The Influence Of Recycled ABS Weight Fraction And One-Month Natural Weathering On The Mechanical And Physical Properties Of Acrylonitrile Butadiene Styrene (ABS)

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Acrylonitrile butadiene styrene (ABS) is widely used in various industries, generating significant post-industrial waste. Mechanical recycling and outdoor exposure are both known to degrade ABS; however, their combined effects under natural conditions remain insufficiently understood. This study investigates the influence of reprocessed ABS (rABS) content ($0 - 100\%$) and short-term natural weathering (one month) on the physical and mechanical behaviour of injection-moulded ABS. A total of 160 specimens, representing five material compositions and two exposure conditions (control and weathered), were characterised through density measurement, tensile, flexural, and impact testing, complemented by macro photography. The density remained relatively stable $\left(1.05 - 1.06\ \mathrm{g/cm^3}\right)$ across all conditions, with a slight increase observed at higher rABS contents. Under control conditions, tensile strength ranged from 41.2 to 44.9 MPa and flexural strength from 66.3 to 73.4 MPa , values approximately $8 - 12\%$ lower than the manufacturer's nominal datasheet values, indicating acceptable agreement with commercial-grade ABS. Following short-term natural weathering, tensile strength decreased by up to 23.6%, while strain at break was reduced by approximately $86 - 89\%$, confirming severe embrittlement. Flexural strength exhibited the most pronounced degradation, with reductions of approximately $88.9 - 92.3\%$, highlighting the high sensitivity of bending resistance to early-stage environmental exposure. In contrast, impact strength showed comparatively moderate variations (within -17.3% to $+1.7\%$), suggesting that dynamic fracture resistance is less sensitive than quasi-static bending during short-term outdoor exposure. These findings demonstrate that recycled ABS blends, particularly at higher recycled fractions, are more susceptible to embrittlement under natural weathering conditions.

Keywords: Recycled ABS; Natural Weathering; Mechanical Properties; Flexural Strength; Impact Toughness; Embrittlement

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1. Introduction

The global production of plastics has increased dramatically since the mid-20th century, with synthetic polymers such as acrylonitrile butadiene styrene (ABS) becoming essential in various industries including automotive, electronics, and consumer goods due to their excellent mechanical strength, processability, and cost-effectiveness [1–3]. However, the petroleum-based nature and high durability of ABS contribute significantly to plastic waste accumulation, posing serious environmental challenges [4–6]. Mechanical recycling has emerged as a promising approach to address this issue by reducing the dependence on virgin raw materials and minimizing waste generation in accordance with the circular economy principles [7, 8].

Despite its advantages, mechanical recycling exposes ABS to multiple heating and shearing cycles that can cause thermo-mechanical degradation, chain scission, and molecular weight reduction, ultimately deteriorating its mechanical performance [9–11]. In addition, ABS products, especially those used outdoors, are vulnerable to environmental degradation due to ultraviolet (UV) radiation, humidity, and temperature fluctuations [12, 13]. Previous studies have reported that accelerated weathering can decrease the tensile strength of ABS by up to 68% [14, 15]. Although the effects of recycling [16, 17] and weathering [12] on ABS have been studied separately, limited research has explored their combined influence under actual outdoor exposure conditions. Understanding this interaction is crucial for developing reliable applications of recycled ABS in environments exposed to natural weathering.

To ensure systematic evaluation and comparability with existing literature, the mixing ratios of virgin ABS(vABS) to reprocessed ABS(rABS) were selected as 100:0, 75:25, 50:50, 25:75, and 0:100 by weight. These ratios are widely adopted as benchmark compositions in ABS recycling studies because they span the full continuum from pure virgin material to fully recycled content, enabling clear mapping of property evolution as a function of recycled fraction [9, 10, 18]. Previous studies consistently report that intermediate blends, particularly in the range of $25-50\%$ recycled content, often provide a practical compromise between mechanical property retention and sustainability objectives, while higher recycled fractions ($\geq 75\%$) are commonly used to assess the upper limits of degradation and recyclability [19, 20].

The virgin and recycled ABS materials used in this study were both obtained from the injection moulding units of PT. ATMI IGI, Surakarta, Indonesia. This industrial source ensures controlled and consistent material quality, as both the virgin ABS (LG Chem HI121H) and the reprocessed ABS originated from the same production stream. This provides not only a consistent basis for evaluating the effects of reprocessing and weathering, but also a strong industrial relevance since the regrinding and reuse of sprues, runners, and non-conforming (NG) parts are common practices in manufacturing to improve efficiency and reduce waste.

Accordingly, this study aims to evaluate the combined effects of recycled ABS content ($0-100\%$) and one-month natural weathering on the mechanical, physical, and thermal properties of ABS. The results are expected to provide valuable insights for improving the sustainable use of recycled ABS materials in outdoor and semi-outdoor applications.

2. Materials and methods

2.1. Materials

The materials used in this study consisted of virgin ABS (vABS) and reprocessed ABS (rABS). Both materials were obtained from the injection moulding unit of PT. ATMI IGI, Surakarta, Indonesia. The virgin ABS used was LG Chem HI121H, a commercial high-impact grade ABS was supplied in pellet form, which served as the baseline material. The reprocessed ABS was produced from post-industrial scraps such as sprues, runners, and non-conforming (NG) parts collected from the same injection unit. These waste parts were first ground into flakes using a flake-type plastic granulator (SDP 400 model) and then re-pelletized using a single-screw extruder (COLLIN Teach Line E20) to ensure a homogeneous material feed for subsequent injection moulding. For reference, the nominal baseline properties of the virgin ABS grade, as reported in the manufacturer's datasheet, are summarized in Table 1.

