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Effect of Carbon Fiber Content on the Mechanical and Thermal Properties of Carbon Fiber-Reinforced Polyvinyl Chloride Composites: Implications for Applications in Pakistan

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ABSTRACT

The performance of polyvinyl chloride (PVC) under mechanical loading and elevated temperatures is an important consideration in the selection of materials for construction, electrical, and transportation applications. This study examines the effect of carbon fiber (CF) content on the mechanical and thermal properties of carbon fiber-reinforced PVC (CF/PVC) composites. Five formulations containing 0, 4, 8, 12, and 16 wt.% CF were evaluated in terms of their microstructure, flexural strength, impact strength, compressive strength, thermal conductivity, Vicat softening temperature (VST), and coefficient of thermal expansion. Scanning electron microscopy revealed relatively uniform fiber distribution at CF contents up to 12 wt.%, whereas partial agglomeration was observed at 16 wt.%. Flexural, impact, and compressive strengths increased initially with increasing CF content and subsequently declined, with the 12 wt.% formulation exhibiting the most favorable overall performance among the compositions examined. At 20 °C, its flexural, impact, and compressive strengths were 45.2%, 44.0%, and 132.1% higher, respectively, than those of unreinforced PVC. At the same CF content, thermal conductivity increased by 57.4%, VST increased by 4.3 °C, and the coefficient of thermal expansion decreased by 70.4%. At 70 °C, the flexural, impact, and compressive strengths of the 12 wt.% CF composite were 2.04, 1.60, and 2.40 times those of unreinforced PVC, respectively; at 80 °C, the corresponding ratios were 2.02, 1.61, and 2.51. These findings demonstrate the importance of fiber content in balancing reinforcement and dispersion and provide a basis for the further evaluation of CF/PVC composites for applications in Pakistan where mechanical performance and dimensional stability are required.

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1. Introduction

Polyvinyl chloride (PVC) is widely used because of its corrosion resistance, low cost, and ease of processing[1]. Its resistance to moisture and wear supports applications in construction, electrical engineering, and automotive manufacturing[2]. Construction applications include formwork, pipes, and waterproofing sheets[3]; electrical applications include wires, cables, and equipment housings[4]; and automotive applications include interior trim and flooring[5]. Nevertheless, conventional PVC can exhibit poor thermal stability and deformation under elevated temperatures, limiting its use in demanding conditions[6,7].

Fiber reinforcement is commonly used to improve PVC properties[8]. Du et al. reported that glass fiber increased the flexural strength and thermal stability of PVC composites while maintaining good tensile strength[9]. Li et al. studied plant-fiber reinforcement and reported maximum hardness, tensile strength, and flexural strength at a rice husk powder content of 20 wt.%; water absorption increased with increasing powder content[10].

Carbon fiber has a preferentially oriented graphitic microcrystalline structure, high elastic modulus and specific strength, and good heat resistance[11,12,13]. CF reinforcement can improve room-temperature mechanical performance and may enhance thermal stability and elevated-temperature behavior[14,15,16]. Applications of CF composites include construction[17,18], electrical engineering[19,20], transportation[21], sports[22,23], and military aviation[24,25]. Skórczewska et al. (2022) reported that adding 10 wt% of a hybrid carbon fibre/carbon nanotube filler to PVC increased the tensile modulus by 44% and reduced the tensile strength by 17% relative to unmodified PVC[26]. The present study examines how carbon fibre content affects the thermal properties of CF/PVC composites and their mechanical performance at room and elevated temperatures.

This study evaluates the influence of CF content on composite microstructure, flexural, impact and compressive strengths, thermal conductivity, VST, and thermal expansion. It also compares the temperature-dependent mechanical properties of unreinforced PVC and the 12 wt.% CF composite. These results may inform future assessments of composite materials for construction, electrical and transportation applications in Pakistan.

2. Materials and Methods

2.1. Materials

PVC (X320, industrial grade, 99.8% purity) was supplied by Dongguan Xingyuan Chemical Co., Ltd.; calcium–zinc stabilizer (industrial grade, 99.0%) by Jinan Junteng Chemical Co., Ltd.; dioctyl phthalate (DOP, industrial grade, 99.0%) by Shandong Baihua Chemical Co., Ltd.; and stearic acid (99%) by Hebei Bangtai Chemical Co., Ltd. Carbon fiber supplied by Hangzhou Gaoke Composite Materials Co., Ltd. had a length of 3 mm, diameter of 7 μm, tensile strength above 3,500 MPa, reported thermal expansion coefficient of 5×10^{-6} °C^{-1}, and thermal conductivity of 8 W/(m·K).

