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Research Article

Elaboration and Characterization of Waste Inked Paper-Poly (Vinyl Chloride) Composites: Effect of Paper Deinking

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ABSTRACT

The waste paper poses environmental problems because it is a wood-based resource. Recovering it as fiber for the preparation of low-cost and environmentally-friendly composite materials offers significant environmental benefits, including reducing deforestation and the preservation of fossil resources. Our study presents an innovative approach by using waste inked and deinked paper as a reinforcement in thermoplastic polymer. Polyvinyl chloride (PVC)-based composites reinforced with waste inked paper (WIP) and waste de-inked paper (WDIP) fibers with loading rates ranging from 10% to 30% (Wt.%) were prepared. The effect of paper deinking processes on the mechanical, morphological, and physicochemical properties of the resulting composites was studied. Fourier Transform Infrared Spectroscopy (FTIR) analysis revealed the de-inking of paper after alkali-treatment. This result was confirmed by morphological analysis using optical spectroscopy. The results for the PVC/WIP and PVC/WDIP composites showed an improvement in the mechanical properties after the de-inking of the paper fiber. The tensile strength and the Young's modulus were increased by 16.90% and 37.80%, respectively, when 30% (Wt.%) of WDIP was added to PVC compared to WIP fiber. These results were confirmed by the optical spectroscopy (OS) analysis, where a better surface was observed in the PVC/WDIP composites. The water uptake test showed that the introduction of WDIP in PVC reduced water absorption by 18.38% compared with WIP fiber at a load charge of 30% (Wt.%). However, an increase in density was recorded. These results demonstrate that the incorporation of WDIP into PVC is not only feasible but also beneficial to environmental sustainability and economic growth.

1. Introduction

The polymeric materials, also known as plastics, are present in the life of every individual; they are used in many applications that it would be very difficult to pass [1]. Increase significantly the use of these materials of synthetic origin, and their intensive exploitation for the current practice has resulted in the accumulation of non-biodegradable waste in the environment. This has caused a footprint of the landfill and pollution of soil and marine environments. Several solutions have been put in place to reduce their impact on the environment. For example, it has been given a new life to these polymers by recycling for the manufacture of new materials or enhancing the product by incineration in order to produce energy. However, the first method suffers from the difficulty of sorting and cleaning rejected materials and leads to recycled materials

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with degraded properties [2]. The introduction of natural fibers in these plastics offers a promising solution to reduce pollution and preserve fossil resources by providing sustainable alternatives to traditional polymers like polyethylene (PE), polypropylene (PP), and rubber [3]. These materials aim to maintain comparable properties to conventional plastics while being environmentally friendly. This new class of materials is characterized by properties such as high stiffness, a low price, low density, and an ecological nature due to the fact that they are derived from renewable and biodegradable resources. Moreover, it requires less energy to be produced, offers good thermal and sound insulation, and presents a range of benefits over traditional materials [4].

The development of composites made from thermoplastics and lignocellulosic waste could be an interesting way of reducing the impact of synthetic polymers on the environment. Waste paper is a good source of inexpensive lignocellulosic fiber, principally composed of cellulose, hemicellulose, and lignin [5-7]. Papers reinforced materials can be used in a number of areas, including construction (windows, doors, and furniture), automobile parts, and interior design [8]. The production of paper was more than 412 million tons in the world in 2019, and the recycling of paper from cardboard, old newspapers, and printed white paper has become an important method of reducing environmental waste [9]. In recent years, different research has highlighted the great prospective of waste paper as an attractive resource for recycling paper from packaging, old newspapers, and printed white paper, which has become a very important method to reduce waste in the environment [10].

Waste paper has wide prospects in the field of composites, since it can be used as a lignocellulosic fiber for the preparation of new composite materials [11], and even more for improving the performance properties of different synthetic polymers [12-20]. Research in this field is now relatively well-developed, which evidences the viability of the application of waste paper as fibers in the production of polymer composites, and gives rise to significant perspectives for the composites industry [9]. López et al. [21] reported that the recycled newspaper fibers performed efficiently as a reinforcement agent, enhancing the tensile strength and Young's modulus of thermoplastic starch by over 260%. Valente et al. [22] introduced recycled paper into composites with a high-density polyethylene (HDPE) matrix. They observed agglomeration and poor dispersion of the paper fibers on the matrix, attributed to the formation of hydrogen bonds between them. The tensile tests indicated that rigidity was fairly constant and that there was a slight increase in strength over the pure matrix. Another study tested waste paper (5% by weight) and chopped basalt (5% by weight) in the HDPE to replace the glazing in the HDPE double-walled greenhouses [23]. The results on composites showed a marginal increase in melting temperature (4°C) and tensile characteristics (8.2% and 11.4% in tensile strength and in Young's modulus, respectively) compared with pure HDPE.

