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Research article

Mechanical characterizations of waste face masks reinforced polyester composites: Recycling wastes into resources

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ABSTRACT

Face masks are made of non-decomposable thin polypropylene sheets. People are discarding them in parks, beaches, drains, landfills, and roadsides because of a deficiency in recycling efforts. It poses health and environmental risks through soil, water, and air pollution, as well as implanting microplastics into aquatic and different active organisms via food chains. Therefore, the environment and ecosystem become unsustainable. This study explored the potential of recycling waste face masks (WFM) into composite materials. In this sense, WFM-reinforced three distinct polyester composites are developed with a 20 % fiber loading in the compression molding machine and employing shredded, parallel, and crisscross patterns of WFM. The tensile, flexural, and impact strengths of composites are assessed as per ASTM guidelines and contrasted with NFRP (natural fiber-reinforced polymer) composites. Besides, void contents and morphological features are investigated using the Field Emission Scanning Electronic Microscope (FE-SEM) to confirm the interaction between WFM and polyester. The maximum tensile and flexural strengths of 32.06 and 41.13 MPa, respectively, are found in the crisscross pattern WFM composite. The maximum impact strength of 0.053 J/mm is found in parallel, and the least void content of 0.63 % is found in crisscross WFM composites. Compared to NFRP composites, the mechanical strengths, void contents, and morphological properties of WFM composites are found promising. It proclaimed that WFM is an appropriate candidate for recycling into composites. It will deter environmental pollution and microplastic insinuation into living things, elevate sustainable development goals, and develop a circular economy by generating resources from WFM.

1. Introduction

Wastes are buried, burned, and discarded in landfills without recycling [1], which causes air, soil, and water pollution and hinders global sustainability. Therefore, controlling, managing, and recycling waste is crucial for a sustainable environment, quality of life, and the development of a circular economy. Scientists are working to turn waste into useful resources and products [1]. Used face masks are one of the solid wastes released to the environment intensely throughout the COVID-19 epidemic since there was a deficiency of suitable waste recycling methods, management, and control measures [2]. Face masks are typical personal protective equipment (PPE)

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utilized by medical staffs and public to protect from dust and pathogens [1]. The utilization of face masks was tremendously high throughout the COVID-19 pandemic, and 89 million face masks were used each month, according to the World Health Organization (WHO) [1,3]. Also, it was mandatory in many parts of the world. Even though the pandemic remains under control currently, worldwide 768 million COVID-19 cases were documented between January 22, 2020 and June 13, 2023 [4], and 509,000 cases were reported within 28 days (until January 28, 2024), as per WHO [1]. However, besides healthcare professionals, still a significant number of people wear face masks daily for protection from germs and dust and personal awareness [1]. Furthermore, air pollution is increasing globally due to population growth, and there is no guarantee that the pandemic will not repeat. Therefore, face mask utilization will increase among people even if there is no pandemic. Consistently, the worldwide market for face masks is predicted to reach US$4.75 billion in 2024 [5]. Face masks form with three layers of nonwoven, nonbiodegradable polypropylene (PP) sheets [1,6]. They end up in landfills, drainage systems, and indirect disposal in urbanized areas like parks, streets, gardens, natural reserves, and beaches because of shortfalls in recycling efforts [1,7]. Even 1 % of used face masks could produce 30–40 tons of non-biodegradable waste worldwide [7]. Besides, based on the weight of a single face mask (75 GSM, three layers, 15 cm × 15 cm size), 151 tons of trash were generated daily during the COVID-19 pandemic and disposed of without recycling [1]. Polypropylene is hydrophobic in nature and non-decomposable. Micro and nanoparticles from waste face masks affect soil physical properties and microbial communities [8]. Microorganisms decompose face masks extremely slowly [8] and take 450 years to decompose entirely [9]. Therefore, waste face masks (WFM) endanger the health and the environment through soil, water, and air pollution, as well as insinuating microplastics into marine and various living organisms via food chains [1,10]. Recently, it has been identified in the placenta, blood, lungs, and intestines of humans [1,11]. Conversely, collection efficiency and filter breathability cannot be restored after autoclave sterilization and ethanol treatment of used face masks [12]. Therefore, recycling waste face masks (WFM) will sustain the environment and ecosystem. Scientists are attempting to develop different methods of recycling used face masks since the appropriate disposal of WFM is not guaranteed yet [13]. This study's primary goal is to explore the possibility of recycling WFM into an engineered product that promotes sustainability and a circular economy. Natural and synthetic fiber-based composites are employed in different fields, including aerospace, automobiles, sports and recreation equipment, biomedical fields, home buildings, marine and defense industries, food packaging, electrical and electronic devices, and household goods [14,15]. Because of their lightweight, higher specific and impact strength, corrosion and wear resistance, and fatigue life, they have become indispensable materials for the progression of humanity [14]. Hence, this study desires to investigate the potential of recycling WFM in composite fields. It can be collected from hospitals, clinics, homes, schools, and offices with an insignificant labor cost. Suitable disposal and collection methods can be implemented, such as using separate containers or trash bins to dispose of WFM and wearing PPE (personal protection equipment like hand gloves, face masks, etc.) during collection. Besides, WFM has no cost and can be decontaminated easily after collection. There will not be an issue with the availability and collection of WFM.