2.2. Specimen Preparation

Five material variants were prepared with different weight fractions of virgin ABS (vABS) and reprocessed ABS (rABS). For each variant, 16 specimens were fabricated and allocated as follows: 5 specimens for tensile testing, 5 specimens for flexural testing, 5 specimens for impact testing, and 1 specimen as a backup. The specimen codes and distribution for both treatment conditions are given in Table 2. Thus, each treatment condition (C0 $=$ control, C 1 $=$ 1-month weathering) consisted of 80 specimens (5 variants $\times$16 specimens), and the total number of specimens prepared for the study was 160 .

Materials were dried at $80-90°$C for $15-20$ minutes, mixed, and compounded into granules using a COLLIN Teach Line Extruder E20. Test specimens were produced by injection moulding on a FANUC Roboshot S-2000i 100A according to ISO 527-2 (dog-bone for tensile).

For the flexural and impact tests, the dog-bone specimens were trimmed to the required length using a precision hand shear, and notches were introduced using a V-notch cutting machine. This ensured that the specimen dimensions complied with ASTM D790 (flexural test) and ASTM D256 (impact test) standards. The flexural test specimens had a nominal thickness of 4 mm, identical to the tensile specimens, and were prepared in accordance with ASTM D790 by applying the appropriate span-to-thickness ratio.

The specimens were grouped based on their weathering exposure conditions as follows:

1. C0 (Control): Specimens tested without any weathering exposure and stored under controlled indoor

Table 1. Baseline properties of virgin ABS HI121H based on the manufacturer's datasheet

Property	Typical value	Test standard
Density (specific gravity)	1.04	ASTM D792
Tensile strength at yield	$\sim$ 51MPa	ASTM D638
Tensile modulus	$\sim$ 2.21GPa	ASTM D638
Elongation at break	$\sim$ 30%	ASTM D638
Flexural strength	$\sim$ 78.4MPa	ASTM D790
Flexural modulus	$\sim$ 2.75GPa	ASTM D790
Izod impact strength (notched, 3.2 mm, 23°C)	$\sim$ 22.5 kJ/m^2	ASTM D256
Glass transition temperature, Tg	$\sim$ 105°C	-

Table 2. The material variants and nomenclature codes for both conditions.

No.	Treatment Condition	Composition (vABS : rABS)	Code
1	Control (no exposure)	100% vABS 75% vABS : 25% rABS	W25C0
		50% vABS : 50% rABS	W50C0
		25% vABS : 75% rABS	W75C0
		100%rABS	WC0
2	1-month weathering exposure	100% vABS : VC0	VC1
		75% vABS : 25% rABS	W25C1
		50% vABS : 50% rABS	W50C1
		25% vABS : 75% rABS	W75C1
		100% rABS	WC1

laboratory conditions (23 ± 2°C, 50 ± 5%RH) without direct UV exposure.

2. C1 (1-month exposure): Specimens were exposed to natural outdoor weathering for one month (end on 10 August 2025). The exposure site was the climatology laboratory field of the Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Indonesia (Coordinates: 7°37′47.6724″ S, 110°56′52.5876″ E). Specimens were mounted on a 45° angled rack facing east, in accordance with ASTM D1435.

To support reproducibility, a summary of the recorded weather parameters (temperature, humidity, and rainfall) during the exposure period, the data are provided in Table 4. It should be noted that these data represent a summarized snapshot of the outdoor exposure conditions rather than a complete or continuous climatic record. Within this context, the specimens were exposed to typical tropical outdoor conditions, with average daily temperatures ranging from $26 - 33$°C, relative humidity of approximately $70 - 85$%, and total rainfall of about 120 mm during the exposure month.

2.3. Characterization Techniques

The physical and mechanical properties of the ABS specimens were characterized using the following methods:

Macro photography was performed using an Olympus SZX7 stereo microscope to document visual changes in surface morphology and fracture patterns before and after weathering exposure and mechanical testing. Specimens were systematically examined for defects including voids, sink marks, weld lines, surface cracks, and color variations.

Fig. 1. Outdoor weathering exposure of ABS specimens at a 45° inclination according to ASTM D1435.

Density measurements were conducted using a Shinko Denshi DME-220E density analyzer operating on the Archimedes principle (ASTM D792). The instrument fea-

Table 3. Specimen preparation process from molding to final test specimens.

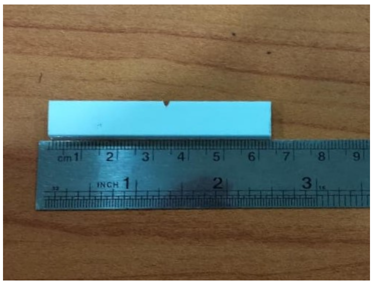
Step	Description	Standard Reference	Specimen Form	Illustration / Photo
1	Injection molding of dog-bone tensile specimens using FANUC Roboshot S-2000i 100A	ISO 527-2 (tensile specimen)	Dogbone (asmolded)	
2	Trimmed to flexural specimen size using hand shear	ASTM D790	Rectangular bar	
3	Trimmed and notched for impact testing using V-notch machine	ASTM D256	Notched bar	

Table 4. Summary of recorded weather parameters during the outdoor exposure period.

