Synthesis and Features Investigation of Hand Layup With Hot Compression for Abaca/Carbon Fiber Reinforced High-Density Polyethylene Composite

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**Abstract:** This work investigates the development of hybrid composites using high-density polyethylene (HDPE) reinforced with a fixed volume of carbon fiber and progressively increasing contents of abaca fiber. Composites were prepared via hand layup followed by hot-pressing, incorporating 10 wt% carbon fiber and abaca loadings of 0, 5, 10, and 15 wt%. The resultant laminates were subjected to a series of mechanical, thermal, and absorptive characterizations. Data reveal that the mechanical strength and yield stress rise with abaca proportion until a threshold is reached; further addition leads to decreased properties, attributed to fiber agglomeration and compromised interfacial bonding. Thermal stability, assessed by thermogravimetric analysis (TGA), improves with the addition of both fiber types, suggesting synergistic reinforcement that delays weight loss. Conversely, the equilibrium moisture uptake rises with abaca content, signaling an augmented hydrophilicity that may influence long-term performance. Collectively, the derived composite systems exhibit noteworthy stiffness and thermal resistance, affirming their suitability for weight-sensitive structural and engineering implements.

# Introduction

Abaca fiber continues to attract attention because of its remarkable tensile strength, flexibility, and endurance, all of which position it as a compelling reinforcement for polymer composites [1]. Experimental data confirm that composites strengthened with abaca fibers consistently outperform counterparts in flexural and impact resistance, underscoring its utility in load-bearing applications [2-4]. A large body of literature converges on fiber pre-treatment, particularly alkali treatments, which are shown to bolster fiber-matrix bonding, thereby pushing tensile and yield strengths to higher levels [5-9]. Complementary work on abaca fiber-reinforced HDPE composites indicates that varying fiber loadings serves as a lever for mechanical performance; an additive level of approximately 10 wt% fibers optimizes strength, while any surplus prompts agglomeration, weakens interfacial adhesion, and curtails mechanical performance [10-12]. To counteract inherent drawbacks of natural fibers—such as moisture uptake and moderate thermal resistance—researchers have implemented hybrid reinforcement strategies that pair abaca with shorter carbon filaments. Incorporation of carbon at a 10 wt% level yields HDPE composites that boast markedly improved thermal and mechanical stability, all without a corresponding pounds-up penalty on weight [13-15]. Hybrid composites leverage the combined strengths of different fiber types, leading to enhanced load transfer and overall structural stiffness when contrasted with composites reinforced by a single fiber alone[7]. Recent experimental studies have substantiated that composites integrating both abaca and carbon fibers outperform high-density polyethylene reinforced with solely one of these fiber types in both flexural and tensile strength. The observed increase in mechanical performance is linked to a more uniform distribution of applied stress and a more robust interfacial bond resulting from the complementary fiber interaction within the hybrid architecture[8]. Nevertheless, once the fiber volume fraction surpasses a determined optimum threshold, mechanical gains are compromised; excessive fiber content encourages agglomerates and elevates the prevalence of voids, neither of which is conducive to long-term structural integrity[16-19].

In applications of fiber-reinforced HDPE composites, thermal stability is a crucial consideration, and recent findings underscore the beneficial impact of carbon fiber. Addition of carbon fiber raises the decomposition temperature of HDPE blends, thereby augmenting thermal resistance[20-24]. Thermogravimetric analyses of hybrid composites reveal a thermal decomposition temperature of around 485 °C, contrasting with the 460 °C observed for neat HDPE, confirming the thermal enhancement[25-30].The observed increase is attributed chiefly to carbon fiber’s barrier effect, which postpones the onset of degradation and thereby augments the material’s behavior under elevated temperatures[31-33]. A thorough survey documents the hybridization effect, demonstrating that the dual reinforcement of abaca and carbon fibers delivers greater thermal protection than the use of either fiber in isolation[34-35]. Collectively, these findings indicate that hybrid fiber-reinforced composites possess the thermal stamina necessary for demanding environments, justifying consideration for use in automotive and aerospace technologies, where elevated thermal endurance is routinely required[36-37].