Some studies report on recycling medical plastic wastes, their environmental effects, and recycling waste face masks (WFM) into composites. Joseph et al. [3] studied the prospect of recycling commonly utilized medical plastic waste. Silva et al. [7] examined the adverse physiological and eco-toxicological effects of waste face masks on the environment and wildlife. Aragaw et al. [10] studied the face mask's chemical structure, thermal properties, and environmental effects. They explored that WFM endangers health and the environment and insinuates microplastic into aquatic and living things via food chains. Grinshpun et al. [12] examined the possibility of reusing face masks through autoclave sterilization and ethanol treatment and found that collection efficiency and breathability could not be restored. Battegazzore et al. [16] examined the potential of recycling WFM into industrial products. Singh et al. [17] studied mechanical features of composites made from recyclable plastic waste, and Sahu et al. [18] assessed the dielectric constant and flexural strength of waste stone-based polymer composites. Vigneshwaran et al. [19] examined the mechanical characteristics of red mud, sisal fiber, and industrial waste-based polyester composites. Besides, researchers Mrówka et al. [20], Kumar et al. [21], Nourbakhsh et al. [22], and Rahman et al. [23] evaluated the mechanical properties of wood waste-based silicone, agro waste-based epoxy, agro waste-based polypropylene (PP), and human hair, jute, and betel nut husk fiber-based polyester composites, respectively. Furthermore, Rahman et al. [24] examined the mechanical features of betel nut stem fiber-based polyester composites with different fiber orientations and explored that mechanical properties vary with fiber orientation. Mobarak et al. [13] evaluated the tensile, flexural, and water absorption attributes of 1–10 mm shredded WFM-reinforced polyester composites with 1 %–5 % (wt.) fractions. However, impact strength, void contents, mechanical strength of the unshredded WFM-reinforced composite, and the effect of WFM orientation on the composite's strength are not investigated. There is a potential research gap in evaluating the mechanical strength of WFM composites with different orientations. In this study, WFM-reinforced polyester composites are made in the compression molding machine employing a 20 % (wt.) fiber fraction and crisscross and parallel orientations and shredded WFM. Composites mechanical characteristics, like tensile, flexural, and impact strengths, and void contents, are assessed according to ASTM criteria. In addition, the influence of WFM orientation on the composite's mechanical characteristics is examined, which is the novelty of this study. The mechanical characteristics of composites are analogized to those of natural fiber-reinforced polymer (NFRP) composites to justify suitable applications. Void contents, micro-cracks, crack propagation, fiber agglomeration, and interaction between the WFM and resin are also investigated via FE-SEM (Filed Emission Scanning Electronic Microscope). This study revealed the potential of recycling WFM in the composite field and its applications. It will aid to deter environmental pollution, promote sustainability in the ecosystem, and develop a circular economy.

2. Material and fabrication process

In this study, waste face masks (WFM) are recycled in the composite field by fabricating WFM-reinforced polyester composites with a 20 % (wt.) fiber loading. Composites are developed in the compression molding machine employing full-size WFM without the ear loop and nose wire, in crisscross and parallel patterns, and using shredded WFM, as shown in Fig. 1. The blend of 1 % (wt.) organic chemical MEKP (Methyl Ethyl Ketone Peroxide) and 99 % (wt.) unsaturated polyester is employed as a resin [15]. MEKP initiates the glueing process and quickens the hardening of polyester [15]. The orientation of parallel and crisscross patterns and the shredded WFM are shown in Fig. 1(a), (b), and 1(c), respectively. Fabrication of WFM composites is shown with a flow chart, shown in Fig. 2.

2.1. Processing of Waste Face Masks (WFM)

Disposable face masks from an identical brand were circulated to friends and relatives, which are made of three different layers of polymer sheets and 75 GSM (gm/sq.m) [1]. The first and third layers are nonwoven polypropylene (PP), and the middle one is melt-blown polypropylene [6,16]. The average mass of each face mask is 1.75 gm. Waste face masks (WFM) were collected after one week from the users, decontaminated in an autoclave for an hour at 120 °C and 15 psi pressure, and then kept in the autoclave for 2 h to cool down [1,12]. Then, it was rinsed thoroughly in clean water to remove dust particles and parched in daylight for a day [23]. Ear loop and nose wire were removed from the WFM, cut into a 15 cm × 15 cm size, and weighted. All three layers of WFM were chosen to fabricate composites. The full-size WFMs are used in parallel and crisscross patterns. WFM is cut into 2 mm × 2 mm (approximately) rectangular pieces for the shredded one.

2.2. Composite fabrication

The WFM-reinforced composites are formed in a compression molding machine employing a 30.5 cm × 30.5 cm mild steel mold. The WFM and the mixture of unsaturated polyester (99 % wt.) and MEKP (1 % wt.) are weighted to ensure 20 % (wt.) fiber loading. The mixture of unsaturated polyester and MEKP was stirred vigorously for 2–3 min in a container to create a homogenous mixture. At first, a thin PVC (polyvinyl chloride) sheet was laid on the cleaned mild steel plate, and then unsaturated polyester was applied on the PVC sheet with a brush, and a layer of WFM was laid on top of it. After that, the polyester is applied on top of the laid WFM with a steel roller and mild pressure. The identical process is repeated for successive layers of WFM and polyester. After laying up the last layer of WFM, it was covered by another PVC sheet and steel plate, and then, the mold was wrapped in a polythene sheet. The mold is placed carefully in the compression molding machine under pressure for 14 h. Then, composites were removed from the mold, and specimens were prepared by laser cutting as per ASTM standards.

3. Mechanical properties evaluation

The mechanical attributes of WFM-reinforced polyester composites, like tensile, flexural, and impact strengths are predicted according to ASTM guidelines [1]. Besides, void contents and morphological features are also investigated by the Field Emission Scanning Electronic Microscope (FE-SEM) [1].

3.1. Tensile test

The ASTM D638-14 criterion is used to evaluate the tensile strength of WFM-reinforced polyester composites, and three dogbone-shaped specimens are stretched in the Hounsfield H10KS UTM (maximum capacity of 50 kN) for each type of composite [23]. Specimens are stretched at a strain rate of 2 mm/min until failure [23]. The crisscross, parallel, and shredded WFM-reinforced composite specimens after tensile tests are shown in Fig. 3(a), and specimen in UTM is shown in Fig. 3(b).