However, the main disadvantage of lignocellulosic fibers as reinforcement in composite materials is their incompatibility with synthetic thermoplastics, due to the fact that these fibers have a hydrophilic character because of the abundance of hydroxyl (OH) groups in their cellulose and hemicellulose components, and thermoplastics have a hydrophobic character, which results in poor interfacial interaction between the fibers and the matrix, which leads to poor mechanical properties of the composites [24]. Therefore, Several researchers indicated that the modification of the surface of lignocellulosic fibers is necessary in order to reduce their hydrophilic nature and improve fiber-matrix interfacial adhesion on the one hand and on the other hand, to remove impurities and the lignin and hemicellulose coating on the surface of these fibers, thus generating a better distribution of the fibre in the matrix and, consequently, an improvement in the mechanical properties of the composites [25-28].

Recycling inked paper has traditionally focused on the majority of the previous research to transform waste paper into new paper products. However, our study presents an innovative approach by using recycled inked paper as a reinforcement in polyvinyl chloride (PVC). This method not only promotes recycling but also contributes to the development of environmentally friendly composite materials.

The aim of this study was: (1) to investigate a recycling process for waste inked paper (WIP) that includes a cost-effective and efficient de-inking method which will use a 2% alkaline solution and 1% of hydrogen peroxide "H_2O_2"; (2) preserving forests and therefore the environment; in fact, each ton of recycled paper can save significant quantities of wood, water, and energy compared to the production of a new paper made from virgin resources and recovering this waste also reduces greenhouse gas emissions [29]; (3) study the effect of the incorporation of the inked (WIP) and deinked (WDIP) in the polyvinyl chloride (PVC) as the matrix, one of the most usually used thermoplastic polymers in the world [30] to prepare new composite materials. The influence of the de-inking of WIP and the effect of its incorporation from 10% to 30%

(Wt.%) on the morphological, structural, and physico-mechanical properties of the resulting composites was studied.

2. Experimental

2.1. Materials

The matrix used in this study is based on PVC, type SE-120 supplied by the CABEL company for "Electrical Câblerie" in Algiers, Algeria. This polymer has the following properties: K-Wert, from 70.2 to 72.0, with a density of 0.52. Additives were added to this polymer before the preparation of the various composites, namely dioctyl phthalate (DOP) as a plasticizer, a Ca/Zn-based thermal stabiliser, and stearic acid as a lubricant. Waste inked paper (WIP) was collected from the administrative offices of various companies in Algiers, Algeria. The chemical composition of waste paper is as follows: 80% cellulose, 5 to 15% hemicellulose, and minor proportions of lignin and proteins [31].

2.2. Preparation of Fibers and Composites

- *Preparation of Waste Inked Paper Fiber*

The waste inked paper fiber was prepared as follows: after collecting, the WIP was cut into small pieces and crushed with an electric crusher.

- *Preparation of Waste De-inked Paper Fiber*

The paper was de-inked using the method proposed by Nedjema et al. [25]. 10 grams of paper were cut into small pieces of about 5 mm2 and then de-inked in distilled water for 24 hours, after which they were filtered and placed in an aqueous solution (2% of sodium hydroxide "NaOH" and 1% of hydrogen peroxide "H2O2") at a temperature of 45°C for 3 hours with magnetic stirring. Finally, the paper pulp was washed with distilled water until the pH of the wash water was 7, filtered, and left to dry at room temperature. Finally, it was crushed with an electric crusher.

- *Preparation of Composites*

The PVC/WIP and PVC/WDIP composites were prepared at the CABEL "Electrical Câblerie" company in Algiers, Algeria. The different formulations presented in Table 1 were prepared by two transformation processes: calendaring and compression moulding. The PVC (50%), lubricant (44%), and Ca/Zn stabilizer (4%) were introduced into a T6HK8 type turbo-mixer at a speed of 2000 rpm. The temperature of the mixture gradually increased, and as soon as it reached 80°C, the plasticizer (DOP) was added (2%), and mixing continued for 15 minutes. Before unloading, the mixture is cooled to 40°C to prevent pre-gelling. The PVC and its additives are introduced into a two-cylinder mixer at a temperature of 140°C. Next, the fiber (WIP and/or WDIP) was added to obtain the mixture for each formulation. The prepared mixture is introduced into the platens of the TONJINE table-top press at a temperature of 170°C, under a pressure of 300 kN, and for a residence time of 5 min. To avoid the presence of air bubbles, degassing is carried out before the final pressure is applied.

