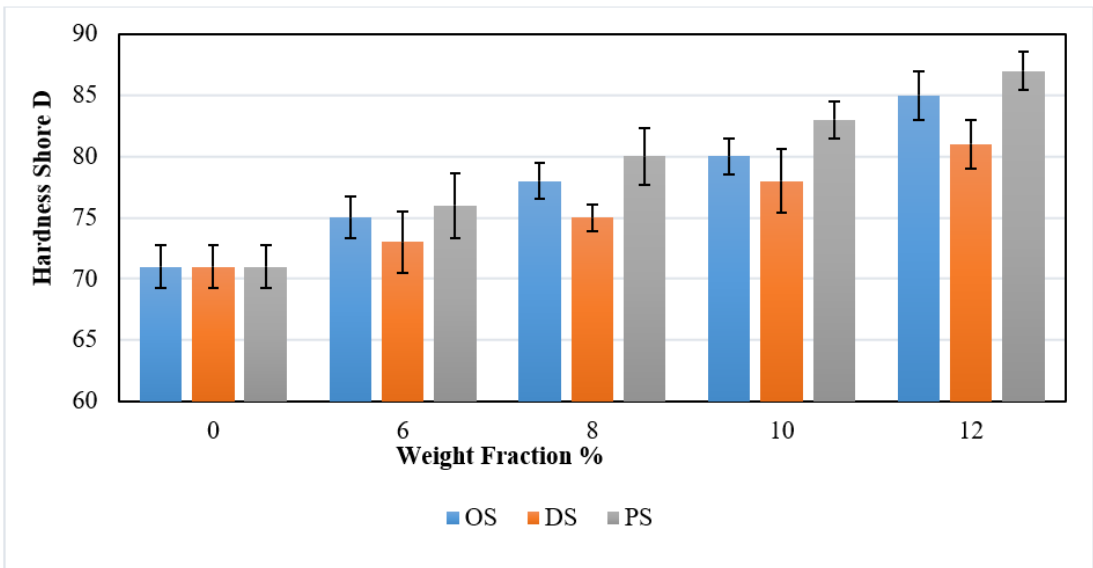


Figure 6. Hardness results

4.1.3 Compressive strength

The compressive strength depended on the weight fraction of the filler, as shown in Figure 7. The findings indicated that the compressive strength increased significantly with an increase in the filler content up to a maximum of 8 wt. %, and after that, it decreases with the increase in filler content. The highest values of compressive strength were observed for the 8 wt. % filler content: 92 ± 2 MPa for pistachio shell composites (M2), 84 ± 2.51 MPa for date seed composites (C2), and 88 ± 3 MPa for olive seed composites (B2).

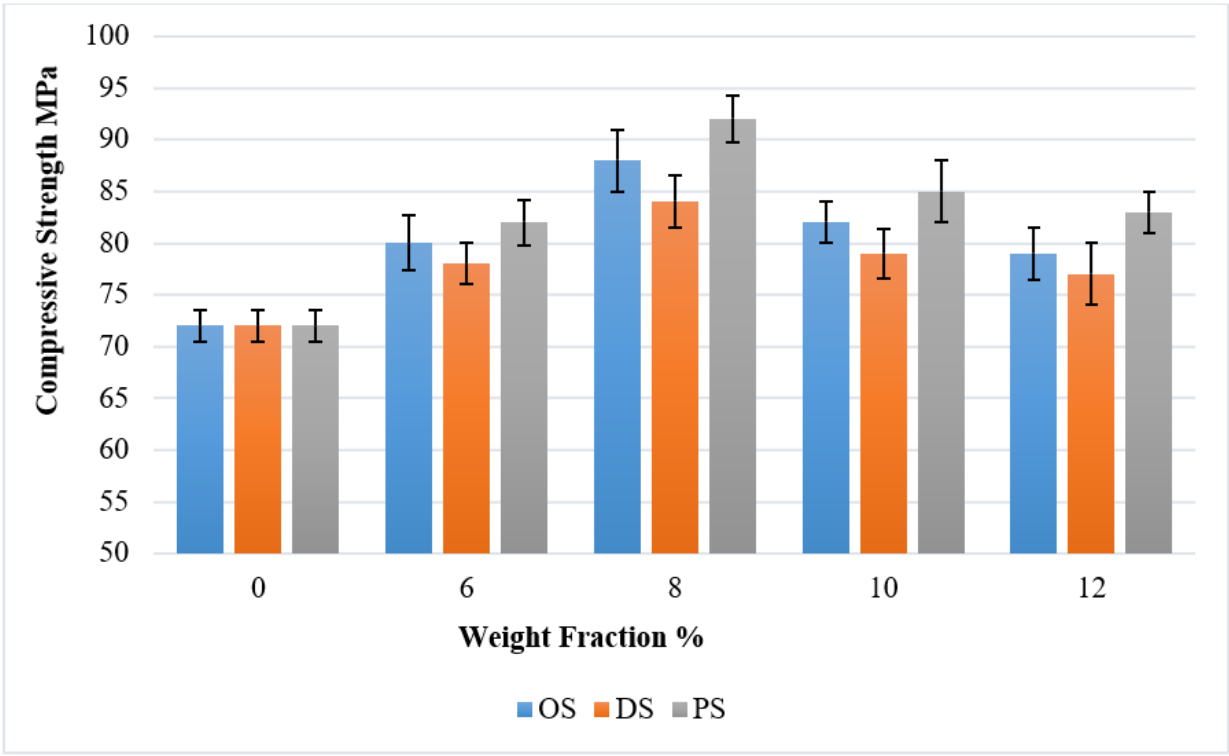


Figure 7. Compressive strength results

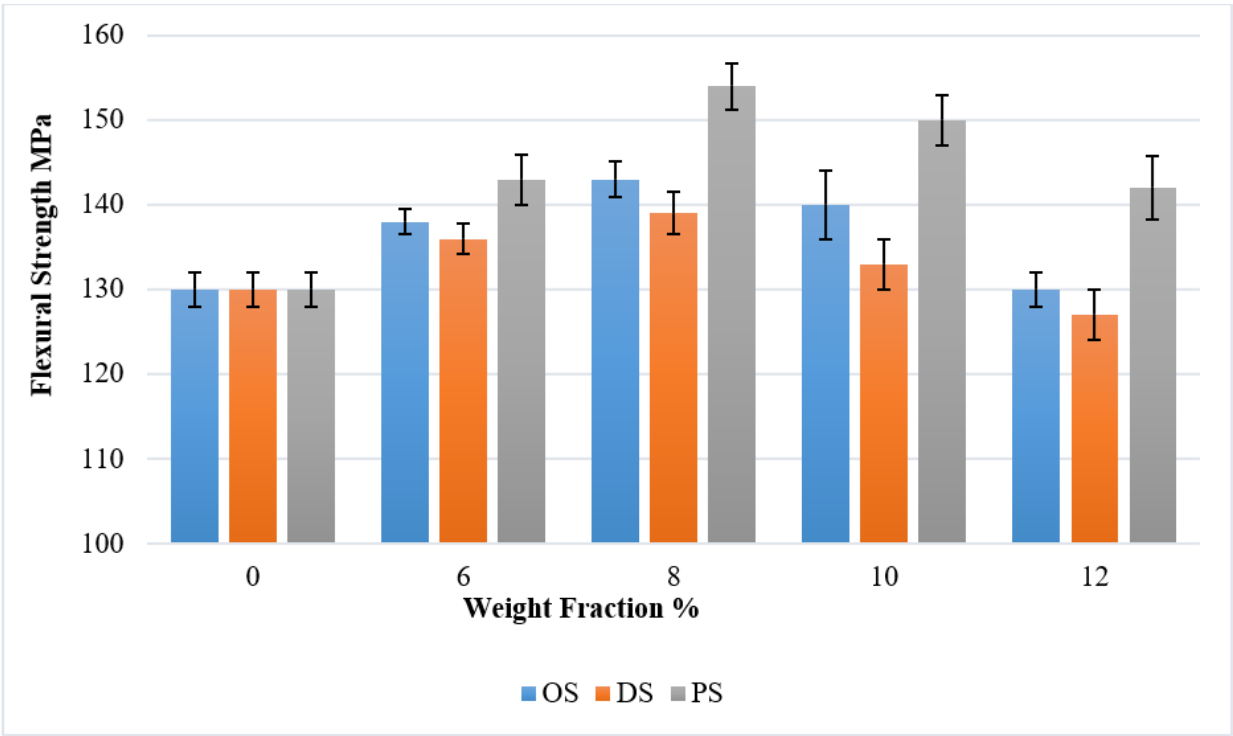


Figure 8. Result of flexural strength (F.S)