3.2. Flexural test

The flexural strength of composites is accomplished in the Hounsfield H10KS UTM as per ASTM-D790-00 guidelines and keeping 64 mm distance between two supports [15]. The flexural load is imposed on specimens at a 2.0 mm/min strain rate until failed [15]. Specimens of crisscross, parallel, and shredded WFM-reinforced composites after flexural tests are shown in Fig. 4(a), and the specimen in UTM is shown in Fig. 4(b).

The equation (1) is used to evaluate the flexural strength of composites [23].

$$\sigma = \frac{3}{2}\left(\frac{PL}{wt^2}\right) \tag{1}$$

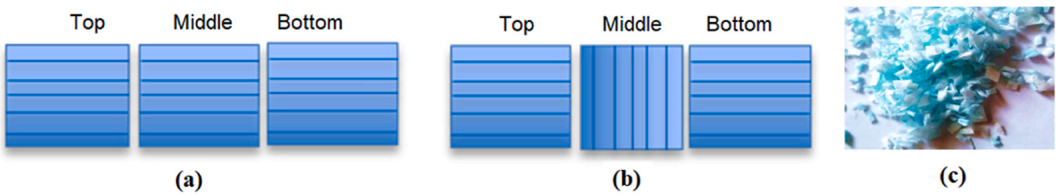

Fig. 1. Waste Face Masks (WFM) in (a) Parallel and (b) Crisscross patterns, and (c) Shredded WFM.

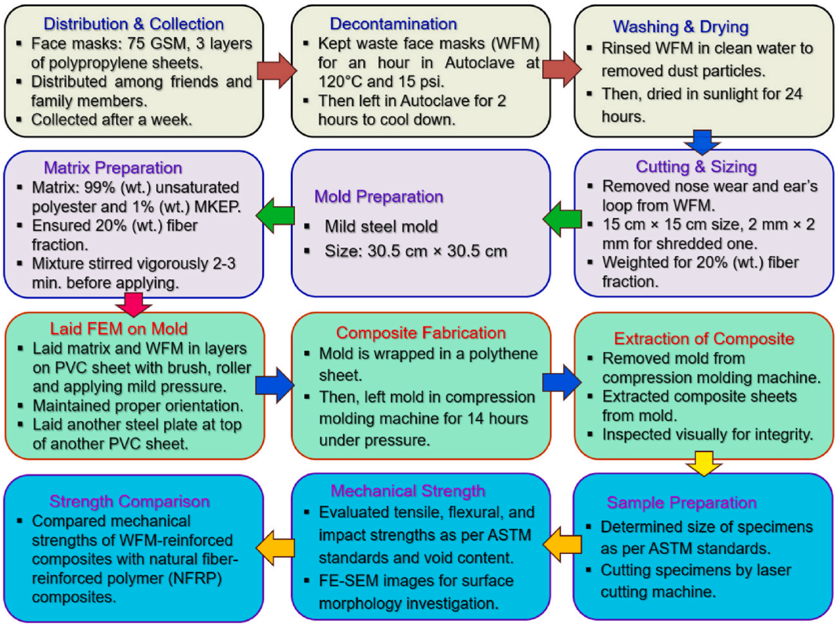

Fig. 2. Steps of fabrication of WFM-reinforced composites.

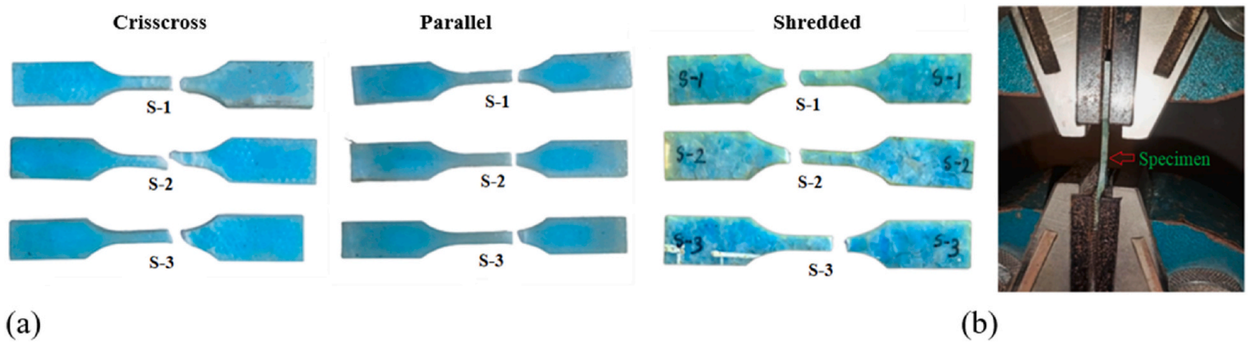

Fig. 3. (a) Failure of specimens after tensile test, and (b) Specimens in Hounsfield H10KS UTM.

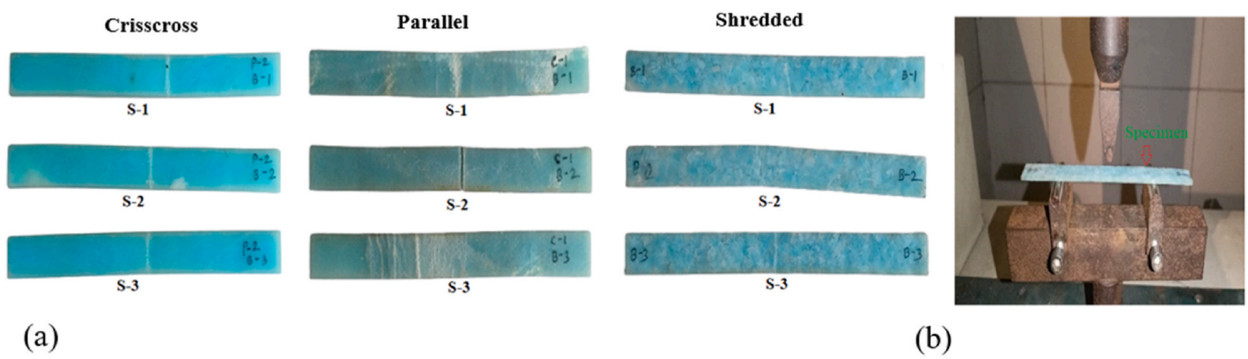

Fig. 4. (a) Failure of specimens after flexural test and (c) Specimen in Hounsfield H10KS UTM.

where, σ = Flexural strength, L = Distance between support spans, w = Width of the beam specimen, t = Thickness of beam specimen, and P = Applied force to the specimen. The flexural strength (σ) of composites is determined using the highest value of 'P' of the respective 'Flexural force vs. Deflection' curves [23].