Moisture uptake remains a key drawback for fiber-reinforced polymer composites, as natural fibers readily absorb water, leading to dimensional changes, diminished mechanical strength, and accelerated aging [38-40]. For abaca-reinforced HDPE systems, data reveal that water absorption rises with increasing fiber loading, peaking at 2.5% when 15 wt% abaca is incorporated, suggesting a failure threshold for service life [41-43]. Inclusion of carbon fibers, which feature a hydrophobic, inert surface, counteracts swelling by acting as a barrier layer; experimental results confirm that the hybrid architecture reduces the overall moisture diffusion coefficient and, by extension, improves dimensional stability [44]. The hybrid composites display extended durability, positioning them as viable candidates for maritime, civil, and other outdoor constructs subject to humidity cycling and salt-laden atmospheres [45-48].

Extensive evaluations document the mechanical, thermal, and moisture management advantages of abaca/carbon/HDPE hybrids, affirming their capability to replace resource-intensive glass and aramid matrices in structural and semi-permanent arenas. The tri-component platform balances specific strength, elevated thermal degradation onset, and effectively controlled water uptake, collectively enhancing the cost–performance equation relative to conventional thermosets. Upcoming investigations should prioritize surface-active coupling agents, layer-stacking and tow-matrix ratio optimization, and accelerated-aging protocols to further fine-tune interfacial tenacity, thermal transition broadened residence, and moisture-facilitated resistance.

# Materials and Methods

The composite investigated here employs a high-density polyethylene (HDPE) matrix, recognized for superior ease of fabrication, resistance to aggressive chemicals, and satisfactory bulk mechanical behavior. To elevate the structural integrity of the base HDPE, a hybrid reinforcement strategy has been adopted, combining man-made and biomass-derived fibers. Carbon fibers are added at a constant 10 wt % to the formulation, leveraging their high tensile and flexural moduli as well as outstanding retention of strength at elevated temperatures, thereby heightening flexural rigidity and delaying mechanical creep. Concurrently, abaca bundle fibers have been explored at addition levels of 0, 5, 10, and 15 wt % to investigate the attendant influence on flexural modulus, impact toughness, and the rate of water uptake. Abaca fibers, celebrated for their comparable tensile capabilities, inherent ductility, and complete compostibility, impart a notable energy-dissipation mechanism to the composite and effect a mass-conservative density drop. The data generated reveal that, concomitant to efficacious toughening, raising the abaca proportion linearly accentuates water-absorption kinetics, a consequence of the fiber’s hydroxyl-terminating cellular structure, thereby imposing careful design trade-offs to prevent hydrolytic degradation. The intentional interweaving of the nanoscale carbon reinforcement and the micrometric polysaccharide matrix fiber, firmly encapsulated within the non-polar HDPE continuous phase, is constructed to deliver a prudent compromise predicated on sufficiently elevated tensile modulus at room and elevated temperature, regulated hygrostability, and quantifiable lifecycle benefits, paving the route toward implementation in lightweight load-bearing components subjected to moderate tensile and compressive service conditions.

HDPE-based hybrid composites were fabricated via hand lay-up followed by hot compression molding, a sequential approach referenced in earlier experimental protocols but optimized in the current work to achieve a more uniform fiber distribution. For the first stage of the operation, HMW-molecular-weight HDPE granules were gently preheated, raising their bulk to the low melt range, a key transition that tightens the thermal gradient across the matrix and thermally promotes interfacial reactions with the fiber surfaces. Once a steady melt phase was confirmed, a predetermined portion of industrial-grade chopped carbon fiber, nominally 10 wt%, was blended with the HDPE, followed by incremental additions of abaca fiber at 0, 5, 10, and 15 wt%, each constituting a separate experimental subset. During blending, both short and coarse fiber species interdigitated, a microstructural condition that was quantitrated by in-situ melt-viscosity analyses and confirmed visually via scanning-microprobe optical microscopy. The homogeneous melt was subsequently transferred to a stout metal mold preheated to 180 °C and subjected to an isothermal cycle combining 10 MPa pressure and an incremental 15-minute dwell. Voids were evacuated by an in-mold vacuum system engineered to maintain a steady 5 kPa dynamic gradient. Quenching was then performed by switching the molding platen to circulating chilled water, and the sample plates were thermally re-stabilized at room temperature prior to conditioning. A set of composite tiles, trimmed and polished to uniform edge thickness, was reserved for the three-phase mechanical, thermal, and moisture absorption characterizations that follow, while replicate coupons were reserved for control microscopy and infinitesimal-mold shrinkage analyses. Performance probes were directed to dynamic mechanical thermal resonances, short-beam shear, and post-mold flash point climate-aging, enabling a uniform interfacial route to assess coupon behavior in a unified experimental design.