This is because the compressive strength of the fillers increases with moderate filler content as the lignocellulosic structure of the fillers is rigid; thus, the polymer matrix becomes stronger, and the chances of the fillers under compressive stress decreasing shape are minimal. The fairly small particle size and even dispersion of the filler enhance the transfer of stress across the filler-matrix interface to provide a more effective load distribution throughout the composite

[26].

As the filler content increased, the compressive strength decreased because the filler was concentrated, the number of voids increased, and the matrix was not held together. These microstructural defects are the source of areas of stress concentration; thus, objects break too soon when they are subjected to compressive stress. Moreover, the compressive stresses of the matrix cannot be transmitted to the fillers as well as they would be when the number of fillers is low, since the adhesion between the fillers and the matrix is not strong enough, as has been demonstrated in other natural filler reinforced polymer systems [27].

4.1.4 Flexural strength

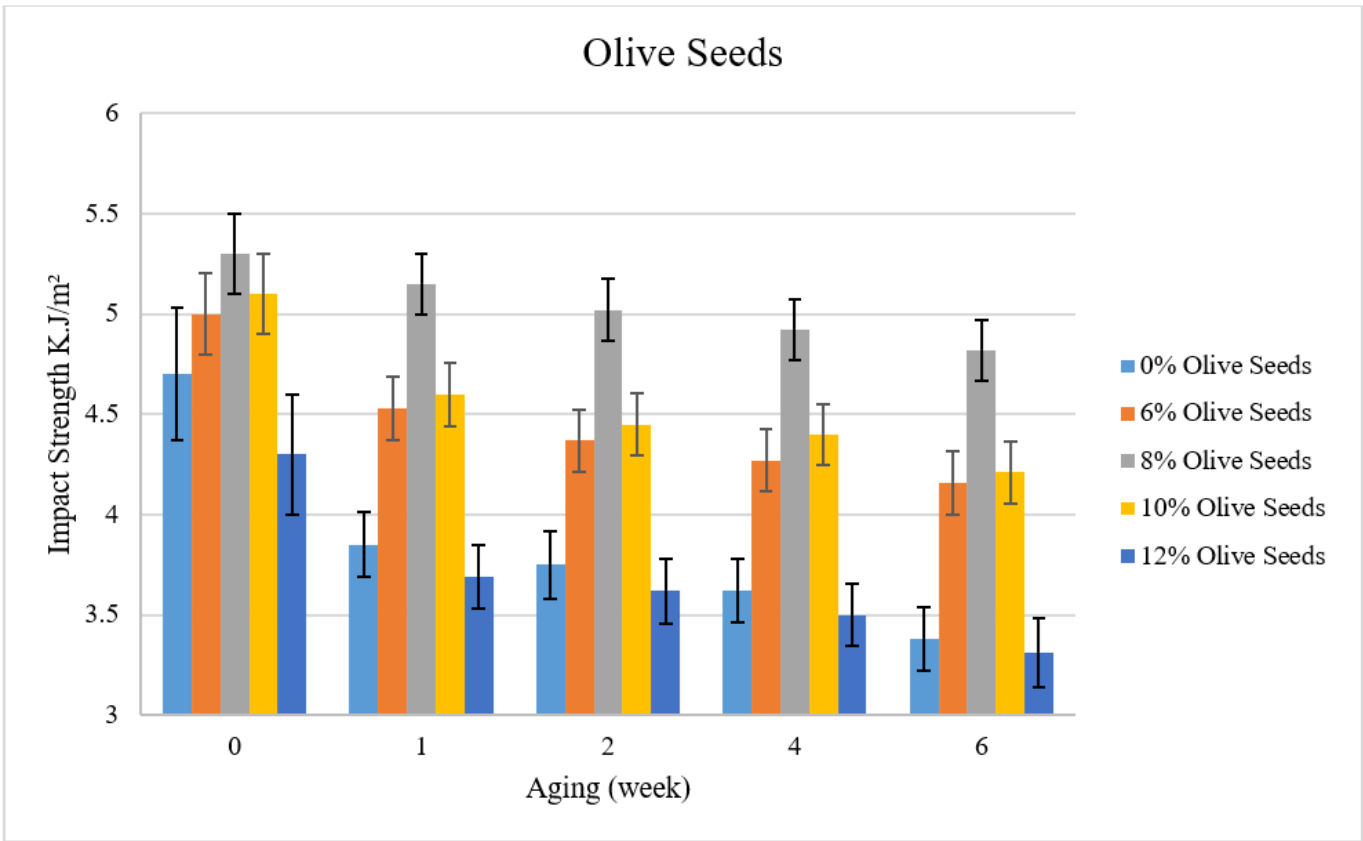
The flexural strength results in Figure 8 exhibit a pattern similar to that of compressive strength. The flexural strength increased with increasing filler content until a certain point, after which it decreased. The maximum flexural strength values were obtained at the highest filler content: 154 ± 3 MPa for pistachio shell composites (M2), 139 ± 3 MPa for date seed composites (C2), and 143 ± 2.8 MPa for olive seed composites (B2).

This is because the flexural strength increases at moderate levels of filler as the mechanical interlocking and bonding between the filler particles and the polymer matrix are enhanced. The effective stress transfer across the interface during the bending loads decelerated the onset of cracks and increased the tensile stresses on the outer surface of the specimen [28].

Increasing the filler content (10 and 12 wt.), on the other hand, reduces the flexibility of the material as the fillers stick together and form voids that render the material less homogeneous and flexible. Such imperfections cause the cracks to begin earlier and cause the composite to have less capacity to deal with the bending loads, as expected previously for polymer composites containing particles [29].

4.2 After aging behaviors

Alkaline aging involves a gradual degradation process that is dependent on solution diffusion, matrix plasticization, interfacial debonding, and microcrack development. These two processes act cumulatively to control the type of filler as well as the loss of mechanical properties. The duration of the composites was determined by placing them in a NaOH solution and observing the change in their mechanical characteristics after a given period of time. Impact resistance is the mechanical property that decays most rapidly, as demonstrated by the impact strength results after aging, as shown in Figure 9. The overall effect of alkaline aging on particulate-reinforced polymer composites is to affect the filler–matrix interface, which governs the energy-absorbing mechanisms. This is affirmed by the rapid decrease in the strength of the impact. Alkaline penetration of the interfacial regions leads to interfacial debonding, micro crack initiation, and weakening of stress transfer pathways. A decrease in impact strength is observable with even a small alkaline attack because impact resistance is very sensitive to interfacial integrity and crack-bridging mechanisms. Therefore, the main controlling mechanism in alkaline aging is interfacial degradation, which is reflected in the excessive decrease in the impact resistance. The effect of aging on the strength of the impact also decreased faster during the initial aging period and more gradually as the aging period increased. This increased sensitivity can be attributed to the fact that interfacial integrity and energy absorption mechanisms play a significant role in the impact behaviour, and the process of alkaline attack has a significant impact on them.