3.3. Impact test

The impact strength of WFM-reinforced polyester composites is evaluated in the Izod Impact Tester (QPI-IC-21 J) according to the ASTM D4812 criterion [15]. Rectangular specimens of 65.0 mm × 12.7 mm size [23] with a 45° angle notch are used in the test. Specimens are anchored vertically by clamping in the anvil, and the striker hits the specimen transverse to its vertical axis during free fall from a fixed height [15,23]. The impact strength is calculated per unit width of the samples, taking an average of three [23]. The failure of composite specimens after the impact test is shown in Fig. 5(a), and the specimen in the Izod Impact Tester is shown in Fig. 5 (b).

3.4. Void content

Investigation of the void content in polymer composites is essential. During the solidification of resin, air traps inside resin, and voids develop in composites [23], which results in poor bonding between resin and fibers, ultimately declining the strength and fatigue life of composites [25]. In this study, the density measurement technique is used to calculate void contents, which is based on the density of fiber, matrix, and composite. Density of unsaturated polyester, $\rho_p = 1.25$ gm/cm^3 [26] and hardener MKEP, $\rho_h = 1.17$ gm/cm^3 [24]. Face mask density is evaluated as $\rho_f = 0.0216$ gm/cm^3 based on 1.75 gm weight of the single face mask, size 15 cm × 15 cm, and thickness 360 μm [27]. The void in composites is determined based on equations (2) and (3) [24,28].

$$\rho_c = 1 \Big/ \left(\frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \right) \tag{2}$$

$$V_v = \frac{\rho_c - \rho_a}{\rho_c} \tag{3}$$

where ρ_f, ρ_m, and ρ_c are the density of fibers, matrix, and composite without void, respectively. W_f and W_m is weight fractions of fibers and matrix. ρ_a = Actual density of composite with void contents, V_v = Volume fraction of voids in composite.

3.5. Surface morphology

Surface morphology reveals the interfacial glueing between fibers and resin, voids, micro-cracks, crack propagation, and fiber agglomeration in composites [23]. It is crucial for enhancing composites mechanical strengths and characterizing fiber bonding with resin [24]. Field Emission Scanning Electron Microscopy (FE-SEM) analysis is used to examine the surface morphology of composites using ZEISS GeminiSEM. Tensile fractured specimens are used to evaluate the morphology of composites.

4. Results and discussion

Mechanical properties of WFM-reinforced polyester composites are predicted according to ASTM guidelines and summarized in Table 1.

4.1. Tensile strength (σ_{ut})

Stress-strain curves of the crisscross and parallel patterns, and shredded Waste Face Mask (WFM)-reinforced polyester composites are shown in Fig. 6(a), 6(b), and 6(c), respectively.

The tensile behavior of the crisscross, parallel, and shredded WFM-reinforced composites is not identical. The stress-strain curves of crisscross and parallel WFM-reinforced composites are flattened within the strain range of 0.01–0.05 and 0.01–0.02 mm/mm, respectively. It happens due to the transfer of tensile load from one layer of WFM to another layer through the polyester resin, and it takes a while to distribute the load uniformly throughout the cross-section of specimens. After that, the stress-strain curves of crisscross

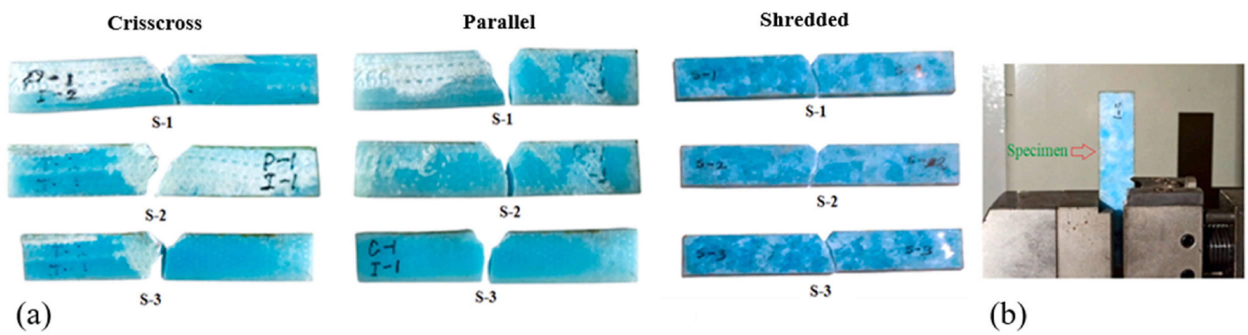

Fig. 5. (a) Failure of specimens after impact test and (b) Specimen in Izod Impact Tester.

Table 1
Mechanical properties of WFM-reinforced polyester composites.