Plates measuring 250*250*2 mm^3 were obtained and cooled to room temperature, which will be used for cutting out samples in the form of dumbbells to be used in the various characterization tests.

Table 1. Weight composition (%) of the different formulations (PVC/WIP and PVC/WDIP)

Compositions	F0	F10	F20	F30
PVC (%)	100	90	80	70
WIP (%)	0	10	20	30
WDIP (%)	0	10	20	30

2.3. Characterization Methods

- *Determination of Dry Matter and Moisture Content of Inked and De-inked Paper*

Two grams of sample are weighed (W_0) into a ceramic crucible (W_1). It is placed in an oven at 105°C for 24 hours. The crucible is then removed from the oven, placed in a desiccator, and weighed (W_2). The dry matter (DM) content is given by the following formula:

$$DM = \frac{W2 - W1}{W0} * 100 \quad (1)$$

W_0: Weight of test sample (g).
W_1: Weight of empty crucible (gr).
W_2: Weight of crucible with residue (gr).

The moisture content (MC) is determined by the following expression:

$$\%MC = 100 - \%MS \quad (2)$$

- *Analyse Spectroscopique (IRTF-ATR)*

FTIR analysis was carried out using a SHIMADZU FTIR-8400 Fourier transform infrared spectrophotometer controlled by a computer equipped with processing software with a resolution of 4 cm^{-1} in the 4000 to 400 cm^{-1} region.

- *Morphological Analysis Through Optical Spectroscopy*

Morphology tests on the various samples were carried out using an optical microscope combined with Optika software at room temperature.

- *Mechanical Properties*

- *Tensile Test*

The tensile test assesses a material's mechanical strength and determines its elastic properties related to rigidity and rupture by measuring parameters like Young's modulus, elongation, and tensile strength. The tensile test was carried out on an MTS Criterion machine in accordance with standard NFC 32-200, controlled by a computer using TXW-type software. The specimens were stretched at a constant speed of 50 mm/min.

- *Shore D Hardness Test*

The objective of shore D hardness measurement is to measure the hardness of plastics and elastomers and to provide an overview of the material's surface properties in accordance with standard NF T51-109. The test consists of subjecting a sample measuring 5x5 cm^2 and weighing 5 g to a force tending to push down the pointed steel needle. The durometer measures between 100 and 0 (100 maximum hardness, zero penetration, 0 maximum penetration). Penetration is indicated by a direct reading on the durometer after 15 seconds.

- *Density Test*

The density of WIP and WDIP is determined in accordance with standard NFT 51-063, using a pycnometer with a volume of 10 cm^3. The pycnometer is weighed (W_1), then a weight of the fiber (W_2) is introduced into the pycnometer, filled with distilled water, and weighed (W_3).

The density of the sample (d_{fiber}) is determined by the following expression:

$$d_{fiber} = \frac{W_2}{W_1+W_2-W_3} * d_{water} \quad (3)$$

The density of samples was determined by measuring the Archimedes' pressure exerted on the volume of the sample immersed in distilled water at a specific temperature. The density was determined using a DSM densimeter.

- *Water Uptake Test*

The samples were dried in an oven at 60°C for 24 h. After cooling the specimens in a desiccator, they were weighed (W_0) to a precision of 0.0001 gr. The samples were then immersed in distilled water at a temperature of 23°C, in accordance with standard NF 51-002. Every 24 hours, a samples are taken and all surface water is removed with absorbent paper and reweighed (W). This test continues until the weight (W) does not change. Three samples were tested for each formulation. The percentage (or variation) in weight is given by the following formula:

$$\Delta W(\%) = \frac{W - W_0}{W_0} \times 100 \quad (4)$$

with:

W_0: Sample weight before immersing.

W: Sample weight after immersing.

3. Results and Discussion

3.1. Characterization of WIP and WDIP Fibers

- *Physical and Chemical Characterization*

The results obtained (Table 2) show that the inked paper has a low density, which increased after deinking. This result is due to the grafted molecules filling during the alkaline treatment. In fact, this treatment eliminates most of the less dense content, such as hemicellulose, lignin, and other extractives in the cellulose fibers that contribute to a less compact structure, resulting in an increase in the content of α-cellulose, which is denser than the other constituents. Also, the chemical modification of the fiber led to the contraction of the fibril. As the fibrils become tighter under the effect of contraction, the overall mass per unit volume of the fiber will increase. This leads to an increase in density [32].