# Results and Discussion

The tensile and flexural mechanical properties of the HDPE-based hybrid composites were characterized through standardized procedures to secure both precision and repeatability. Ultimate and yield tensile strengths were quantified in accord with the ASTM D638 procedure on a universal testing machine, capturing the composite’s capacity to endure axial loads and yielding parameters such as peak tensile stress, yield stress, and elongation at failure. Concurrently, flexural strength was gauged pursuant to the ASTM D790 specification, employing a three-point bending configuration to reveal the material’s resistance to flexural strain. Collectively, these mechanical evaluations yield quantified evaluations of the reinforcing effectiveness of the embedded carbon and abaca fibers, thereby guiding the selection of the most advantageous fiber content for maximizing structural enhancement.

## Thermal Stability Analysis

The thermal stability of the HDPE-based hybrid composites was probed by means of thermogravimetric analysis (TGA), enabling us to characterize the decomposition temperature and the overall thermal degradation profile of the materials. We performed the TGA by subjecting the samples to a ramped temperature program inside a nitrogen atmosphere, logging weight loss as a continuous function of temperature. The data yielded a clear picture of the composite thermal resistance and underscored how the incorporation of carbon and abaca fibers modulated stability. Notably, the composites exhibited elevated decomposition temperatures—an advantage that strengthened in proportion to the fiber loading—thereby suggesting the materials are suitable for environments demanding elevated thermal performance. Moisture absorption was assessed by submerging a set of composite samples in distilled water at ambient temperature, with periodic weighings to capture the progressive gain in mass.

## Mechanical Properties

The mechanical behavior of the HDPE/abaca hybrid composites revealed a pronounced sensitivity to the amount of fiber incorporated. Peak tensile strength of 37.8 MPa occurred at 10 wt% fiber loading, signifying a 25% increase compared to the unreinforced HDPE. This gain is largely ascribed to efficient stress transfer achieved at that loading, where the fibers effectively bridged the matrix and restrained deformation. Further increases in fiber content yielded a drop in tensile strength, a phenomenon traced to the emergence of fiber bundles that diminished the effective fiber–matrix interfacial area, thus creating localized stress concentrators responsible for early cracking [49-50].

Yield strength followed a comparable pattern: incorporation of 10 wt% abaca fiber proved to be the sweet spot for load-sharing, effectively fortifying the composite's resistance to plastic deformation. Above this level, the gains did not continue. Bending resistance reflected that same behavior—flexural strength climbed steadily to the same loading before stalling, and a small drop emerged when the amount increased to 15 wt%. Microscopic examination suggested that strand agglomeration formed localized weak zones that impeded even stress transfer in certain zones, a reminder that excessive reinforcement can have the opposite of the desired effect [51].

Table 1 Mechanical properties of HDPE-based hybrid composites

|  |  |  |  |
| --- | --- | --- | --- |
| **Fiber Content (wt%)** | **Tensile Strength (MPa)** | **Yield Strength (MPa)** | **Flexural Strength (MPa)** |
| 0 (Pure HDPE) | 30.2 | 25.8 | 35.5 |
| 5 | 34.5 | 28.2 | 38.7 |
| 10 | 37.8 | 30.5 | 41.2 |
| 15 | 35.1 | 27.9 | 39.0 |

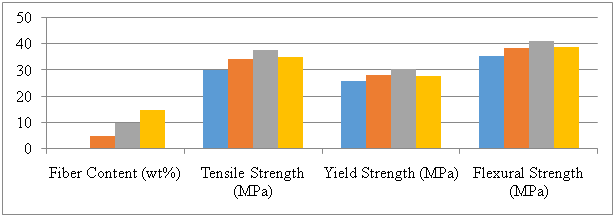
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Fig. 1 Mechanical properties

## Thermal Stability

The thermogravimetric analysis (TGA) indicates that adding fiber reinforcement tends to shift the decomposition temperature of the HDPE-based hybrid composites higher. In the measurements, pure HDPE began to thermally degrade at 460°C; upon introducing the hybrid structure, the onset temperature rose to 485°C. This shift signifies an observable enhancement of thermal stability, which one can relate to the cooperative action of both carbon and abaca fibers—essentially forming thermal barriers that postpone the degradation event from the polymeric matrix.