Properties of composites	Type of WFM-reinforced		
	Crisscross pattern	Parallel pattern	Shredded WFM
Tensile strength, σ_{ut} (MPa)	32.06 ± 0.99	17.36 ± 1.29	10.32 ± 0.82
Flexural strength, σ_b (MPa)	41.13 ± 3.09	37.27 ± 1.82	25.15 ± 0.44
Impact strength, W_i (J/mm)	0.023 ± 0.002	0.053 ± 0.003	0.034 ± 0.003

WFM composites become stiffer until failing like brittle materials, and the parallel WFM composites curves behave like ductile materials and deform rapidly before failing. The stress-strain curves of parallel WFM composites are stiffer than those of crisscross and shredded WFM composites. However, it is least stiff in the shredded WFM composites due to the lack of continuity of WFM in the matrix. The ultimate tensile strength (**σ_{ut}**) is the highest for the crisscross and the lowest for shredded WFM-reinforced polyester composites. It happened because of robust interaction and bonding between WFM and polyester resin in the crisscross WFM-reinforced composites. Due to the lack of continuity of fibers (WFM), the lowest tensile strength is found in the shredded WFM composite. Tensile strength is found to be 32.06, 17.36, and 10.32 MPa for the crisscross, parallel, and shredded WFM-reinforced polyester composites, respectively, as shown in Fig. 7(a) and Table 1. The tensile strength of the WFM-reinforced composites is analogized to other natural fiber-reinforced polymer (NFRP) composites, as shown in Fig. 7(b).

The ultimate tensile strength (**σ_{ut}**) of WFM-reinforced polyester composites is more than double of the randomly oriented caryota [29], coir [30], pineapple leaf [31], and 77.42 % higher than the bamboo [32] fiber-reinforced polymer composites, shown in Fig. 7 (b). Although, in some cases, the fiber weight fraction is higher than in this study. In contrast, it is found to be much less than the banana and kenaf woven fiber (**σ_{ut}** = 139 MPa, 40 % wt.) [33], 45°/0°/-45° oriented laminated jute fiber (**σ_{ut}** = 58.61 MPa, 30 % vol.) [15], and glass (**σ_{ut}** = 78.83 MPa, 60 % wt.) [34] fiber-reinforced polyester composites. Face masks are made of polypropylene sheets [6]. Polypropylene and polyester are hydrophobic and interact through non-polar covalent bonds [35]. In contrast, plant-based natural fibers contain cellulose, which is hydrophilic and interacts with unsaturated polyester through hydrogen bonds [36]. The covalent bond is stronger than the hydrogen bond [37]. This is one of the reasons the WFM-reinforced composite exhibits higher tensile strength than some of the NFRP composites. However, besides the bonding mechanism, the mechanical strength of composites depends on fiber characteristics, such as natural/synthetic, woven/nonwoven, long/short, weight/volume fraction, orientation, number of laminations, and fiber treatment, as well as the type of matrix, fiber strength, and fabrication method. Therefore, the tensile property of WFM-reinforced composites is less than banana/kenaf, jute, and glass fiber-reinforced composites. The tensile strength of unsaturated polyester and polypropylene sheets is 63 MPa [38] and 21 MPa [39], respectively. Therefore, the tensile strength of the WFM-reinforced polyester composite, 32.06 MPa, is logical and acceptable. This study reveals that WFM could be a suitable candidate for reinforcing polymer composites.

4.2. *Flexural strength (σ_b)*

Flexural load vs. Deflection curves of the crisscross, parallel, and shredded WFM-reinforced polyester composites are shown in Fig. 8(a), (b), and 8(c), respectively.

The flexural behavior of composites under transverse load differs slightly between crisscross, parallel, and shredded WFM-reinforced polyester composites. The flexural strength (**σ_b**) is evaluated based on equation (1) and found to be 41.13, 37.27, and 25.15 MPa for the crisscross, parallel orientations, and shredded WFM-reinforced polyester composites, respectively, as shown in Fig. 9 (a) and Table 1. The crisscross WFM-reinforced composite has the highest flexural strength since its tensile property is also superior to the parallel and shredded WFM-reinforced composites. The shredded WFM-reinforced composites have the lowest flexural strength because of insufficient fiber continuity within the matrix. The flexural strength of WFM-reinforced polyester composites is analogized to some natural fiber-reinforced polymer (NFRP) composites, as shown in Fig. 9(b).

Under flexural load, tensile stress develops in specimens, which plays a critical role in the failure of composites. Therefore, the flexural strength (**σ_b** = 41.13 MPa) of WFM-based polyester composites is much higher than the caryota [29], pineapple leaf [31],

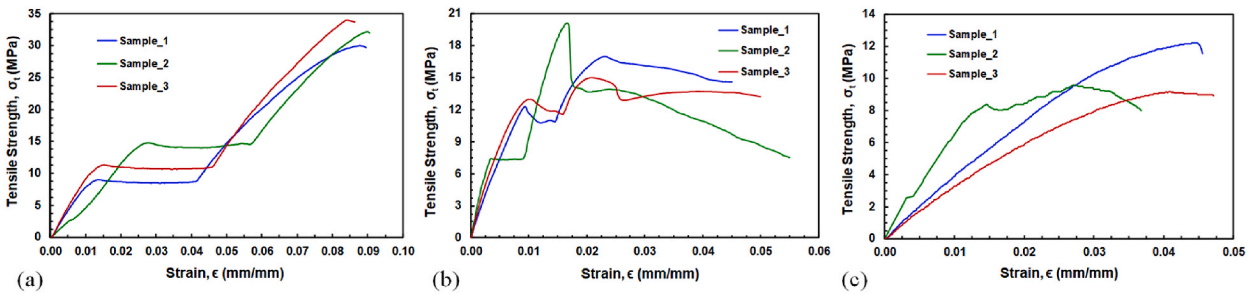

Fig. 6. Stress-strain curve of WFM-reinforced composites with (a) Crisscross and (b) Parallel patterns, and (c) Shredded WFM.