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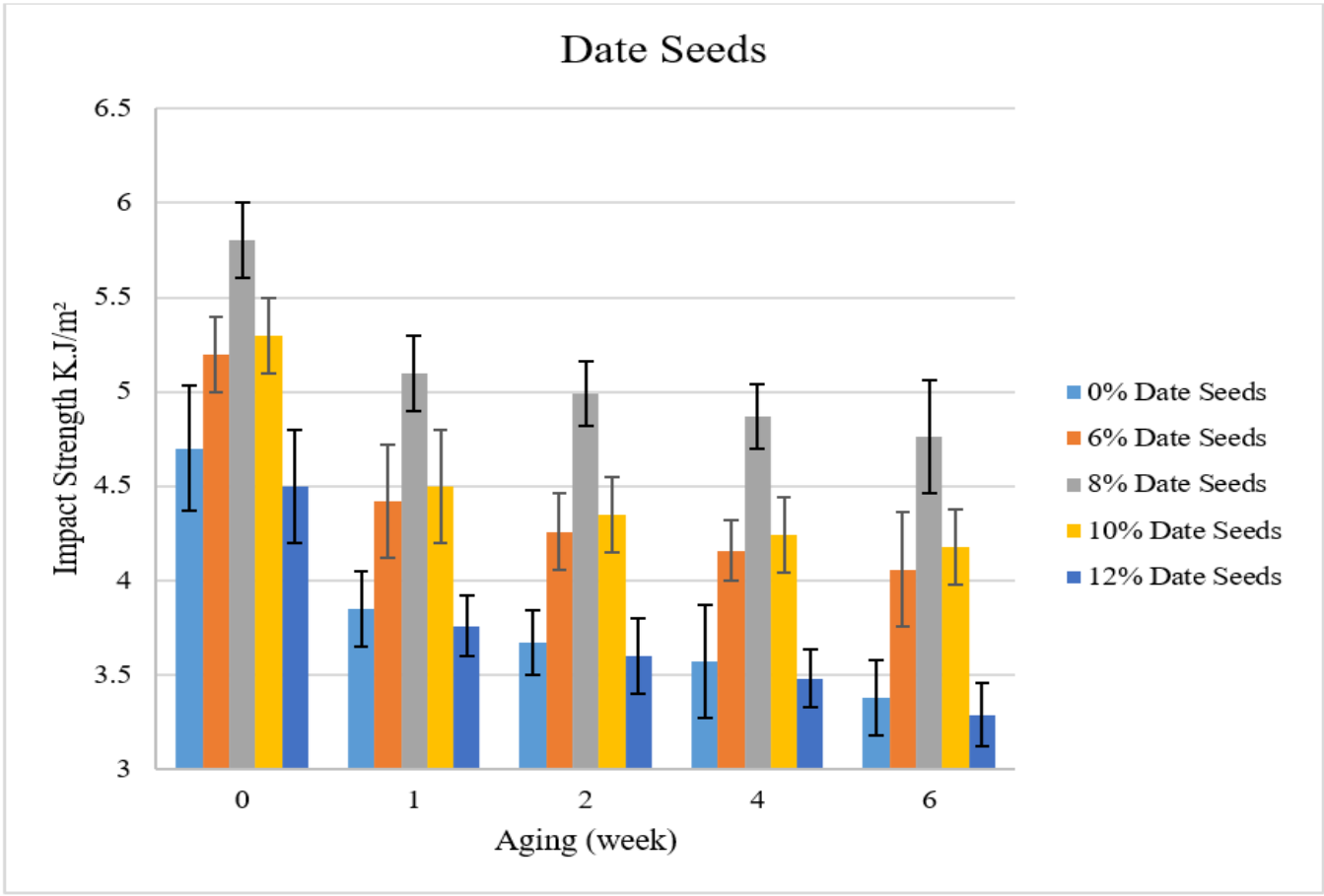

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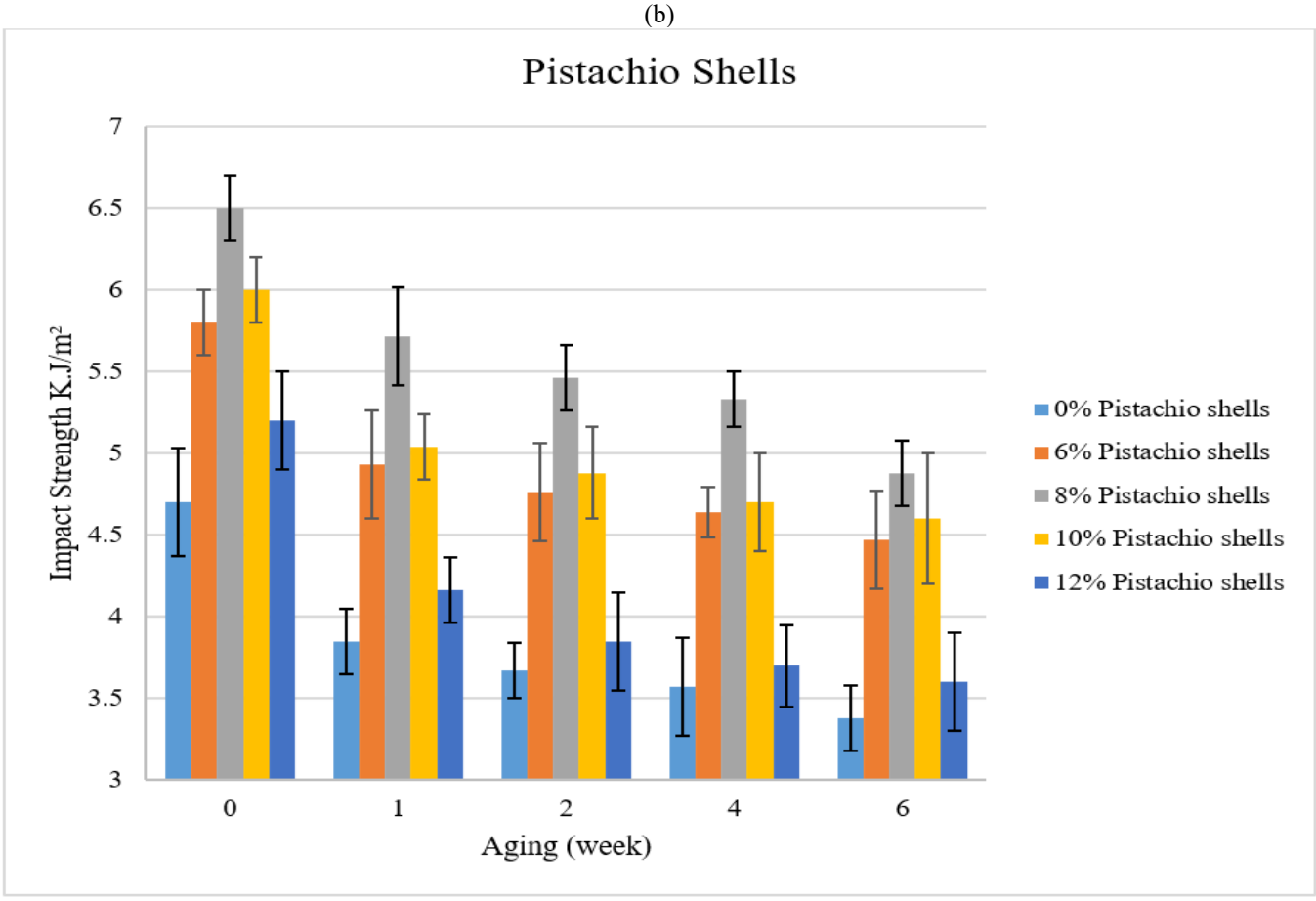