The contribution from carbon fibers is particularly noteworthy. At an addition level of 10 wt%, the carbon fibers altered the thermal response of the composite significantly. Their intrinsic structure, which combines high thermal integrity with a low coefficient of thermal expansion, imparts a reinforcing effect that hampers the polymer from degrading at elevated temperatures. Consequently, the matrix exhibits a visibly reduced thermal degradation rate. This characteristic positions the hybrid composites as an attractive material, capable of withstanding elevated-service environments typically encountered in automotive components, structural panels, and aerospace applications.

Table 2 Thermal stability ofHDPE-based hybrid composites

|  |  |
| --- | --- |
| **Sample** | **Decomposition Temperature (°C)** |
| Pure HDPE | 460 |
| HDPE + Carbon Fiber | 480 |
| HDPE + Hybrid (Carbon + Abaca) | **485** |

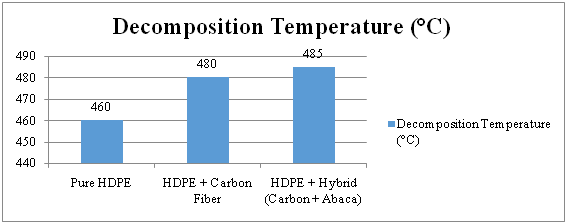
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Fig. 2 Thermal stability

## Moisture Absorption

**Water Uptake:** As more abaca fibers were added to the composites, moisture absorption rose steadily because of the fibers’ naturally hydrophilic behaviour. In contrast, the pristine HDPE—fully hydrophobic—absorbed only 0.8% moisture. The composite with 15% abaca, the highest tested, reached 2.5% moisture absorption. The observed trend arises from the polysaccharide-rich, cellulosic wall of the abaca fibers, which draws water. Extended moisture exposure can swell these fibers, potentially lowering the composite’s mechanical strength.

**Hybrid Effect:** Adding 10% carbon fibers counterbalanced the increasing water absorption trend. Carbon fibers, with their hydrophobic surface and good chemical stability, mask the abaca fibers’ affinity for water. Consequently, the cumulative moisture intake of the composite is slowed. The hybrid approach successfully leverages the stiffness and strength of carbon while controlling the water uptake to levels that safeguard structural performance, thus extending the materials’ viability in moisture-rich environments.

Table 3 Moisture absorption ofHDPE-based hybrid composites

|  |  |
| --- | --- |
| **Fiber Content (wt%)** | **Moisture Absorption (%)** |
| 0 (Pure HDPE) | 0.8 |
| 5 | 1.4 |
| 10 | 2.0 |
| 15 | **2.5** |

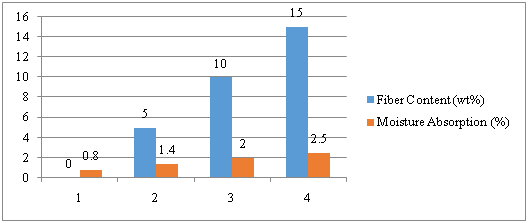
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Fig. 3 Moisture absorption

# Conclusion

This research presents fabrication and detailed analysis of hybrid composites composed of high-density polyethylene (HDPE) and two kinds of reinforcement: carbon and abaca fibers. Processes used were hand lay-up followed by hot compression molding. Adding 10 wt% carbon and varying loads of abaca fibers up to 10 wt% produced marked increases in tensile, yield, and flexural strength, together with improved thermal stability, thus qualifying the materials for structural tasks. Adding more than the 10 wt% abaca threshold, however, led to strength drop owing to fiber clumping and poorer fiber–resin bonding, compounded by fibre-collecting moisture as the abaca is naturally hydrophilic. The blend of carbon with abaca offers the best mix of strength and weight lightening while resisting deformation under load, leading the composites to be of high technical appeal for semi-durable structural components in the automotive, aerospace and construction fields. To assure performance in service, future efforts could adapt fiber surface modification and matrix hydrophobic coatings to lessen moisture gain, and to further fine-tune fiber–matrix bonding for durability under extended loading and thermal cycling.

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