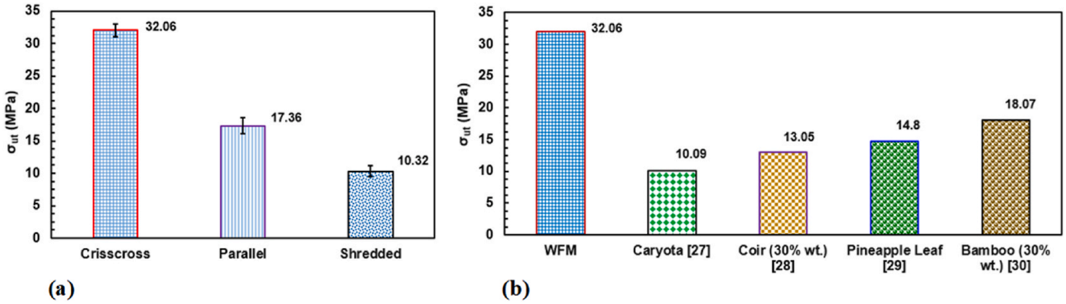

Fig. 7. (a) Ultimate tensile strength (σ_{ut}) of WFM-reinforced polyester composites and (b) Comparison with Natural fiber-reinforced composites.

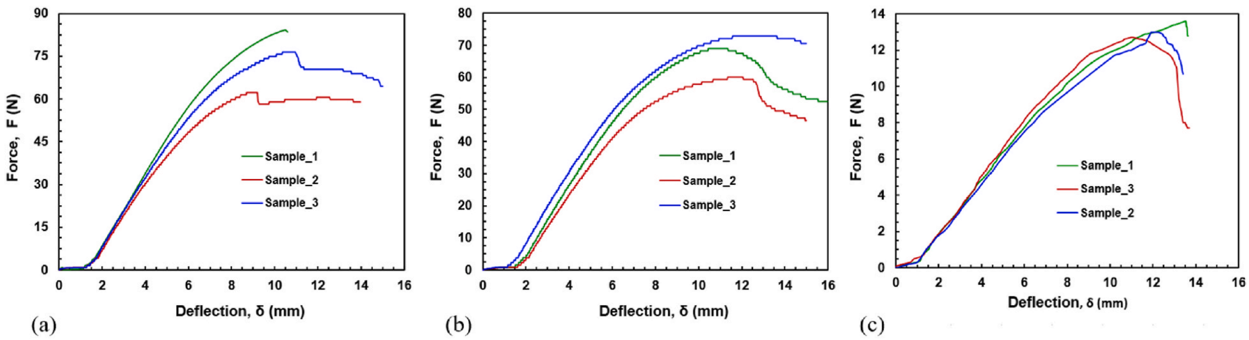

Fig. 8. Flexural load vs Deflection curve of WFM-reinforced composites with (a) Crisscross and (b) Parallel patterns, and (c) Shredded WFM.

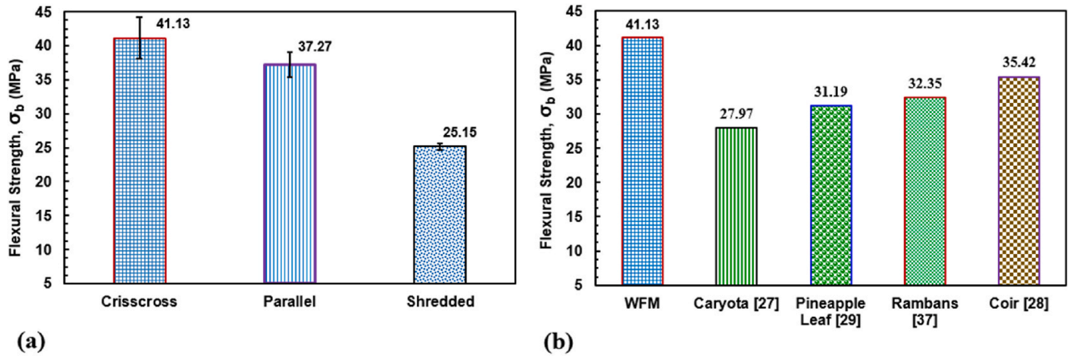

Fig. 9. (a) Flexural strength (σ_b) of WFM-reinforced polyester composites and (b) Comparison with Natural fiber-reinforced polymer composites.

rambans [40], and coir [30] fiber-reinforced polymer composites (Fig. 9). Since WFM-reinforced composites have a higher tensile property than those composites (Fig. 7). However, it is much less than the banana/kenaf woven (σ_b = 172.2 MPa, 40 % wt.) fiber-reinforced hybrid [33], 0°/90°/0° oriented laminated jute (σ_b = 145.6 MPa, 30 % vol.) [15], and glass (σ_b = 119.23 MPa, 60 % wt.) fiber-reinforced polyester composites [34]. Since the tensile strength of WFM-reinforced composites is less than the banna/kenaf, jute, and glass fiber-reinforced composites. This study reveals that WFM-reinforced polyester composites have suitable strength to resist bending concerning some NFRP composites, such as caryota, pineapple leaf, rambans, and coir.

4.3. Impact strength

The impact strength is found to be 0.023, 0.054, and 0.034 J/mm for the crisscross, parallel, and shredded WFM-reinforced polyester composites, respectively, as shown in Fig. 10(a) and Table 1. It is the highest of 0.054 J/mm for the parallel and the least of 0.023 J/mm for the crisscross WFM-reinforced composites. The impact load is imposed on the specimen in a direction transverse to its longitudinal axis, and stress also develops along the longitudinal axis. In parallel orientation, all layers of WFM are laid along the longitudinal direction of the specimen. In contrast, in crisscross orientation, only half of the layers of WFM are laid along the longitudinal direction. Furthermore, the crisscross WFM composite behaves like brittle materials, and the parallel one behaves like ductile materials and deforms rapidly before failing, as shown in Fig. 5. Therefore, parallel-orientation WFM composites absorb higher impact energy than the crisscross and shredded WFM-reinforced composites. The impact strength of WFM-reinforced polyester composites is compared with NFRP composites, as shown in Fig. 10(b).