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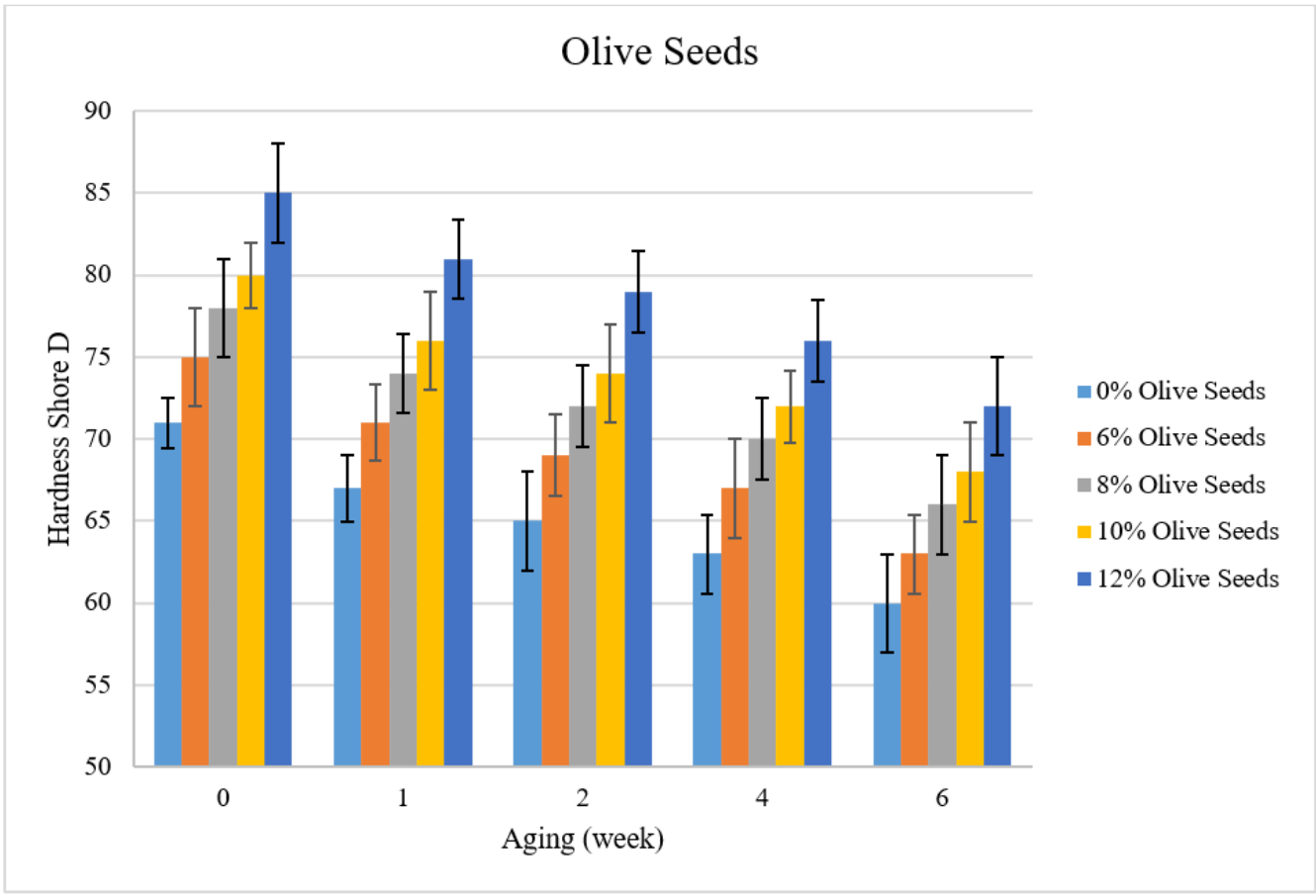
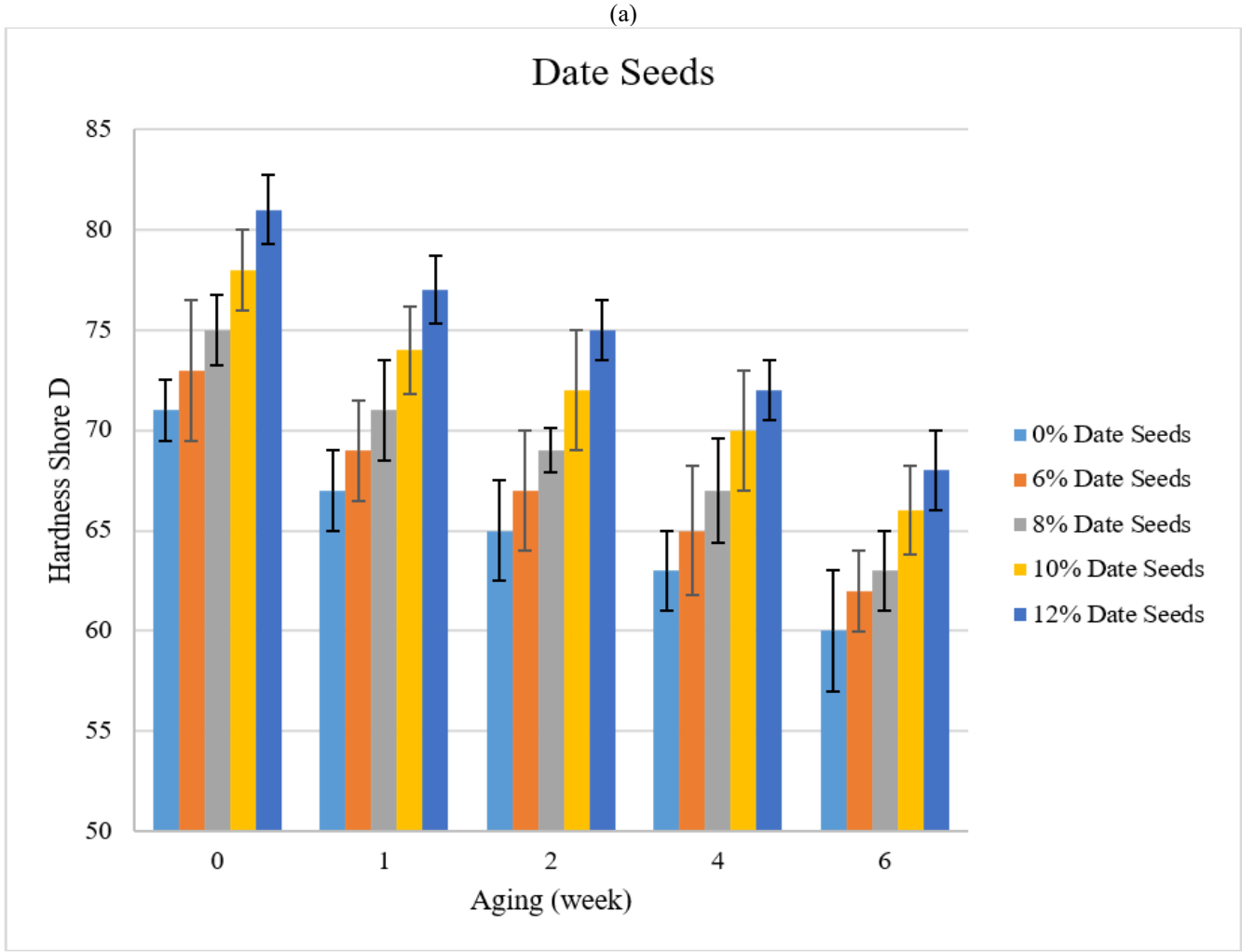
Figure 9. Impact strength graphs, (a) Olive seeds, (b) Date seeds, (c) Pistachio shell-reinforced composites aged in NaOH solution


Olive Seeds
Hardness Shore D
90
85
80
75
70
65
60
55
50
0
1
2
4
6
Aging (week)
0% Olive Seeds
6% Olive Seeds
8% Olive Seeds
10% Olive Seeds
12% Olive Seeds