2.2. Equipment

In this study, scanning electron microscopy was performed using a Nano 430 scanning electron microscope (FEI, United States). Tensile tests at high and low temperatures were conducted using an SHK-A103 tensile testing machine, and cantilever impact tests were performed using a ZOT-6032 impact tester. Thermal expansion, softening temperature, and thermal conductivity were measured using a ZRPY-DW thermal expansion instrument, a GC-WK-A softening temperature tester, and a Hot Disk TPS 2500 thermal conductivity analyzer (Hot Disk, Sweden), respectively.

2.3. Formulations and Sample Preparation

Table 1 presents the five formulations. The CF content increased from 0 to 16 wt.% while the PVC fraction decreased and additive concentrations remained constant.

Table 1. Formulations of PVC and CF/PVC composites (wt.%).

Sample	PVC	Ca–Zn stabilizer	DOP	Stearic acid	CF
1	95	3	0.5	1.5	0
2	91	3	0.5	1.5	4
3	87	3	0.5	1.5	8
4	83	3	0.5	1.5	12
5	79	3	0.5	1.5	16

In this study, the composite ingredients were weighed and blended in a high-speed mixer for 15 min. The resulting blend was compounded on a two-roll mill at 175 °C and subsequently hot-pressed at 180 °C under a pressure of 15 MPa for 10 min. After the molded composites had cooled to room temperature, they were cut to the required test specimen dimensions.

2.4. Characterization and Testing

Fracture surfaces were examined using scanning electron microscopy following liquid-nitrogen treatment. Flexural testing referenced GB/T 1449—2005, using 40 × 15 × 2 mm specimens and a loading rate of 1 mm/min. Compression testing referenced GB/T 5258—2008, using the reported specimen dimensions of 125 × 25 × 4 mm and a loading rate of 1 mm/min. Impact strength was measured with reference to GB/T 1843—2008, using type A notched specimens measuring 80 × 10 × 4 mm. These tests were conducted at 20 °C; samples 1 and 4 were also compared at elevated temperatures.

In this study, the mean longitudinal coefficient of thermal expansion was determined over the temperature range of −20 to 80 °C at a heating rate of 10 °C/min using specimens measuring 120 × 10 × 6 mm. The Vicat softening temperature (VST) was determined with reference to GB/T 1633–2000 using specimens measuring 10 × 10 × 4 mm under a load of 50 N and at a heating rate of 120 °C/h. Thermal conductivity was measured at 20, 40, 60, 70, and 80 °C using specimens measuring 50 × 50 × 4 mm.

3. Results and Discussion

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3.1. Microstructure and Carbon Fiber Distribution

Figure 1 shows the fracture-surface microstructure. At CF contents up to 12 wt.%, the fibers were reported to be relatively uniformly distributed within the PVC matrix. At 16 wt.%, partial agglomeration was observed. Agglomeration can create nonuniform reinforcement and reduce effective load transfer between fibers and matrix. The observations support 12 wt.% as the most favorable content among the tested formulations.

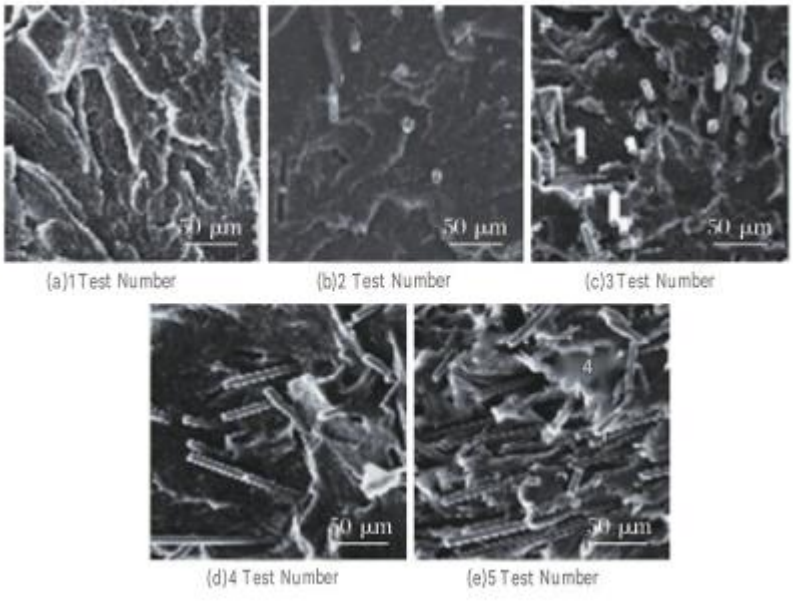

Figure 1. SEM images of PVC and CF/PVC composites at 500×. Samples 1–5 correspond to 0, 4, 8, 12, and 16 wt.% CF.