Month	Rainfall (mm)	Rainy Days (days)	Relative Humidity (%)	Sunshine Duration (%)	Air Temp. (°C)
July	4.0	2.0	78.1	80.5	29.1
Aug.	11.1	8.0	79.2	86.1	29.0

tures a maximum capacity of 220 g with 0.01 g/cm^3 resolution, employing tuning fork vibration technology for precise solid density determination. Five replicates per variant were tested in distilled water at room temperature $(23 \pm 2°C)$.

Tensile and flexural properties were evaluated using a Zwick/Roell Z020 Universal Testing Machine with 20 kN capacity and servo-motor drive system. Tensile tests followed ISO 527-2 at 5 mm/ min crosshead speed, while three-point bending tests complied with ASTM D790 at 2 mm/min with 16 : 1 span-to-depth ratio. Data acquisition and analysis were performed using the testXpert II software, with five specimens tested per variant.

Impact toughness was determined using a Zwick/Roell HIT 5.5p instrumented impact tester according to ASTM D256. The system features a 5.5 J maximum energy capacity and digital sensor technology for precise energy measurement. Notched specimens were tested at room temperature $(23 \pm 2°C)$, with five replicates per variant.

All mechanical testing was performed under controlled laboratory conditions $(23 \pm 2°C, 50 \pm 5\%RH)$. Results are reported as mean ± standard deviation, with statistical significance assessed using one-way ANOVA and Tukey's post-hoc test $(p < 0.05)$.

3. Results and discussion

3.1. Macro Photography

Macro photography was used to qualitatively evaluate the fracture surfaces of tensile, flexural, and impact specimens. The visual differences between the control (C0) and the weathered (C1) groups clearly indicate a transition from ductile to brittle behaviour. As shown in Fig. 2, tensile specimens in the control condition (VC0-WC0) exhibited necking and fibrillated tearing typical of ductile fracture, whereas weathered specimens (VC1-WC1) displayed granular, rock-like fracture surfaces characteristic of brittle failure [21].

Although the W75C1 fracture surface appears relatively flat compared to other weathered variants, fracture did occur. The smoother morphology may be associated with brittle crack propagation under reduced plastic deformation following weathering.

Similar morphological degradation was also evident in the flexural and impact specimens (Figs. 3 to 5), where smooth fracture planes in unweathered samples became rougher and more irregular after exposure.

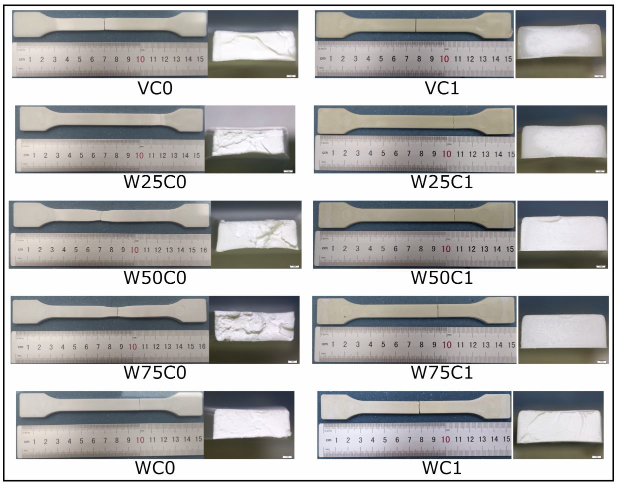
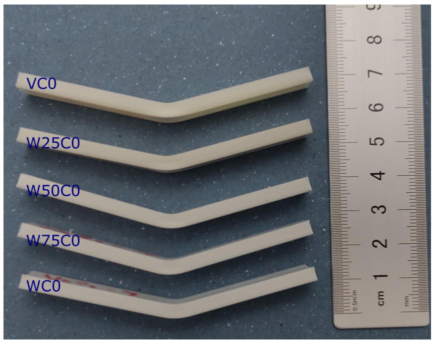
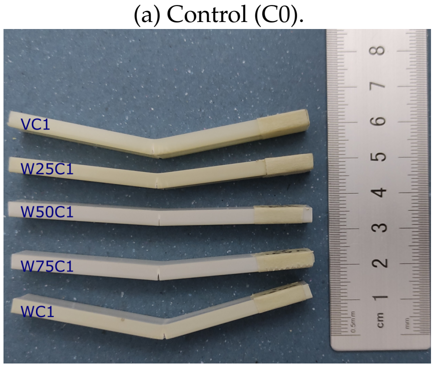


Fig. 2. Macro images of tensile test specimens (VC0, W25C0, W50C0, W75C0, WC0 and VC1, W25C1, W50C1, W75C1, WC1).

This morphological evolution supports the assumption that outdoor weathering promotes surface embrittlement through oxidation and UV-induced chain scission. Comparable ductile-to-brittle transitions have been reported by Ramesh et al. [14] after accelerated weathering of ABS, confirming that even short-term tropical exposure can trigger similar degradation. These visual observations provide a qualitative foundation for the subsequent quantitative mechanical results, as the fracture morphology trends correspond closely with the changes in tensile, flexural, and impact properties are discussed below.



(a) Control (C0).