The density differences between WIP and WDIP can have a considerable impact on the composites' performance, in particular in their mechanical properties. The higher density of WDIP contributes to the stiffness of composites and leads to increased hardness. Indeed, higher densities can improve mechanical properties and offer specific advantages in terms of durability and performance in different applications [33].

The dry matter content recorded is 93.35% and 86.14% for WIP and WDIP, respectively, and the moisture content result showed that WDIP is wetter than WIP, with values of 13.86% and 6.65%, respectively. This is probably due to the increase in the accessible surface area of the WDIP fiber caused by swelling of the fibers. This treatment has altered the physical properties of the paper fibers, leading to higher moisture levels in WDIP. In effect, the application of an aqueous solution can increase the retention capacity of water molecules by the paper fibers, resulting in higher water absorption in the case of WDIP [34, 35], which can lead to better bonding between fibers and other materials in composite applications. These result in enhanced mechanical properties, such as tensile strength and flexibility [36].

Table 2. Physical and chemical characteristics of WIP and WDIP

Characteristics	Type of paper	
	WIP	WDIP
Density	00.65	00.90
Dry matter (%)	93.35	86.14
Water content (%)	06.65	13.86

- *Spectroscopic Analysis (FTIR-ATR)*

Figure 1 shows the FTIR spectra recorded on the WIP and WDIP fibers. From this figure, we can see the characteristic band of hydroxyl groups in the paper fiber located between 3600-3000 cm^{-1} [7], and the area of this peak is more intense for the WIP fiber. This is attributed to the decrease in the concentration of hydroxyl groups after the deinking of the paper and to the elimination of a certain quantity of hemicelluloses and lignin, and the establishment of a new bond between Na^+ and the fiber. This is also probably due to the elimination of the ink, which has an absorption band at 3373 cm^{-1} [26].

In addition, a decrease in the intensity of several bands showed that deinking removes some of the paper's hemicellulose and lignin as follows [37]:

- At 2920 cm^{-1}, which can be assigned to the vibrations of asymmetric elongation of the C-H bonds of the CH_2 group.
- At 1500-1400 cm^{-1}, which can be assigned to the vibrations of the aromatic ring.
- At 1235-1270 cm^{-1}, which can be assigned to the vibration of asymmetric deformation of the C-H bonds of the aromatic ring.
- At 1039 cm^{-1}, which may be assigned to the deformation vibrations of the C-O-C bonds of cellulose and hemicellulose.
- At 600 cm^{-1}, which may be assigned to out-of-plane O-H hydroxyl elongation vibrations in polysaccharides.
- At 1421 cm^{-1}, which is assigned to CH_2OH groups.

By eliminating hydrophobic components and modifying the fiber surface (equation 5), alkali treatment improves the compatibility between hydrophilic natural fibers and the hydrophobic polymer matrix, which can enhance interfacial adhesion between the fiber and the polymer matrix and lead to improvements in the mechanical properties of the composites, such as tensile strength, elongation at break and tensile modulus [23, 29].

$$Fiber\text{-}OH + NaOH \rightarrow Fiber\text{-}O\text{-}Na + H_2O \quad (5)$$

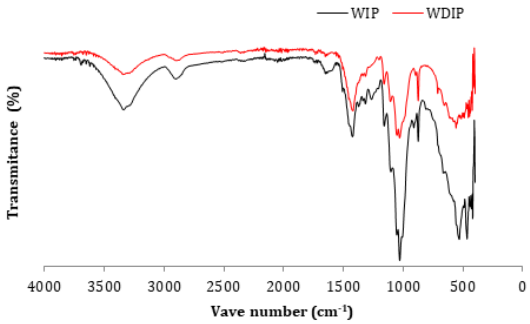

Fig. 1. The FTIR-ATR spectra of WIP and WDIP

- *Morphological Analysis*

Figures 2 and 3 show optical microscope images of waste inked paper and waste deinked paper fibers, respectively, at different amplifications. The images (Figure 2) show that the WIP fibers form agglomerates with a random orientation, and where the ink can be clearly seen on the fibers. On the other hand, the images recorded on the WDIF (Figure 3) show that the fibers are distinctly visible, are long, and have a cleaner appearance, which is explained by the elimination of the ink during the deinking process with the hydroxyl solution [38, 39]. This confirms the results recorded in FTIR analysis on the decrease in the concentration of hydroxyl groups (which show an absorption band at 3373 cm^{-1}) after the paper deinking process, which is explained by the removal of the ink. This observation probably also involves eliminating the impurities, lignin, and other non-fibrous components present in the inked paper, allowing for better visibility of the structure of cellulose fiber, which can lead to good wettability between the fiber and the polymer matrix and facilitate a more uniform distribution of the fibers within the matrix. Madueke et al. [27] indicated that fewer hydroxyl groups lead to decreased moisture absorption and better compatibility with coir fibers and PVC matrix, which contributes to a more cohesive bond between the fibers and the polymer matrix, therefore, enhanced mechanical properties of the resulting composites.