3.2. Mechanical Properties

Flexural, impact, and compressive strengths initially increased with CF content, reached their highest reported values at 12 wt.%, and declined at 16 wt.% (Figure 2). At 12 wt.% CF, the respective strengths were 45.2%, 44.0%, and 132.1% higher than those of unreinforced PVC.

Well-dispersed fibers can carry load, transfer stress, and hinder crack propagation. Increasing fiber content may increase fiber interactions and reinforcement. At excessive loading, agglomeration and poor interfacial contact may create stress concentrations and permit debonding or pull-out, reducing mechanical strength [27].

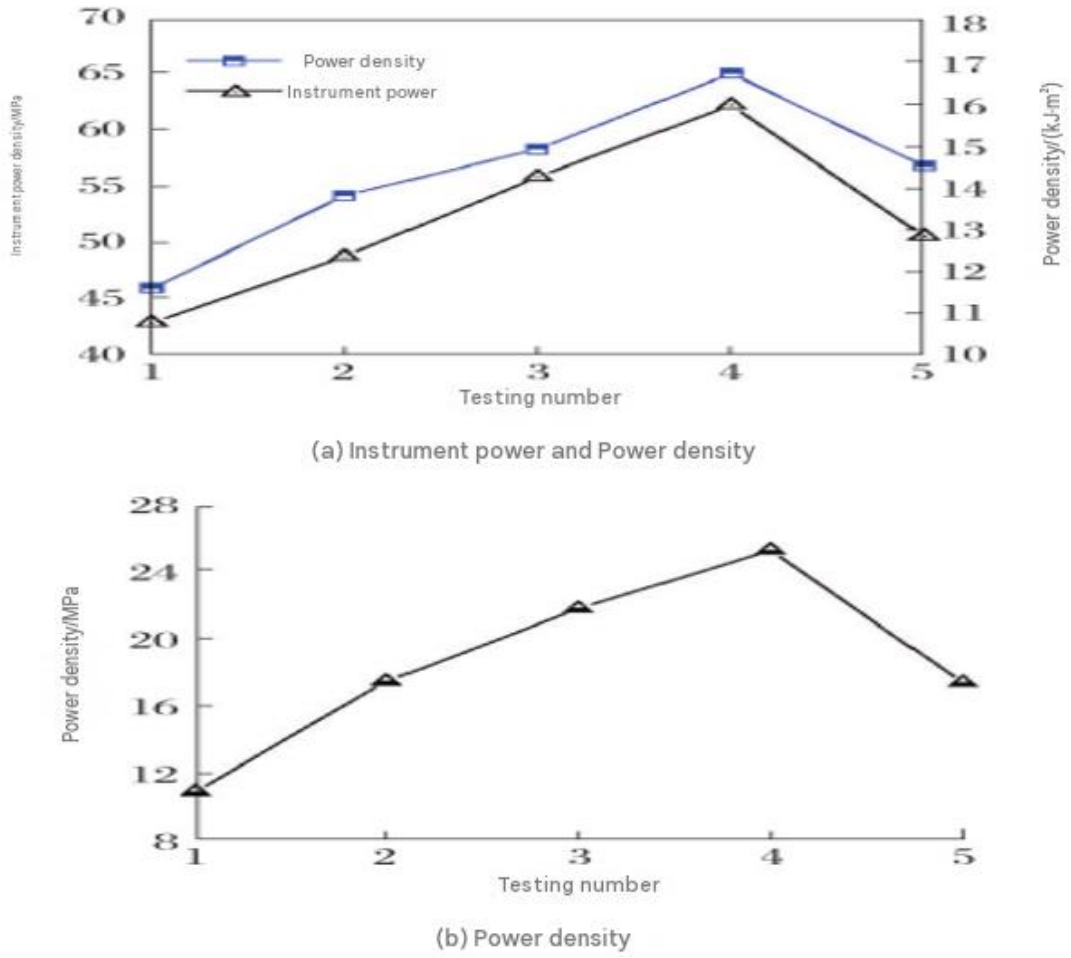

Figure 2. Mechanical properties of PVC and CF/PVC composites: (a) flexural and impact strengths; (b) compressive strength. Samples 1–5 correspond to 0, 4, 8, 12, and 16 wt.% CF.