(b) Weathered (C1).

Fig. 3. Macro images of flexural test specimens.

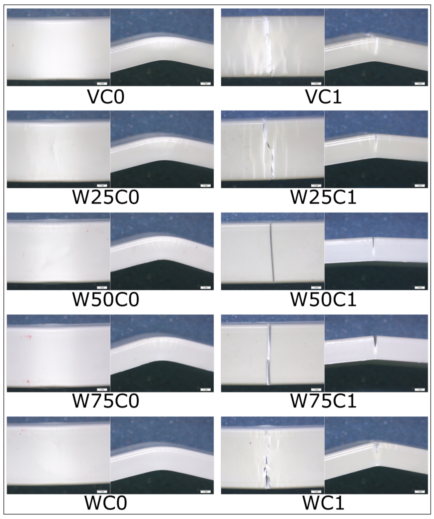


Fig. 4. Macro images of flexural test specimens at the bent/fracture region.

It is important to clarify that the observed ductile-to-brittle transition in the weathered specimens is not associated with the ductile-brittle transition temperature (DBTT) of ABS. According to established literature, the DBTT of virgin ABS is typically reported in the range of approximately -40 to -20°C, which is far below both the natural weathering temperature experienced in this study ($26-33^{\circ}$C) and the mechanical testing temperature ($23 \pm 2^{\circ}$C) [2]. Therefore, under the present testing conditions, ABS is expected to remain in a ductile regime from a purely thermal perspective. The brittle fracture morphology observed after weathering should instead be attributed to environmental degradation mechanisms, particularly photooxidation and oxidative chain scission in the butadiene-rich phase, which progressively reduce molecular mobility and impact resistance without requiring a transition across the intrinsic DBTT [10, 14]. Similar embrittlement phenomena at ambient temperature have been widely reported for ABS subjected to thermal or UV aging, supporting the interpretation that the mechanical degradation observed in this study is driven by weathering-induced microstructural damage rather than temperature-induced brittle transition.

3.2. Density

The density values of all material variants under both control (C0) and weathered (C1) conditions are presented in Fig. 6. The results remained within $1.05-1.06\ \mathrm{g/cm^3}$, consistent with reported values for ABS [2]. A slight increase in density was observed in higher-rABS compositions (W75 and W), which may be attributed to residual inorganic contaminants or oxidation-induced densification during reprocessing. Cress et al. [9] observed similar behaviour, linking it to microstructural rearrangement and localized cross-linking in recycled polymers.

Although the variation is minor, the gradual increase in density correlates with the stiffening effect discussed later in the tensile and flexural data. This suggests that mild oxidation and cross-linking during weathering may have contributed to denser surface layers, influencing subsequent mechanical responses.

3.3. Mechanical Properties

1. Tensile Properties.

   The tensile performance of all specimens is summarised in Fig. 7, and the representative stress-strain curves are shown in Fig. 8. Under the control condition (C0), the ultimate tensile strength decreased gradually with increasing recycled content, from 44.893 MPa for VC0 to 41.243 MPa for WC0. This trend is consistent with molecular chain scission and molecular weight reduction during repeated reprocessing cycles, as reported by Bai et al. [10].

   For clarity, the average tensile strength, strain at break, and tensile modulus values for all compositions are summarised in Table 5.

   After one month of natural weathering (C1), tensile strength exhibited moderate reductions for most compositions. The decrease was approximately 19.3% for VC1, 17.0% for W25C1, 23.6% for W50C1, and 13.4% for W75C1. Interestingly, WC1 showed a slight increase of 3.2%, indicating a possible surface stiffening effect. Similar temporary hardening behaviour has been reported following thermal or environmental exposure due to oxidative cross-linking within the butadiene phase [10].

   In contrast, strain at break showed a drastic reduction after weathering, decreasing from 7.6-15.1% under control conditions to only 1.4-2.6% after exposure. This corresponds to reductions of approximately 86-89%, confirming severe embrittlement despite the relatively moderate changes in tensile strength.

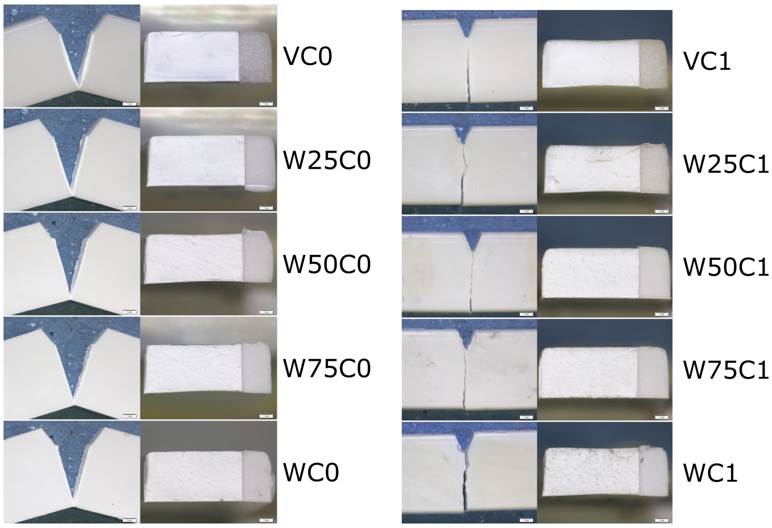
   The tensile modulus remained relatively stable across all compositions, ranging from approximately 2491 to 2657 MPa , suggesting that short-term natural weathering primarily affected ductility and fracture behaviour rather than the initial elastic stiffness of the material.