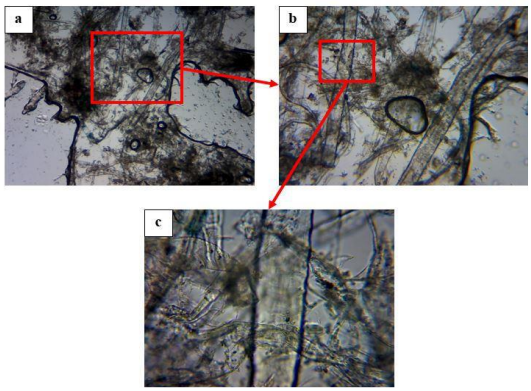

Fig. 2. Morphological analysis of the WIP using a light microscope at magnifications of (a)×4, (b)×10, and (c)×40

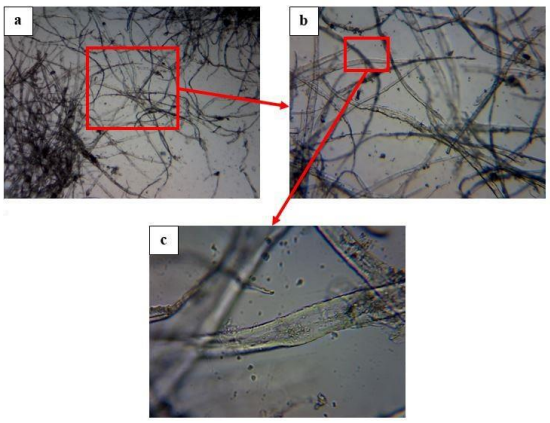

Fig. 3. Morphological analysis of the WDIP using a light microscope at magnifications of (a)×4, (b)×10, and (c)×40

3.2. Characterization of PVC/WIP and PVC/WDIP Composites

- *Tensile Properties*

The tensile strength and Young's Modulus of different composites prepared with treated and untreated waste paper are presented in Figures 4 and 5, respectively.

For the variation in the tensile strength of PVC/WIP and PVC/WDIP composites as a function of filler content (Figure 4), it can be seen that this property tends to decrease with the addition and increase in the filler content of treated and untreated fibers in the PVC matrix. This decrease is probably due to the non-reinforcement of the matrix by the fibers, which can be explained by the tendency of the fibers to group and form agglomerates that induce heterogeneity and non-uniform stress transfer within the matrix, resulting in embrittlement of the material [35, 40]. Comparing the different results recorded on treated and untreated composites, it can be noted that composites prepared with treated fiber (WDIP) recorded an improvement in tensile strength compared with composites filled with untreated fiber (WIP). For loadings of 10, 20, and 30% (Wt.%), an increase of 14.39%, 18.39%, and 21.74%, respectively, was obtained after chemical treatment of fibers. This is explained by better adhesion and interaction between the WDIP and the matrix, which is the result of the elimination of surface impurities and the partial treatment of the fibers as well as amorphous hemicellulose and lignin, which ultimately improve the mechanical properties of the composites [27, 42, 43]. Several studies have shown that the alkali treatment improves the compatibility between hydrophilic natural fibers and the hydrophobic polymer matrix, which can enhance interfacial adhesion between the fiber and the polymer matrix and lead to improvements in the tensile strength of the composites [25-27, 32, 36]. Seisa et al. [45] reported that treatment of date palm fibers with 2% NaOH for 2 hours resulted in a 27.74% improvement in fiber tensile strength compared to untreated fibers. This decreases the humidity affinity of the fiber and also enhances mechanical properties by providing a high level of interfacial adhesion when these fibers are used as reinforcement with a polymer matrix.