(a)


Date Seeds
Hardness Shore D
85
80
75
70
65
60
55
50
0
1
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10% Date Seeds
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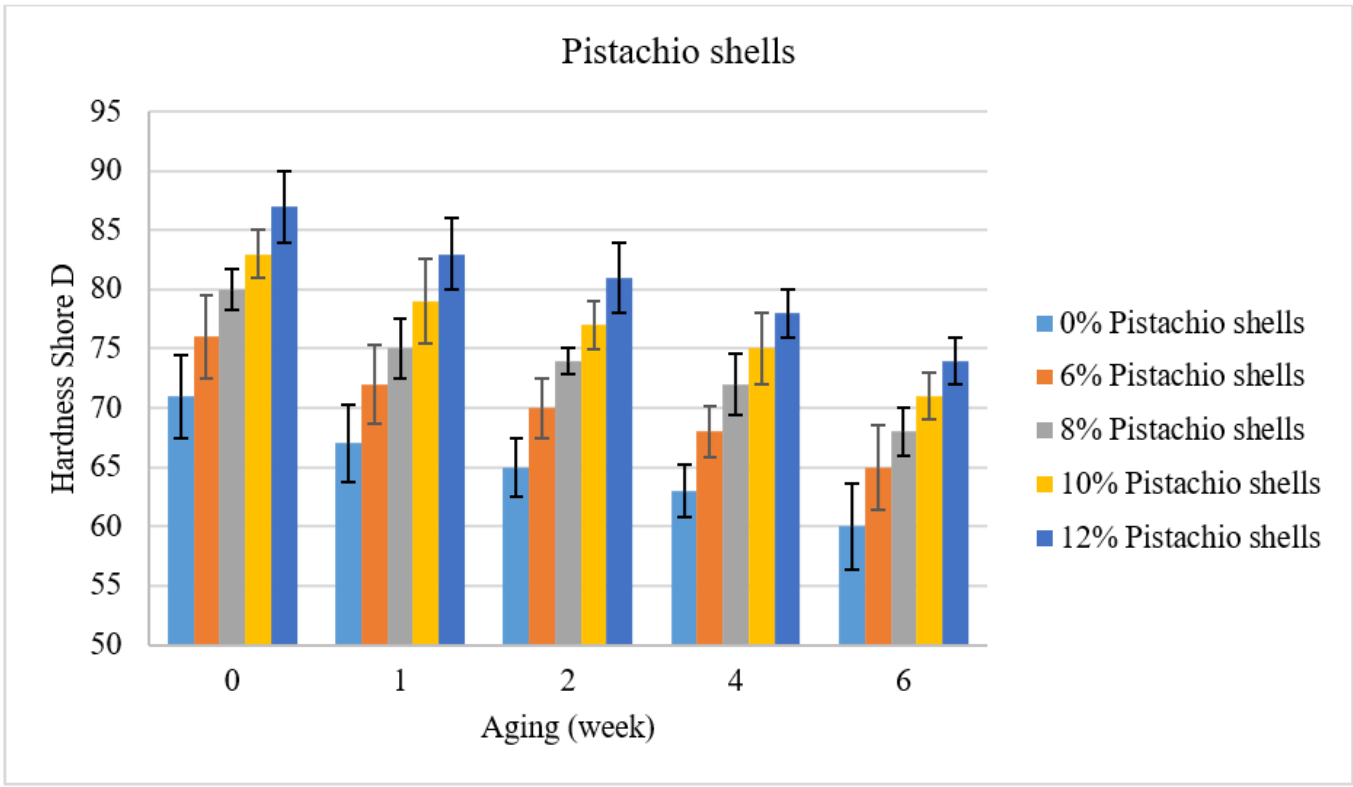
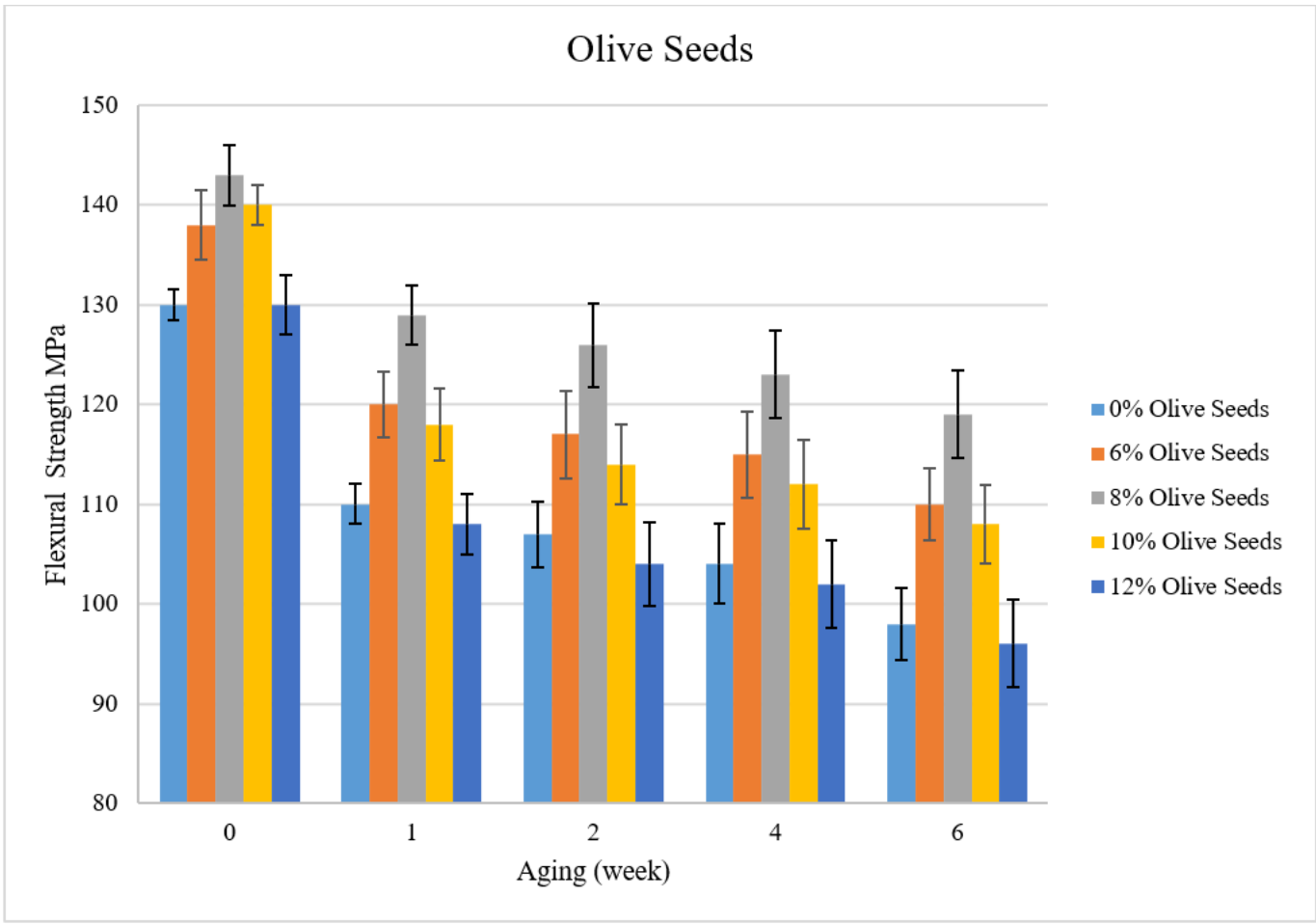
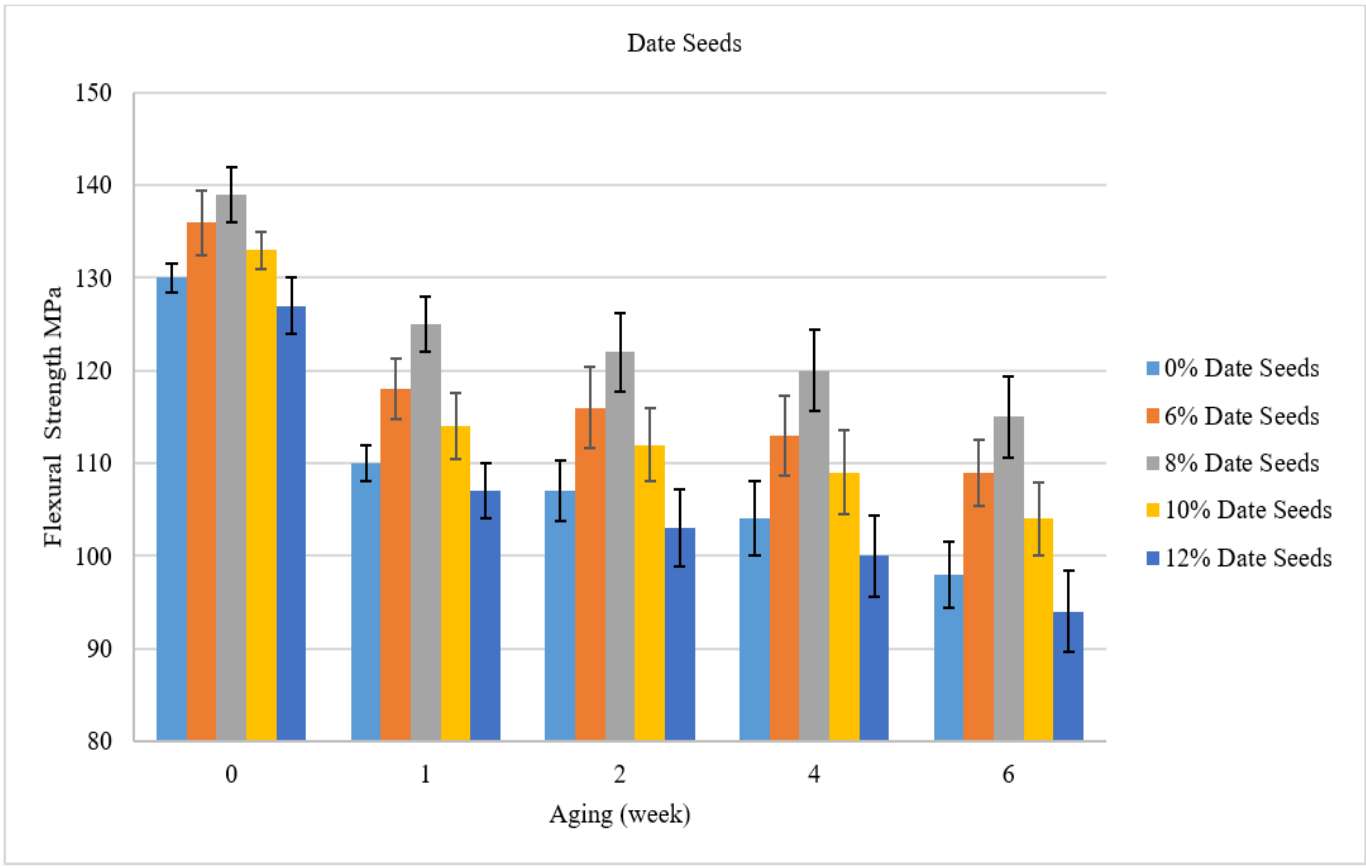