2. Flexural Properties

   The flexural results, illustrated in Figs. 9 and 10, reveal a markedly higher sensitivity to natural weathering compared to tensile strength. Under control conditions (C0), flexural strength ranged between $66.3-73.4$MPa, with W50C0 exhibiting the highest value (73.4 MPa), while WC0 showed the lowest.

   After one month of natural weathering (C1), flexural strength decreased drastically across all compositions. The reductions reached approximately 90.6% for VC1, 90.7% for W25C1, 92.3% for W50C1, 91.0% for W75C1, and 88.9% for WC1. This substantial degradation indicates that bending resistance is highly vulnerable to early-stage environmental exposure.

   Such pronounced reductions may be attributed to surface oxidation and microcrack initiation under tensile-compressive stress gradients during bending. Similar oxidative degradation mechanisms in aged ABS systems have been reported by Ramesh et al. [14], while crack propagation behaviour under brittle conditions has been discussed by Milovanovic et al. [22]. The drastic loss in flexural performance suggests that surface-initiated damage plays a dominant role during bending, where tensile stresses amplify crack growth more readily than in uniaxial tensile loading.



(a) Control (C0). (b) Weathered (C1).

Fig. 5. Macro images of impact test specimens.

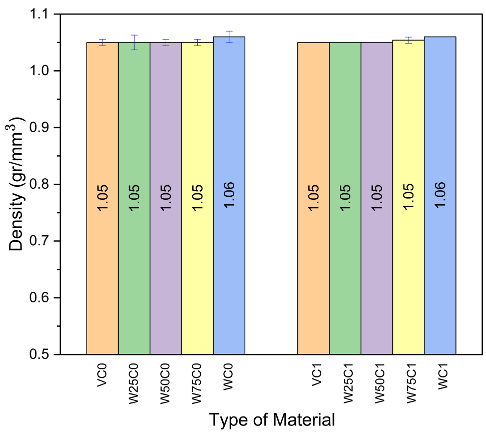


Fig. 6. Density of ABS variants under control (C0) and 1-month natural weathering (C1) conditions (mean ± SD, n = 5). Error bars represent standard deviation.

3. Impact Strength (Izod) The impact toughness results (Fig. 11) exhibit a different sensitivity pattern compared to tensile ductility and flexural strength. Under control conditions (C0), W25C0 demonstrated the highest impact strength (18.01 kJ/m^2), representing an increase of approximately 22.2% compared to virgin ABS (VC0, 14.74 kJ/m^2). This suggests that a moderate recycled fraction may enhance energy absorption capability, possibly due to microstructural heterogeneity that promotes stress redistribution.

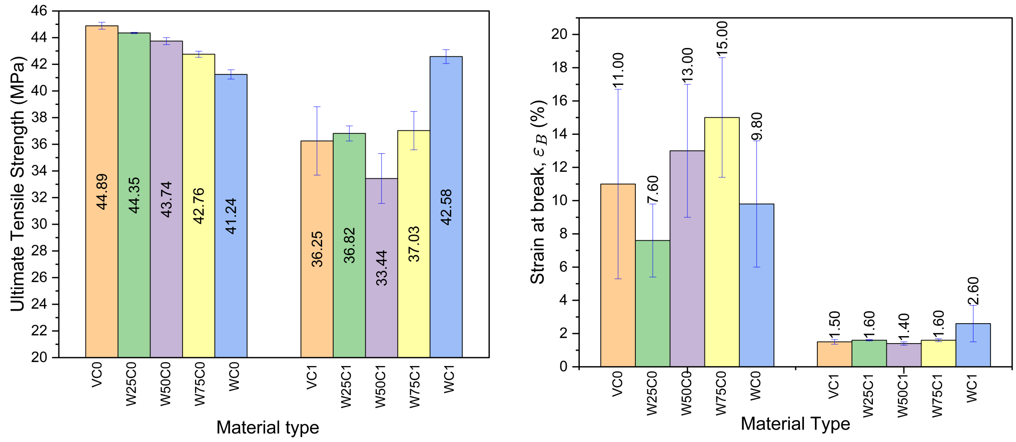
After one month of natural weathering (C1), the reduction in impact strength was relatively limited. The decreases were approximately 7.2% for VC1, 17.3% for W25C1, and 15.2% for W75C1, while W50C1 exhibited only a minor reduction (1.1%) and WC1 showed a slight increase (1.7%). Compared with the drastic reductions observed in flexural strength and strain at break, the impact performance remained comparatively stable during short-term exposure.

Previous studies have reported decreased impact energy in aged ABS systems under environmental conditioning [12]. However, the present results indicate that short-term natural weathering induces only moderate changes in dynamic fracture resistance, suggesting that impact performance may be less sensitive than quasi-static bending behaviour during early-stage degradation.