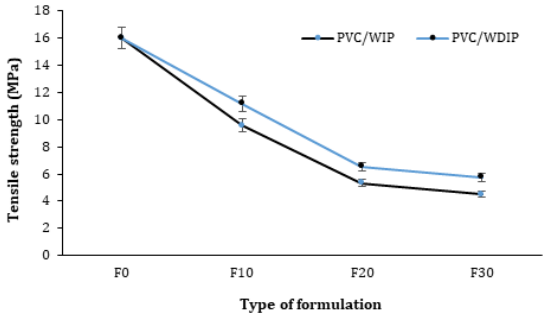

Fig. 4. Tensile strength of PVC, PVC/WIP, and PVC/WDIP composites

The evolution of Young's modulus (Figure 5) indicates that the introduction of WIP and WDIP into the PVC matrix increases the stiffness of the materials, which is reflected in a substantial increase in Young's modulus with the increase in the loading rate. This is explained by the fact that paper fiber is stiffer than PVC, which leads to a higher stiffness of the materials [7, 25, 26]. These results also show that the introduction of WDIP into the matrix results in stiffer materials than those reinforced with WIP. An increase of 23.16%, 24.37%, and 87.04% in Young's moduli, respectively, was obtained. Various studies have reported an increase in the Young's modulus of composites after treatment of the fibers with sodium hydroxide [27, 44, 45]. They indicate that this treatment enhances interfacial adhesion between the fibers and the matrix, which leads to better mechanical properties in composites produced using these fibers. In fact, the alkaline treatment eliminates most of the lignin and wax, which have a malleable character. This leads to an increase in the cellulose content, which has a rigid character [43].

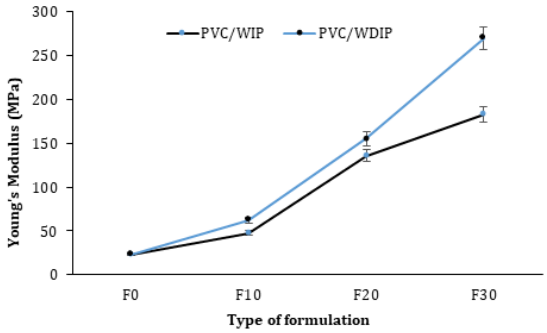

Fig. 5. Young's Modulus of PVC, PVC/WIP, and PVC/WDIP composites

- *Hardness Test*

It can be seen (Figure 6) that the hardness increases with the increase in the loading of treated and untreated fiber, compared with virgin PVC. This result is to be expected, as newsprint fiber is made up of cellulose microfibrils, which are classified as hard fibers, making it difficult for the durometer needle to penetrate the composite material.

It was also observed that composites prepared with WDIP are harder than those prepared with WIP. This is due to the good dispersion of the fiber in the matrix, with greater fiber-matrix interfacial adhesion, which is explained by the deinking of the paper with hydroxide sodium, which eliminates the lignin and wax from the fiber, leaving only the cellulose, which has a hard and rigid character [46, 47].

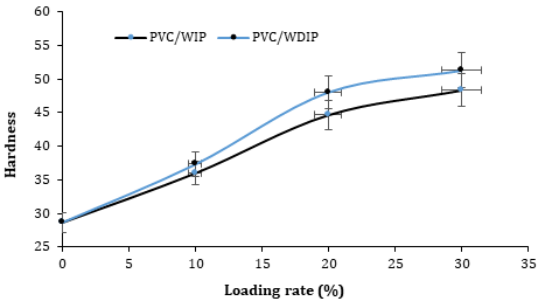

Fig. 6. Hardness of PVC, PVC/WIP, and PVC/WDIP composites

- *Morphological Analysis*

Figure 7 shows the surface appearance of PVC, PVC/WIP, and PVC/WDIP with a 30% (Wt.%) loading rate, obtained using an optical microscope at 10x magnification. It can be seen that the introduction of WDIP fibers makes the surface smoother and more homogeneous than that of PVC/WIP composites. This can be explained by the better dispersion of the fibers on the matrix after chemical treatment of inked paper, which reduces hydroxyl groups and removes most of the ink in the paper, as shown in Figure 3, filling the voids on the PVC surface.

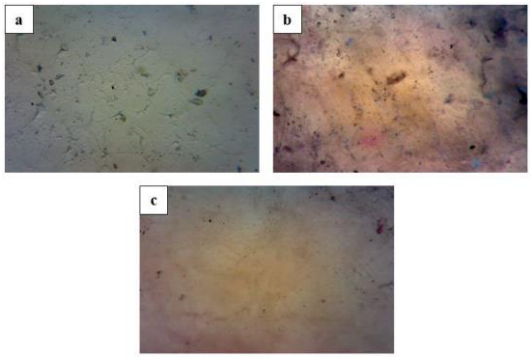

Fig. 7. Morphological analysis of (a) PVC and (b) PVC/WIP, (c) PVC/WDIP composites using a light microscope at magnifications of 10.