3.3. Thermal Conductivity

Thermal conductivity increased with CF content (Figure 3). Compared with unreinforced PVC, the increases were 6.8%, 33.3%, 57.4%, and 59.3% at 4, 8, 12, and 16 wt.% CF, respectively. CF can provide heat-transfer pathways within the matrix. At low loading, fibers may remain separated; increased fiber interactions may improve heat transport. The small increase between 12 and 16 wt.% suggests diminishing additional benefit. Agglomeration and possible voids may also affect conductivity, although the latter mechanism requires direct verification.

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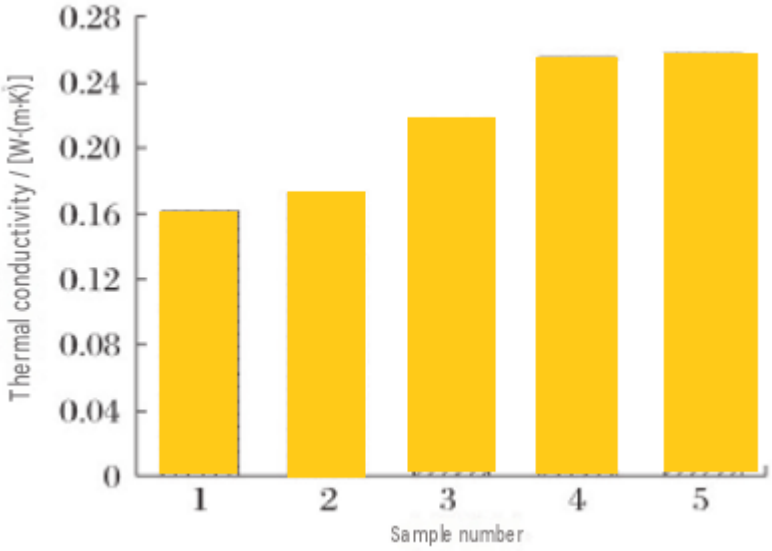

Figure 3. Thermal conductivity of PVC and CF/PVC composites. Samples 1–5 correspond to 0, 4, 8, 12, and 16 wt.% CF.

3.4. Vicat Softening Temperature

The VST of unreinforced PVC was 76.5 °C. It increased by 1.6, 2.5, 4.3, and 4.6 °C at CF contents of 4, 8, 12, and 16 wt.%, respectively (Figure 4). Fibers may constrain polymer deformation under the test conditions. The smaller increase between 12 and 16 wt.% indicates diminishing additional benefit, potentially associated with nonuniform dispersion at the highest loading.

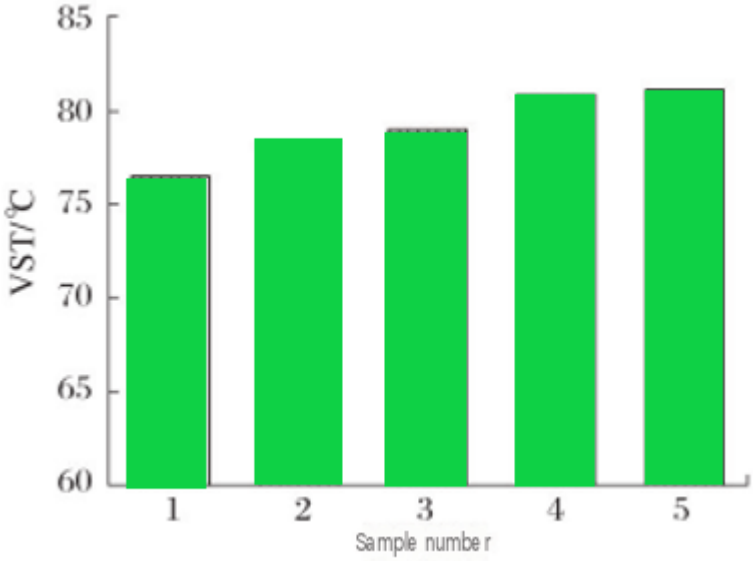

Figure 4. Vicat softening temperature of PVC and CF/PVC composites. Samples 1–5 correspond to 0, 4, 8, 12, and 16 wt.% CF.