The impact strength of WFM-based polyester composites is almost double that of bamboo [41], 29.27 % higher than jute [15], 9.28 % higher than alkali-silane-treated woven fan palm [42], and 8.1 % higher than the caryota [29] fiber-reinforced polymer composites, Fig. 10(b). However, it is lower than the banana/kenaf woven (W_i = 26 kJ/m2 ≈ 0.104 J/mm, 40 % wt.) fiber-reinforced [33] and glass (W_i = 6.5 J ≈ 1.3 J/mm, 60 % wt.) fiber-reinforced polyester composites [34]. This study reveals that WFM-reinforced composites are more suitable for sudden and intense impact loads than some NFRP composites.

4.4. Void content

The void content in composites is evaluated based on equations *(2)* and *(3)*. It is found to be 0.63 %, 0.78 %, and 1.14 % in the crisscross, parallel, and shredded WFM-reinforced composites, respectively. Void content is found the lowest in the crisscross WFM-reinforced composite due to the uniform flow of the resin within crisscross WFM layers. There is a lack of continuity of fibers in the shredded WFM-reinforced composite. Therefore, weak bonding and more voids are found in the shredded WFM-reinforced composite. Void content significantly affects the mechanical, thermal, fatigue, and electrical characteristics of composites. The lowest void content represents strong bonding and interaction between fibers and matrix and higher mechanical strengths of composites. Therefore, the tensile and flexural strengths of the crisscross WFM composite are found to be higher than the parallel and shredded WFM-reinforced composites (Figs. 7 and 9). It validates the void prediction as well as the appropriate evaluation of the tensile and flexural strengths of WFM-reinforced composites. However, based on the fabrication method, some voids in composites are unavoidable and difficult to minimize. In addition, WFM interacts with polyester matrix by covalent and natural fiber by hydrogen bond. The hydrogen bond is weaker than the covalent bond. Therefore, the void content in NFRP composites will be higher than the synthetic fiber-reinforced composites for an identical matrix, fiber volume fraction, and fiber characteristics. In this study, the maximum void content was found to be 1.14 %, which is less than the jute (3.43 %) [43] and betel nut stem (1.16 %) fiber-reinforced composites [24] and higher than the ramie and roselle (0.58 %) fiber-reinforced composites [43]. However, it is found within the industrial acceptable limit of 2 % of carbon-epoxy composites [44]. This study reveals the strong bonding of WFM to the unsaturated polyester, and it is a suitable candidate for reinforcing polymer composites.

4.5. Morphological analysis

The magnified (60 ×) images of the tensile fractured surface of WFM-reinforced composites are captured by the Field Emission Scanning Electronic Microscope (FE-SEM) to investigate the interaction between WFM and polyester matrix. Voids, micro-cracks, fiber agglomeration, and bonding between WFM and polyester in the crisscross, parallel pattern, and shredded WFM-reinforced composites are shown in Fig. 11(a), (b), and 11(c), respectively.

Voids, micro-cracks, fiber agglomeration, fiber pullout cavities, bonding, protruded fibers, WFM layers, and smooth polyester surfaces are identified in FE-SEM images, as shown in Fig. 11. The crisscross WFM-reinforced polyester composite exhibits strong bonding between WFM and polyester, fewer voids, and micro-cracks than the parallel and shredded WFM-reinforced composites, as shown in Fig. 11(a). Therefore, the tensile and flexural strengths are observed higher in the crisscross WFM-reinforced composite, shown in Table 1. In the parallel WFM-reinforced composite, voids, micro-cracks, fiber agglomeration, and protruded fibers are observed to be higher than in the crisscross WFM-reinforced composite, as shown in Fig. 11(b), which leads to lower tensile strength than the crisscross WFM-reinforced composite. However, due to parallel layers of WFM in the polyester resin, the parallel WFM-reinforced composite provides higher resistance against impact loads. Therefore, impact strength is higher in the parallel WFM than in the crisscross WFM-reinforced composite (Table 1). The shredded WFM-reinforced composite exhibits more voids, cracks, fiber pullout, fiber agglomeration, and protruded fibers, as shown in Fig. 11 (c). Besides, there is a lack of continuity of fibers in the shredded WFM-reinforced composite. Therefore, its mechanical strength is much lower than the crisscross and parallel WFM-reinforced

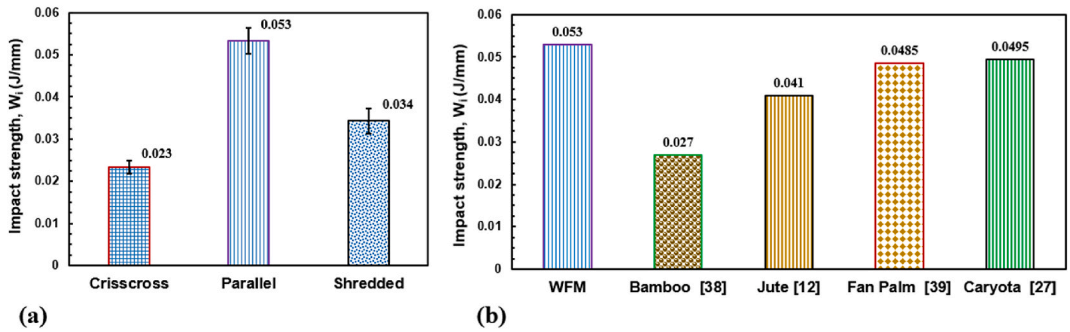

Fig. 10. (a) Impact strength of WFM-reinforced polyester composites and (b) Comparison of impact strength with natural fiber-reinforced polymer composites.