- *Spectroscopic Analysis (FTIR-ATR)*

An analysis of the FTIR spectra of PVC and PVC/WIP, and PVC/WDIP composites would provide a better understanding of how these composites modify or retain the spectral characteristics of virgin PVC. FTIR analysis of PVC and composites with PVC/WIP and PVC/WDIP (Figure 8) reveals absorption peaks that correspond to specific molecular vibrations within the PVC structure of the lignocellulosic fibers of paper. The main absorption peaks in the PVC spectrum are a peak at 614 cm^{-1} assigned to C-Cl bond elongation, a peak at 1259 cm^{-1} attributed to C-H deformation vibrations in the polymer chain, and two peaks at 2853 cm^{-1} and 2924 cm^{-1} corresponding to stretching vibrations of the CH_2 and C-H groups, respectively. These absorption peaks recorded in the spectrum of virgin PVC correspond well to those given in the literature [48].

By comparing the FTIR spectra of the composites with those of virgin PVC, we can see that we have not recorded any new peaks apart from those corresponding to virgin PVC and those of the WIP and WDIP fibers already shown in Figure 1. We can therefore conclude that the addition of these fibers does not modify the absorption peaks characteristic of PVC and that there are only physical interactions between the PVC matrix and these fibers.

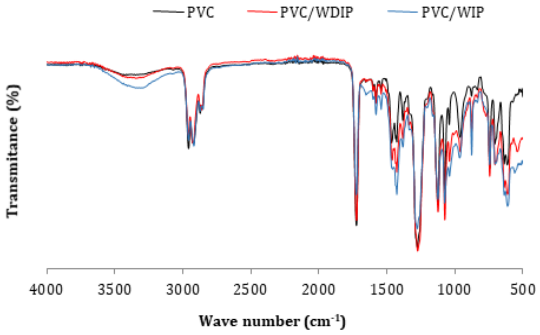

Fig. 8. FTIR-ATR spectra of PVC, PVC/WIP, and PVC/WDIP composites with 30% (Wt.%) fiber charge.

- *Density Test*

The results of the density test of the materials produced as a function of the loading rate for treated and untreated fiber are shown in Figure 9. These results show a slight increase in density for the filled materials compared with virgin PVC. It can also be seen that the PVC/WDIP composites are denser than the composites prepared with untreated fiber. This result is explained by the fact that the density of the WDIP fiber is greater than that of the WIP (Table 1). Some researchers explain this increase by the improved reinforcement of the matrix by the filler after the chemical treatment of the fiber, which eliminates most of the less dense content, such as

hemicellulose, lignin, and other extractives in the cellulose fibers. This improvement in the interaction between the fiber and the PVC matrix results in a denser material, as the treated fibers offer better mechanical bonding and reinforcement within the composite structure [49]. Baghloul et al. indicated that higher densities in materials can significantly enhance their mechanical properties, leading to increased durability and performance across various applications [33].

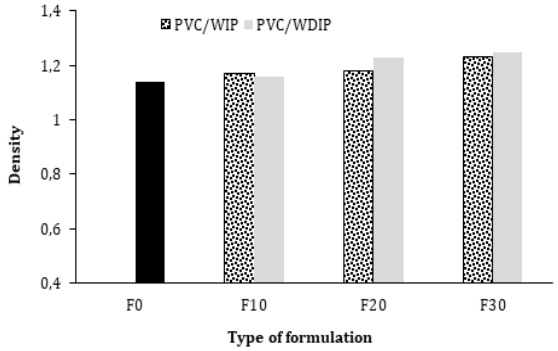

Fig. 9. Density of PVC, PVC/WIP, and PVC/WDIP composites.

- *Water Uptake Test*

Water uptake properties are very useful in understanding the characteristics of composite materials, and it is a crucial parameter affecting their mechanical properties and durability. Figure 10 shows the water uptake of composites prepared with treated (T) and untreated (UT) fiber as a function of fiber loading rate and immersion time in distilled water. We can see that the absorption rate increases with immersion time and with the increase in the fiber content of the paper, inked and de-inked in the matrix. This result is to be expected, as paper fibers are rich in hydroxyl groups, which form hydrogen bonds with water molecules. So the higher the loading, the higher the OH concentration, and consequently, the higher the rate of water absorption. It can therefore be said that the presence of fibers is responsible for the increased sensitivity of composites exposed to water. It can also be noticed that the rate of water uptake of the samples is rapid in the time interval [0-6 days], then decreases as a function of time until saturation, where the rate of water absorption becomes constant for a few days.