3.4. Synthesis of Results

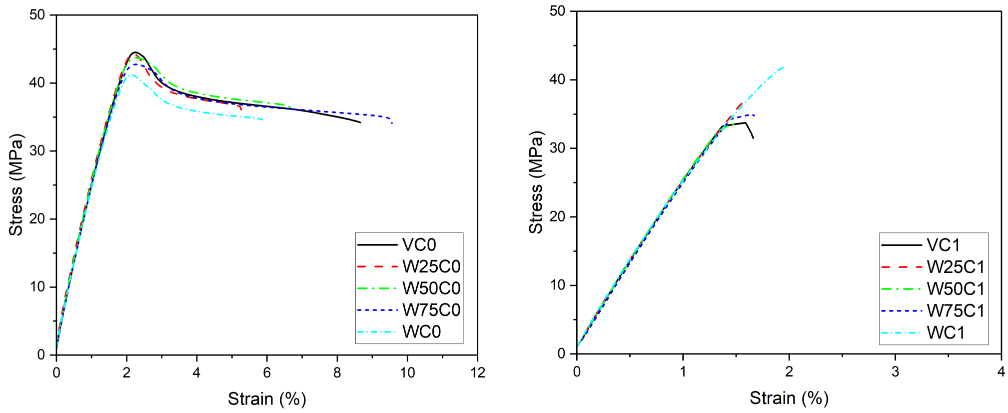
The combined interpretation of all results presented throughout Tables 1 to 5 and Figs. 2 to 11 reveals a coherent and quantitatively differentiated pattern of degradation. Macro observations confirm the ductile-to-brittle transition; density data indicate subtle but meaningful structural compaction; and mechanical tests quantitatively verify the loss of toughness and elasticity.

Quantitatively, natural weathering produced distinct degradation magnitudes depending on the mechanical loading mode. Tensile strength decreased by up to 23.6% (W50C1), while strain at break exhibited a drastic reduction of approximately 86 − 89% across all compositions, confirming severe embrittlement despite moderate changes in ultimate strength. Flexural strength showed the most pronounced sensitivity, with reductions ranging from approxi-



(a) Ultimate tensile strength (UTS). (b) Strain at break.

Fig. 7. Effect of recycled ABS content and one-month natural weathering on ultimate tensile strength and strain at break. Error bars indicate standard deviation (n = 5). For some variants, the error bars are smaller than the marker size due to minimal variation among replicates.



(a) Control (C0). (b) Weathered (C1).

Fig. 8. Stress–strain curves of ABS variants.

Table 5. Summary of average tensile strength, strain at break, and tensile modulus of ABS blends under control (C0) and one-month natural weathering (C1) conditions ($n = 5$).

Sample	Tensile Strength (MPa)	Strain at Break (%)	Tensile Modulus (MPa)
VC0	44.9	11.2	2559.9
W25C0	44.4	7.6	2656.7
W50C0	43.7	13.0	2627.0
W75C0	42.8	15.1	2578.1
WC0	41.2	9.8	2582.9
VC1	36.3	1.5	2617.7
W25C1	36.8	1.6	2637.8
W50C1	33.4	1.4	2617.4
W75C1	37.0	1.6	2491.4
WC1	42.6	2.6	2654.7

mately 88.9% to 92.3%, indicating that bending resistance is highly vulnerable to early-stage surface degradation. In contrast, impact strength displayed comparatively moderate variations (from -17.3% to $+1.7\%$), suggesting that dynamic fracture resistance is less sensitive than quasi-static bending under short-term outdoor exposure.

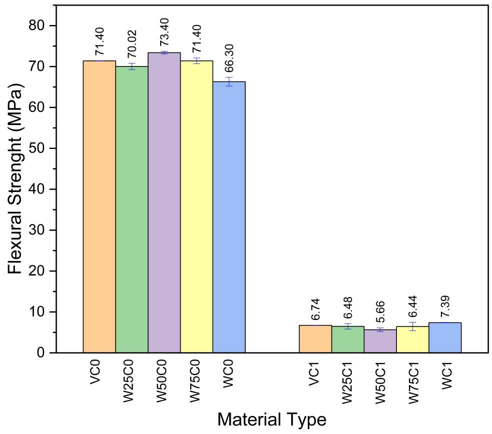
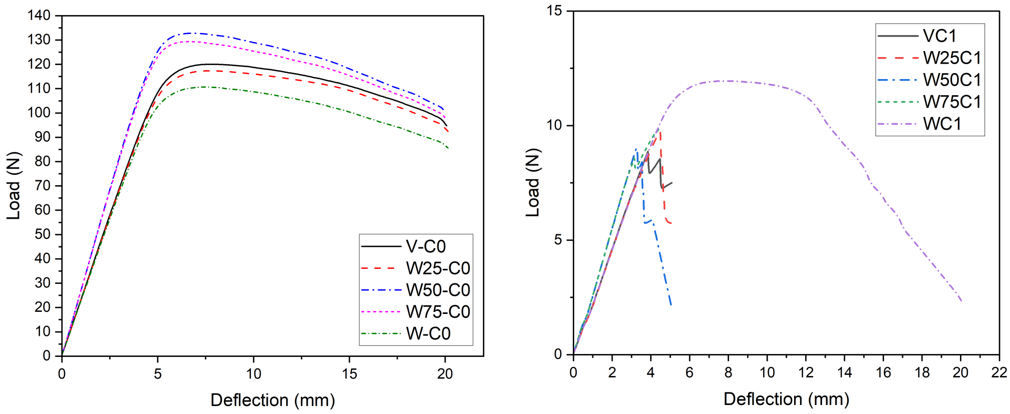


Fig. 9. Effect of recycled ABS content and one-month natural weathering on the flexural strength of ABS variants. Error bars represent standard deviation (n = 5).