(c)

Figure 10. Hardness graphs, (a) Olive seeds, (b) Date seeds, (c) Pistachio shell-reinforced composites aged in NaOH solution



(a)



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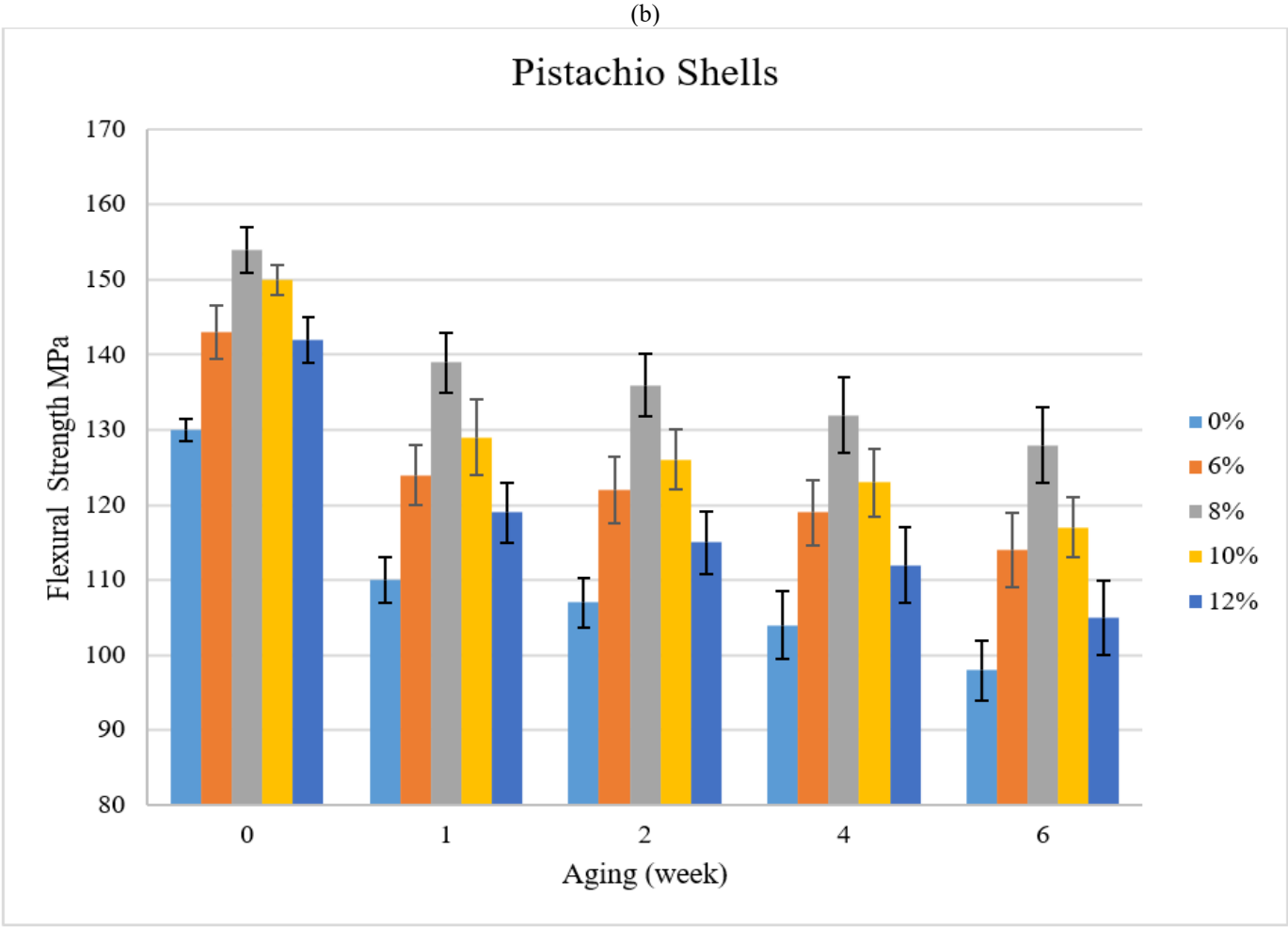


(c)