3.5. Thermal Expansion

The thermal expansion coefficient progressively decreased with increasing CF content (Figure 5). Compared with unreinforced PVC, the reductions were 31.0%, 57.7%, 70.4%, and 73.2% at 4, 8, 12, and 16 wt.% CF, respectively. Fiber reinforcement may restrict thermal deformation of the matrix and improve dimensional stability in the direction tested. The contribution of improved heat dissipation to the measured expansion behavior cannot be established from the supplied results alone.

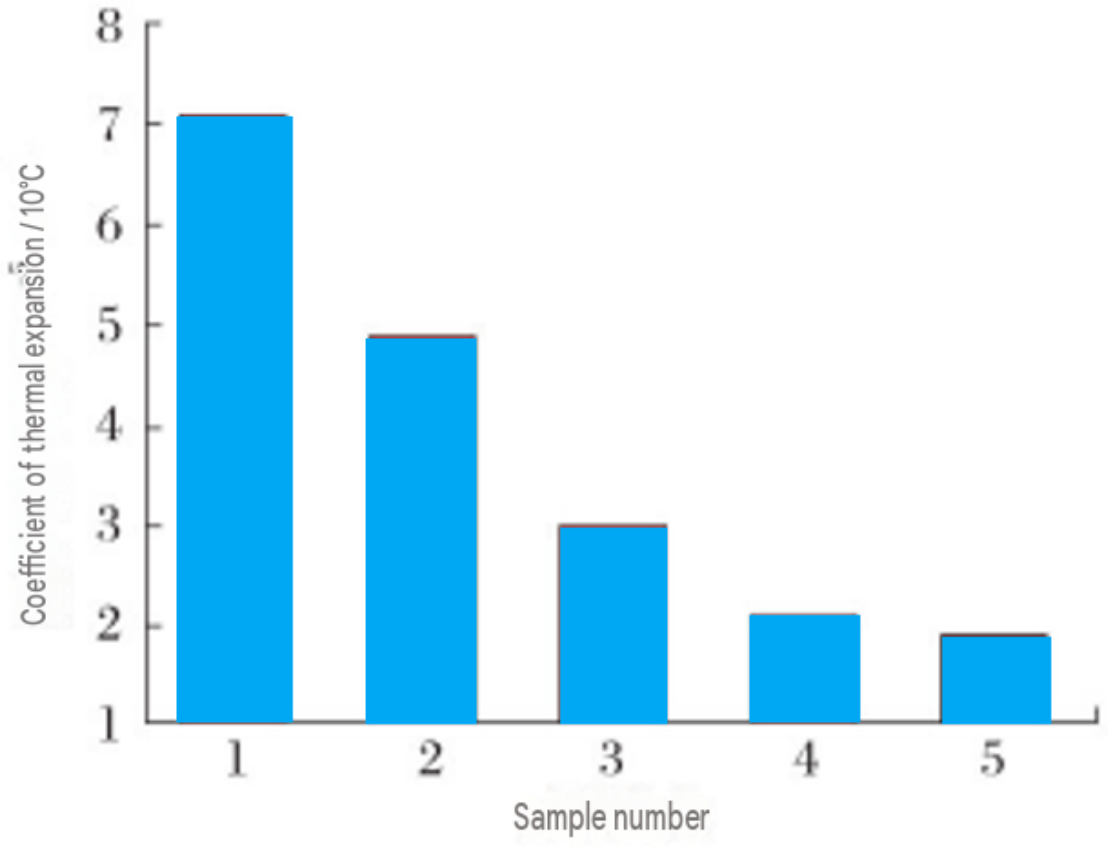

Figure 5. Coefficient of thermal expansion of PVC and CF/PVC composites. Samples 1–5 correspond to 0, 4, 8, 12, and 16 wt.% CF.

3.6. Mechanical Properties at Different Temperatures

Unreinforced PVC (sample 1) and the 12 wt.% CF composite (sample 4) were tested at 20–80 °C. All three measured strengths decreased with increasing temperature (Table 2 and Figure 6). For unreinforced PVC, flexural strength, impact strength, and compressive strength decreased by 56.6%, 37.9%, and 38.5%, respectively, at 70 °C relative to 20 °C. At 80 °C, the corresponding decreases were 77.4%, 56.0%, and 58.7%.