(a) Control (C0). (b) Weathered (C1).

Fig. 10. Load–deflection curves of ABS variants.

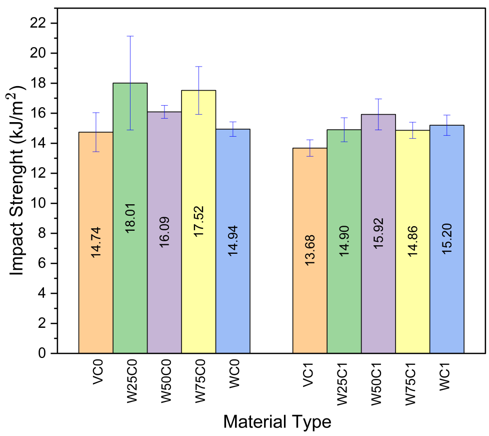


Fig. 11. Effect of recycled ABS content and one-month natural weathering on impact strength of ABS variants. Error bars indicate standard deviation (n = 5).

When benchmarked against the manufacturer's datasheet values (Fig. 11), the experimental tensile strength of virgin ABS (44.9 MPa) was approximately 12% lower than the nominal 51 MPa, while the control flexural strength (approximately $70 - 73$MPa) was around 8-12% lower than the reported 78.4 MPa. Such deviations are considered reasonable given differences in processing parameters, specimen preparation, and testing configurations. Importantly, the relative degradation trends observed across recycled compositions remain internally consistent, supporting the validity and reliability of the experimental findings.

The minor increase in density and stiffness observed in weathered and high-rABS specimens supports the hypothesis of surface oxidation and partial cross-linking [9, 10, 14]. Collectively, these findings demonstrate that short-term natural weathering induces substantial mechanical deterioration, particularly under bending, while recycled content amplifies susceptibility to embrittlement within the investigated exposure duration.

It is acknowledged that the absence of quantified UV dose data limits direct quantitative comparison of the present results with accelerated weathering studies or outdoor exposures conducted under different climatic conditions. Accordingly, the findings of this study should be interpreted within the framework of early-stage natural weathering under tropical conditions rather than dose-controlled degradation metrics.

4. Conclusion

This study examined the combined influence of recycled ABS content and one-month natural weather exposure on the mechanical performance of injection-moulded ABS blends. The results demonstrate that short-term outdoor weathering induces mechanically differentiated degradation behaviour depending on the loading mode.

Tensile strength decreased by up to 23.6%, while strain at break exhibited a drastic reduction of approximately $86 - 89\%$, indicating severe embrittlement across all compositions. Flexural strength showed the most pronounced deterioration, with reductions ranging from approximately 88.9% to 92.3%, highlighting the high sensitivity of bending resistance to early-stage surface degradation. In contrast, impact strength exhibited comparatively moderate variations (within -17.3% to $+1.7\%$), suggesting that dynamic fracture resistance is less sensitive than quasi-static bending during short-term exposure.

Blends containing 25-50% recycled ABS maintained impact performance comparable to virgin ABS under control conditions; however, substantial losses in ductility and flexural capacity were observed after weathering. At higher recycled content, the susceptibility to embrittlement became more evident, indicating limitations for applications involving sustained outdoor exposure or bending-dominated loading.

Within the investigated exposure duration, moderate recycled fractions may still be considered for non-critical or short-term outdoor applications, provided that bending stresses are limited. Nevertheless, the present findings are restricted to early-stage natural weathering under tropical conditions, and extended exposure durations or accelerated aging protocols are necessary to comprehensively assess long-term durability.

Acknowledgment

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References

[1] M. A. A. AlMaadeed, D. Ponnamma, and A. A. El-Samak. “Chapter 1 - Polymers to improve the world and lifestyle: physical, mechanical, and chemical needs”. In: *Polymer Science and Innovative Applications*. Ed. by M. A. A. AlMaadeed, D. Ponnamma, and M. A. Carignano. Elsevier, 2020, 1–19. DOI: 10.1016/B978-0-12-816808-0.00001-9.

[2] D. Li and S. Wang. “Acrylonitrile–Butadiene–Styrene (ABS) Polymers”. In: *Kirk-Othmer Encyclopedia of Chemical Technology*. John Wiley & Sons, Ltd, 2021, 1–27. DOI: 10.1002/0471238961.01021911211209.a01.pub3.

[3] M. Bharne and S. Bhosle, (2014) *“Mechanical and Thermal Properties of Fly Ash Filled ABS”* **International Journal of Engineering Research and Technology** *3*: 750–756.

[4] N. Evode, S. A. Qamar, M. Bilal, D. Barceló, and H. M. N. Iqbal, (2021) *“Plastic waste and its management strategies for environmental sustainability”* **Case Studies in Chemical and Environmental Engineering** *4*: 100142. DOI: 10.1016/j.cscee.2021.100142.

[5] M. A. Nikousaleh, R.-U. Giesen, H.-P. Heim, and M. Hartung, (2023) *“MC-Injection Molding with Liquid Silicone Rubber (LSR) and Acrylonitrile Butadiene Styrene (ABS) for Medical Technology”* **Polymers** *15*: 3972. DOI: 10.3390/polym15193972.