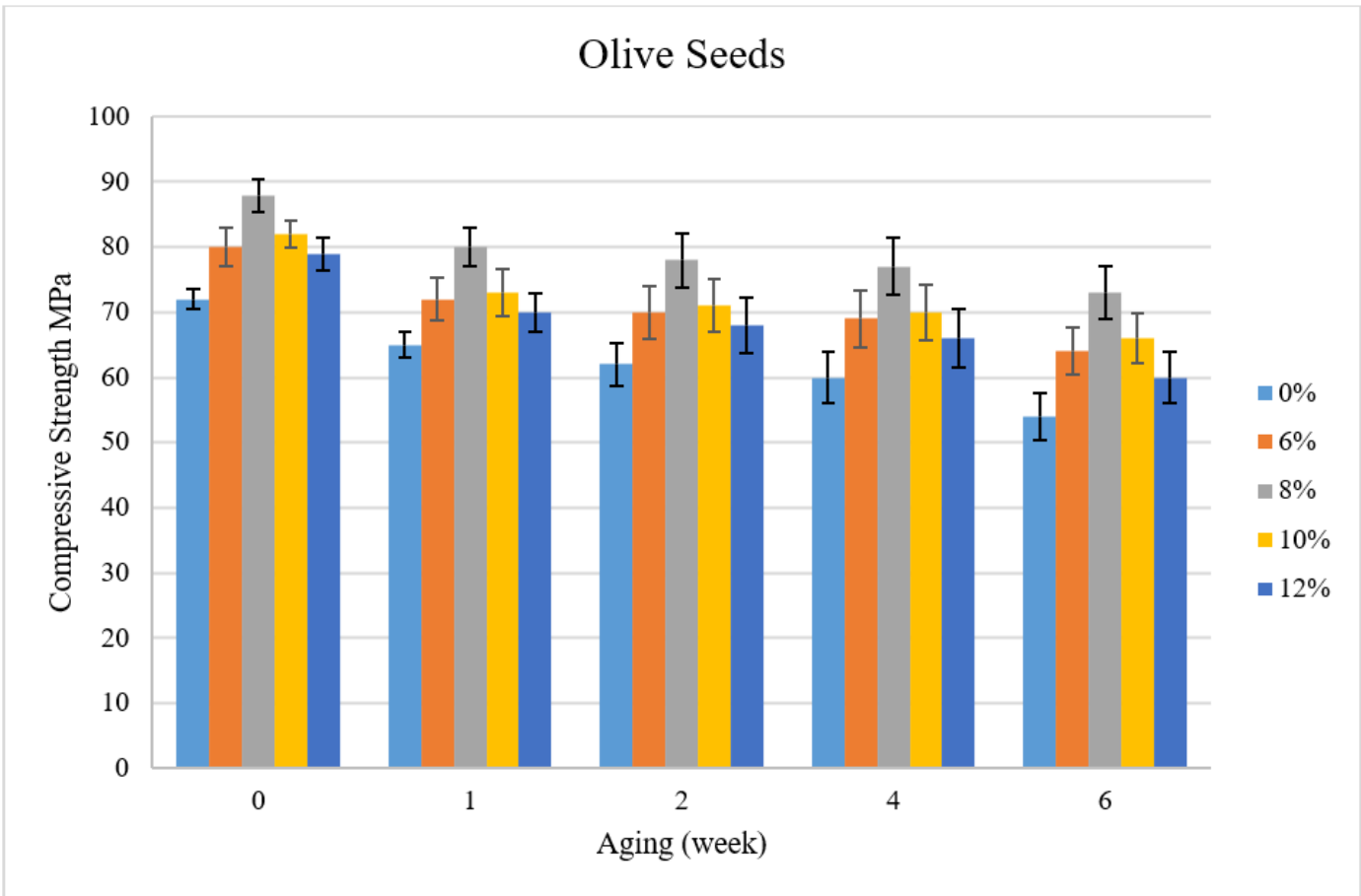
Figure 11. Flexural strength graphs, (a) Olive seeds, (b) Date seeds, (c) Pistachio shell-reinforced composites aged in base solution

Composites with 8 wt. % filler had the highest capacity to maintain their impact strength even after aging, compared to all the other compositions. This implies that the optimum filler content increases the resistance of the material to alkaline degradation by promoting the deflection of cracks, pull-out resistance of fillers, and regulated plastic deformation of the matrix. Conversely, an increase in filler stiffens and increases the brittle nature of the material and thus increases the difficulty of the energy to escape when subjected to dynamic loading and accelerates the degradation when subjected to alkaline conditions [12, 13].

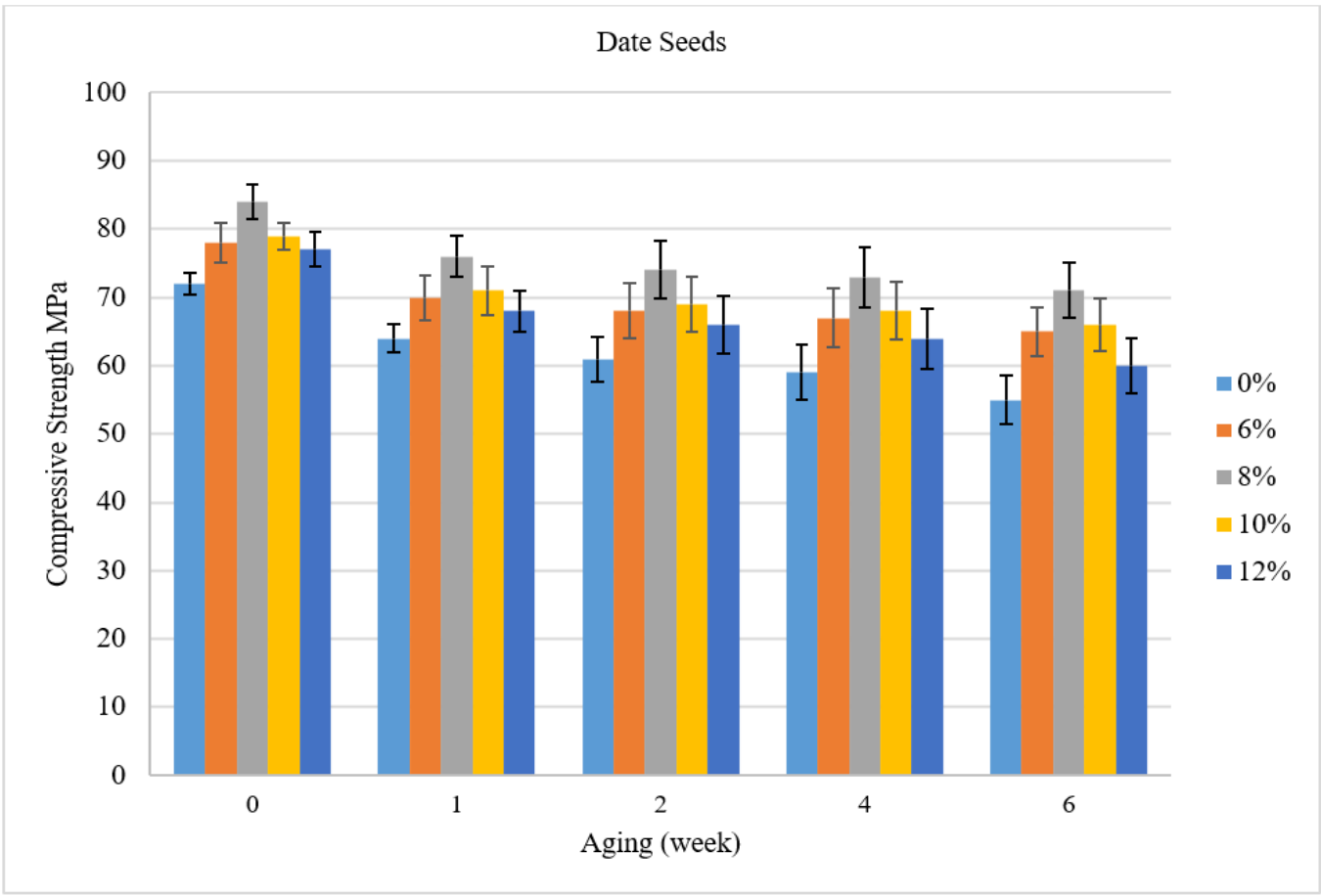
The change in hardness with time is shown in Figure 10. This demonstrated that every composite formulation softened over time. However, the change in hardness was not as evident as the change in the impact, compressive, and flexural properties. This behavior indicates that the surface resistance to localized deformation is not alkaline age-sensitive, as is the bulk mechanical performance. Composites that contained a higher number of fillers (10-12 wt. %) retained their hardness values after aging due to the fact that the fillers were more solid and stiff. However, this increased hardness was accompanied by reduced toughness, as indicated by the reduced impact resistance of the composites.