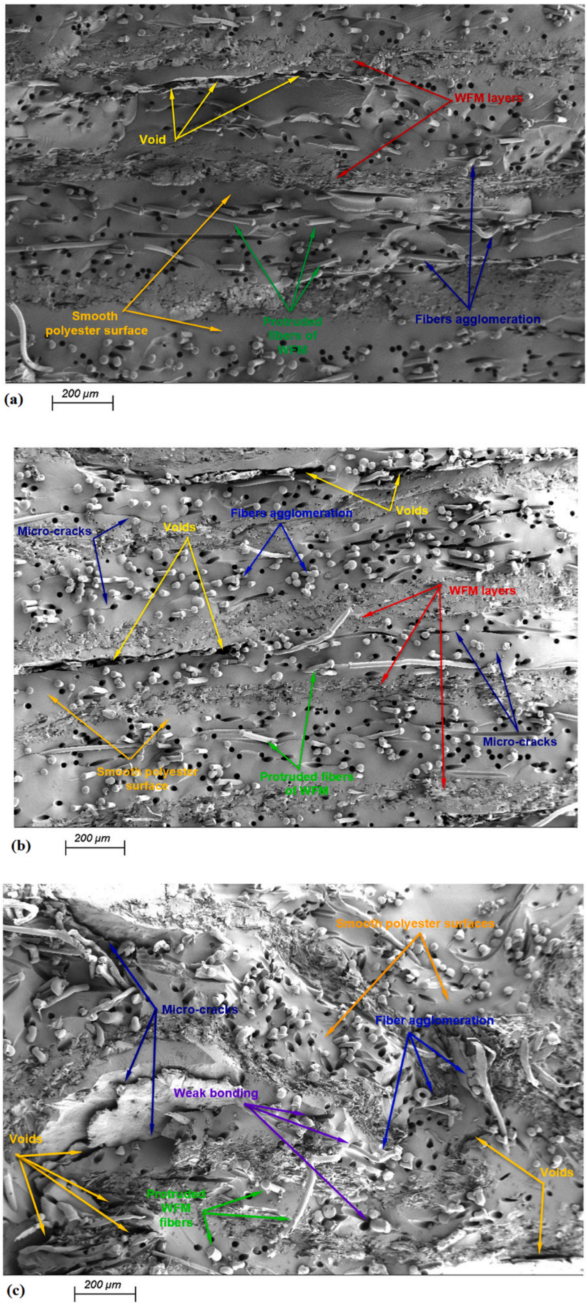

Fig. 11. FE-SEM image (60 × magnified) of tensile fractured specimen of (a) Crisscross and (b) Parallel patterns, and (c) Shredded WFM-reinforced polyester composites.

composites. In addition, void contents are 0.63 %, 0.78 %, and 1.14 % in the crisscross, parallel, and shredded WFM-reinforced composites, respectively. The lowest and highest void contents indicate more robust and weaker bonding and interaction between fibers and resin , respectively. Polypropylene sheets of face masks and unsaturated polyester interact through stronger covalent bonds, whereas plant-based natural fibers interact through weaker hydrogen bonds [36]. Therefore, WFM-reinforced composites exhibit superior tensile property than some NFRP composites. FE-SEM images agree with the tensile and flexural strengths and void prediction of WFM-reinforced composites, which supports the appropriateness of this study and the validity of mechanical property prediction.

5. Conclusions

This study investigated the feasibility of recycling waste face masks (WFM) into composites. Three distinct composites are developed with a 20 % (wt.) fiber loading in a compression molding machine employing unsaturated polyester and WFM in crisscross and parallel patterns and shredded ones. Their mechanical attributes, like tensile, flexural, and impact strengths, and void contents, are predicted using ASTM guidelines. The maximum tensile and flexural strengths and the lowest void contents are found 32.06 and 41.13 MPa and 0.063 %, respectively, in the crisscross WFM-reinforced composites. The maximum impact strength of 0.053 J/mm is observed in the parallel WFM-reinforced composite. It reveals that the mechanical strengths of WFM-reinforced composites vary with the orientation of WFM. Tensile and flexural strengths of WFM-reinforced composites are compared to NFRP (natural fiber-reinforced polymer) composites and found higher than the caryota, coir, pineapple leaf, bamboo, and rambans fiber-reinforced polyester composites (Figs. 7 and 9). Impact strength is also superior to bamboo, jute, fan palm, and caryota (Fig. 10) and lower than the woven banana/kenaf and glass fiber-reinforced polyester composites. WFM interacts with polyester through covalent bonds. In contrast, natural fibers interact through relatively weak hydrogen bonds, which deliver higher mechanical strength in WFM-reinforced composites than some NFRP composites. The investigation of FE-SEM (Field Emission Scanning Electronic Microscope) images of tensile fractured specimens discloses morphological properties of WFM composites and strong bonding of WFM with the polyester, which agrees with mechanical characteristics and void prediction of composites. It reveals the potential of recycling WFM into composites. The moderate or desirable size of WFM composite boards or panels can be made by stitching multiple WFMs together after treatment or using shredded ones. It can be implemented in automotive interior panels, bumpers, floors, trunk mats, and engine covers, and interior partitions of trains, buses, boats, and homes. WFM can be collected conveniently from hospitals, clinics, homes, schools, offices, etc., at a tiny cost. Suitable disposal and collection methods for WFM can be implemented, such as using separate containers or trash bins to dispose of and wearing personal protection equipment (PPE) during collection. In addition, there is no cost for WFM. Therefore, it will be a suitable candidate for reinforced polymer composites. It will help to reduce the insinuation of microplastics into aquatic and living organisms via food chains, as well as water, soil, and air pollution. Recycling WFM into composites will significantly impact the environment and provide economic benefits. It will promote healthy ecosystems, develop a circular economy, and attain sustainable development goals. This study also opens the scope to enhance the mechanical features of WFM-based polymer composites. There will be no issue with the economic feasibility and scalability of recycling WFM into composites since it can also contribute to fabricating hybrid composites with natural and synthetic fibers as a low-cost constituent.

Data availability

Data of this study is available on request.

CRediT authorship contribution statement

Fazlar Rahman: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Dipta Chandra Dey:** Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis. **Tanvir Mahabub Tamim:** Writing – original draft, Visualization, Validation, Software, Formal analysis, Data curation. **Preetom Ahamad Shoykot:** Writing – original draft, Visualization, Validation, Software, Formal analysis, Data curation. **M.A. Gafur:** Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

No Conflict of Interest.

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