[6] G. Shanthi, J. Beula Isabel, R. Thankachan, and M. Premalatha, (2024) *"Sustainable strategies towards better utilization of synthetic polymers"* **Biopolymers** ***115***(4): e23581. DOI: 10.1002/bip.23581.

[7] F. Di Maio and P. C. Rem, (2015) *"A robust indicator for promoting circular economy through recycling"* **Journal of Environmental Protection** ***6***(10): 1095–1104. DOI: 10.4236/jep.2015.610096.

[8] A. Lamtai, S. Elkoun, M. Robert, F. Mighri, and C. Diez, (2023) *"Mechanical Recycling of Thermoplastics: A Review of Key Issues"* **Waste** ***1***(4): 860–883. DOI: 10.3390/waste1040050.

[9] A. K. Cress, J. Huynh, E. H. Anderson, R. O'Neill, Y. Schneider, and Ö. Keleş, (2021) *"Effect of recycling on the mechanical behavior and structure of additively manufactured acrylonitrile butadiene styrene (ABS)"* **Journal of Cleaner Production** ***279***: 123689. DOI: 10.1016/j.jclepro.2020.123689.

[10] X. Bai, D. H. Isaac, and K. Smith, (2007) *"Reprocessing acrylonitrile–butadiene–styrene plastics: Structure–property relationships"* **Polymer Engineering and Science** ***47***(2): 120–130. DOI: 10.1002/pen.20681.

[11] V. Mishra, S. Negi, and S. Kar, (2023) *"FDM-based additive manufacturing of recycled thermoplastics and associated composites"* **Journal of Material Cycles and Waste Management** ***25***(2): 758–784. DOI: 10.1007/s10163-022-01588-2.

[12] L. Hýlová and M. Maňas. "Impact behaviour of acrylonitrile-butadiene-styrene after temperature and humidity load". In: *MATEC Web of Conferences*. ***125***. 2017, 02048. DOI: 10.1051/matecconf/201712502048.

[13] P. Kakanuru and K. Pochiraju, (2020) *"Moisture Ingress and Degradation of Additively Manufactured PLA, ABS and PLA/SiC Composite Parts"* **Additive Manufacturing** ***36***: 101529. DOI: 10.1016/j.addma.2020.101529.

[14] V. Ramesh, S. Mohanty, M. Biswal, and S. K. Nayak, (2015) *"Effect of Reprocessing and Accelerated Weathering on Impact-Modified Recycled Blend"* **Journal of Materials Engineering and Performance** ***24***(12): 5046–5053. DOI: 10.1007/s11665-015-1743-3.

[15] G. A. Munshi and V. M. Kulkarni, (2025) *"A comprehensive study on restoring properties in expired/aged ABS materials: advanced techniques, additive integration and challenges for sustainable industrial reuse and manufacturing"* **Journal of Materials Science: Materials in Engineering** ***20***(1): 48. DOI: 10.1186/s40712-025-00260-5.

[16] J. Finnerty, S. Rowe, T. Howard, S. Connolly, C. Doran, D. M. Devine, N. M. Gately, V. Chyzna, A. Portela, G. S. N. Bezerra, P. McDonald, and D. M. Colbert, (2023) *"Effect of Mechanical Recycling on the Mechanical Properties of PLA-Based Natural Fiber-Reinforced Composites"* **Journal of Composites Science** ***7***(4): 141. DOI: 10.3390/jcs7040141.

[17] P.-W. Huang and H.-S. Peng, (2021) *"Number of Times Recycled and Its Effect on the Recyclability, Fluidity and Tensile Properties of Polypropylene Injection Molded Parts"* **Sustainability** ***13***(19): 11085. DOI: 10.3390/su131911085.

[18] V. Mishra, C. K. Ror, S. Negi, S. Kar, and L. N. Borah, (2023) *"Development of sustainable 3D printing filaments using recycled/virgin ABS blends: Processing and characterization"* **Polymer Engineering and Science** ***63***(7): 1890–1899. DOI: 10.1002/pen.26330.

[19] N. Vidakis, M. Petousis, A. Maniadi, E. Koudoumas, A. Vairis, and J. Kechagias, (2020) *"Sustainable Additive Manufacturing: Mechanical Response of Acrylonitrile-Butadiene-Styrene over Multiple Recycling Processes"* **Sustainability** ***12***(9): 3568. DOI: 10.3390/su12093568.

[20] O. T. Türkan and E. Çetin, (2023) *"Evaluating combination of solvent-based recycling and mechanical recycling of ABS materials for mitigating plastic pollution and promoting environmental consciousness"* **Orclever Proceedings of Research and Development** ***3***(1): 672–693. DOI: 10.56038/oprd.v3i1.410.

[21] J. Sedlak, Z. Joska, J. Jansky, J. Zouhar, S. Kolomy, M. Slany, A. Svasta, and J. Jirousek, (2023) *"Analysis of the Mechanical Properties of 3D-Printed Plastic Samples Subjected to Selected Degradation Effects"* **Materials** ***16***(8): 3268. DOI: 10.3390/ma16083268.

[22] A. Milovanovic, M. Milosevic, I. Trajkovic, A. Sedmak, N. Razavi, and F. Berto, (2022) *"Crack path direction in plane-strain fracture toughness assessment tests of quasi-brittle PLA polymer and ductile PLA-X composite"* **Procedia Structural Integrity** ***42***: 1376–1381. DOI: 10.1016/j.prostr.2022.12.175.