The flexural strength observed after aging was less sensitive to NaOH exposure than the compressive strength, with moderate degradation over time. This phenomenon is attributed to the significance of the surface layers and interfacial bonding during flexural loading, rather than the bulk matrix properties. Surface and near-interface damages rather than bulk matrix failure are the major contributors to the decay of flexural strength with alkaline aging. Flexural loading places tensile and compressive loads on the outer surface layers and the filler-matrix interface. As the penetration of the alkaline solution increases, the flexural strength is reduced over time through the plasticization of the matrix and interfacial de-bonding. Nevertheless, the degradation rate remains relatively moderate compared to the impact and compressive ones because the flexural response is less sensitive to bulk void development compared to compressive loading. Composites with 8 wt. % filler exhibited the highest flexural strengths, indicating a good balance of stiffness and flexibility. In contrast, composites with 12 wt. % filler degraded more quickly due to their brittleness and reduced strain capacity [13]. Figure 11 shows the flexural strength results after aging.

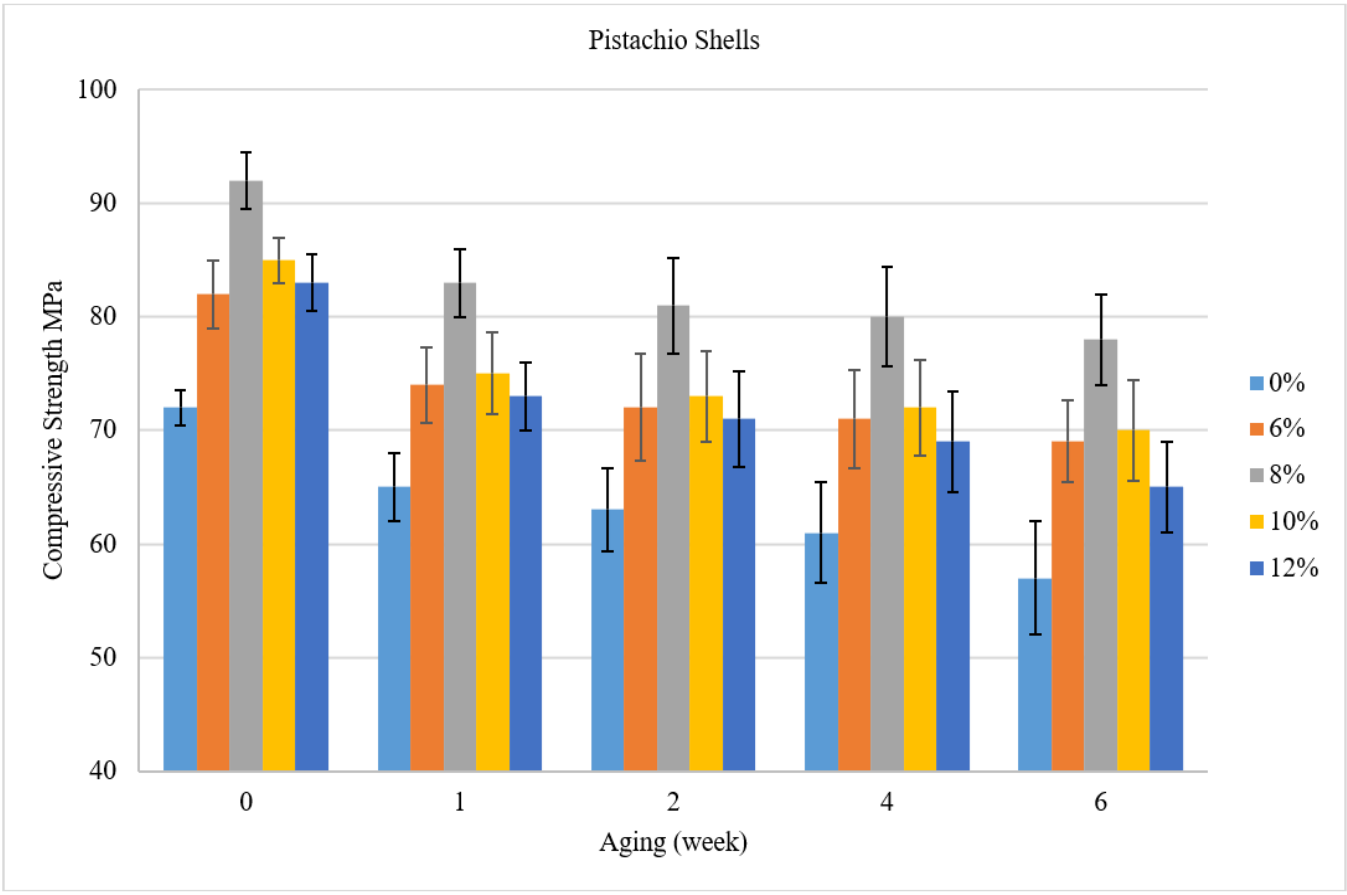
Figure 12 shows the variation in the compressive strength after alkaline aging. The main factors that cause the loss of compressive strength through alkaline aging are matrix softening and progressive increase in voids due to the diffusion of alkaline solutions. NaOH enters the polymer matrix and reduces its stiffness and load-bearing capacity, and interfaces between the plates debond and form microvoids, which are stress concentration sites. These microscopic faults lead to local buckling and premature failure under compressive stress, which is why the compressive strength was constantly reduced with increasing age. The compressive strength of all filler ratios gradually decreased, with the greatest loss occurring during the first week of aging. Initial failure occurs when the alkaline solution enters the polymer matrix, whereby the polymer matrix becomes soft, microcracks develop, and the filler and polymer matrix are separated to some extent. As the equilibrium of the diffusion process approaches, the rate of material degradation with age decreases.



(a)



(b)



(c)

Figure 12. Compressive strength graphs, (a) Olive seeds, (b) Date seeds, (c) Pistachio shell-reinforced composites aged in NaOH solution

The compressive strengths of the composites with 8 wt. % filler was the highest before and after aging, demonstrating that there is an optimal filler loading. Above a filler content (10–12 wt. %), acceleration degradation takes place since filler clumps together, the void content increases, and the sites of stress concentration are easy to create load transfer mechanisms and easy to allow alkaline attack to occur and weaken load transfer mechanisms [14, 15].

5. CONCLUSIONS

From this study, it can be seen that the resistance level against such degradation is mainly determined by the filler material, while the main factor for the degradation of EP/UP hybrid composites is alkaline aging. When the filler content reaches 8 wt. %, and this was the best level in enhancing the mechanical properties. The maximum effect, compressive strength, and flexural strength were observed at this level, and the hardness increased to 12 wt. %. All the mechanical properties in NaOH gradually deteriorated owing to alkaline aging, and the impact strength was the most influenced. Composites containing 8 wt. % filler performed best in mechanical performance after aging, implying that they had the best balance between strength and durability. Among the considered fillers, pistachio shell-reinforced composites exhibited the most beneficial general performance, which assures the sustainability of agricultural waste fillers in the production of polymer composites in alkaline environments.

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