Comparing the water absorption of the different composites, it is clear that the absorption rate of composites with WIP fiber is higher than that of composites filled with WDIP fiber. A decrease of 13.37%, 17.52%, and 18.38% is recorded for materials filled with 10, 20, and 30% (Wt.%) respectively, of WDIP fiber compared with composites filled with untreated fiber for the same loading rate and for the same duration of immersion. The observed reduction in water absorption rates for composites filled with WDIP fiber can be attributed to the treatment process relating to deinking with sodium hydroxide. This process alters the fiber's surface properties, leading to a decrease in its hydrophilic character, which is attributed to the decrease in the concentration of hydroxyl groups after the deinking of the paper as observed on FTIR spectra (Figure 1). As a result, the treated WDIP fibers become less capable of absorbing water compared to untreated WIP fibers.

Less uptake of water generally results in an improvement in the mechanical properties of the composite, including tensile strength. Reduced water content minimizes hydrolytic degradation of the polymer matrix, helping to maintain the structural integrity of the composite over time [50]. This explains the improved tensile mechanical properties of PVC/WDIP composites compared to untreated composites (Figures 4 and 5). Therefore, the overall water absorption of the composites was reduced by the alkaline treatment, and the tensile strength increased. However, an increase in fiber loading increased the amount of water absorbed and reduced the overall tensile strength. Prabhakar et al. [35] reported similar results for banyan/banana composites, untreated and treated with 5% NaOH, which they attributed to the interaction between the fibers and the matrix, to the removal of impurities from the fiber surfaces, and to the increase in the crystallinity due to NaOH treatment.

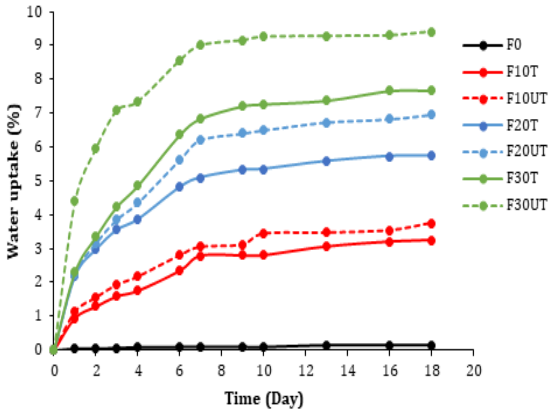

Fig. 10. Density of PVC, PVC/WIP, and PVC/WDIP

4. Conclusions

One of the major objectives of this work is to focus on the change in the properties between chemically treated and untreated fiber composites. This relationship underscores the importance of fiber treatment in enhancing the mechanical properties of polymer composites, making them suitable for various applications where increased stiffness is desirable.

The results (FTIR and optical spectroscopy analysis) show a change in fiber structure after alkaline treatment of inked paper by reducing the intensity of the hydroxyl group band. Alkaline treatment leads to the elimination of the ink and the partial disappearance of hemicellulose and lignin.

The results of PVC/WIP and PVC/WDIP composites indicate that :

1. The use of deinked paper fiber in the PVC matrix improves the mechanical properties of the composite by improving the interfacial adhesion between the surface of the fibers and the PVC matrix compared with composites prepared with untreated fiber. For example, the tensile strength, the Young's modulus, and the hardness were increased by 16.90% and 37.80%, and 7.06%, respectively, when 30% (Wt.%) of WDIP was added to PVC compared to WIP fiber.
2. Both immersion time and fiber content significantly influence the water absorption characteristics of paper-based composites. The findings indicate that incorporating WDIP fiber into composites can effectively reduce water absorption compared to using untreated WIP fiber (a decrease of 18.38% is recorded for materials filled with 30% (Wt.%) after treatment). This reduction is beneficial for enhancing the longevity and performance of composite materials in applications where moisture exposure is a concern.
3. The results of the density show that the PVC/WDIP composites are denser than the composites prepared with untreated fiber.

In conclusion, the recovery of waste inked paper for the preparation of new composite materials is a sustainable approach to materials science that can have a significant impact on their applicability in various industries to partially replace or reduce the consumption of wood and the synthetic polymers obtained from petroleum, which are harmful to the environment and human health, offering an environmentally-friendly alternative to traditional materials.

PVC-based composites reinforced with de-inked paper fibers have a number of potential applications in the construction industry in flooring, screens, exterior applications for decking, panels, fencing, and other elements. Their chlorine composition can give them a better fire classification, which is advantageous for facade applications. These materials can also be used in interior applications for furniture, for example.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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