For the reinforced composite, the respective reductions were 39.2%, 31.1%, and 36.4% at 70 °C, and 68.5%, 50.9%, and 55.3% at 80 °C. The reduction is consistent with softening of the PVC

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matrix, particularly near and above the unreinforced formulation's VST. Despite substantial losses at elevated temperatures, the reinforced sample remained stronger than the control at every reported temperature.

Table 2. Mechanical properties at different temperatures.

Temp. °C	Flexural PVC / CF (MPa)	Impact PVC / CF (kJ/m²)	Compression PVC / CF (MPa)
20	42.9 / 62.3	11.6 / 16.7	10.9 / 25.3
40	41.8 / 60.5	10.9 / 15.9	10.1 / 24.1
60	38.9 / 55.7	9.5 / 12.3	9.2 / 20.2
70	18.6 / 37.9	7.2 / 11.5	6.7 / 16.1
80	9.7 / 19.6	5.1 / 8.2	4.5 / 11.3

At 70 °C, the flexural, impact, and compressive strengths of the 12 wt.% CF composite were 2.04, 1.60, and 2.40 times those of unreinforced PVC, respectively. At 80 °C, the corresponding ratios were 2.02, 1.61, and 2.51. These results do not by themselves establish suitability for sustained high-temperature service.

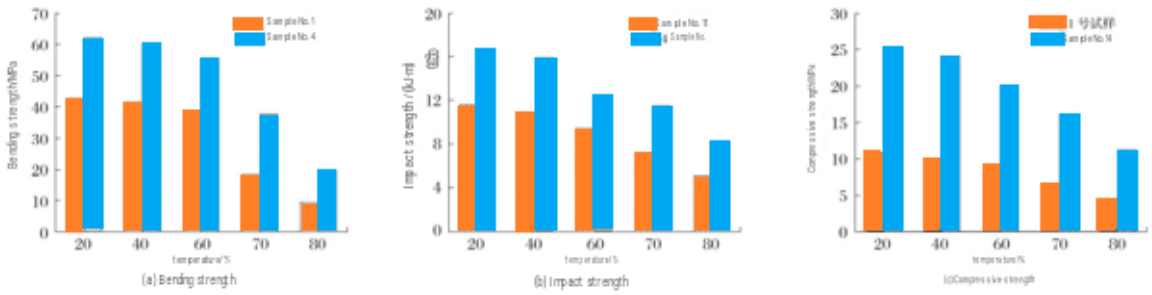

Figure 6. Mechanical properties of sample 1 (unreinforced PVC) and sample 4 (12 wt.% CF) at different temperatures: (a) flexural strength; (b) impact strength; (c) compressive strength.

3.7. Implications for Applications in Pakistan

The reported improvements in mechanical strength, thermal conductivity, resistance to softening, and dimensional stability may inform future evaluation of PVC-based products for construction, electrical, and transportation applications in Pakistan. Formulation selection would depend on the intended use, processing, cost, durability, and applicable standards. The original results do not establish performance under Pakistan-specific environmental or industrial conditions.

4. Conclusions

CF was relatively uniformly distributed in the PVC matrix up to 12 wt.%, while partial agglomeration appeared at 16 wt.%. Flexural, impact, and compressive strengths initially increased and then decreased as CF content rose. The 12 wt.% formulation provided the best overall mechanical performance among those tested. At 20 °C, its respective strengths exceeded those of unreinforced PVC by 45.2%, 44.0%, and 132.1%.

Thermal conductivity and VST increased as CF content increased, while thermal expansion decreased. At 12 wt.% CF, conductivity increased by 57.4%, VST by 4.3 °C, and thermal expansion decreased by 70.4%. Both unreinforced and reinforced PVC lost strength with rising temperature, although the composite maintained higher strengths at all reported temperatures. Further testing is required to establish suitability for specific applications in Pakistan.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(PVC): polyvinyl chloride; **(CF):** carbon fiber; **(VST):** Vicat softening temperature;

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Author Contribution:

M.T., S.A., S.N.S., Y.M., M.A.Z., A.H.N., and S.M. conducted the experiments. H.E.N.K. contributed to manuscript proofreading and revision prior to publication. All authors read and approved the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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Conflicts of Interest:

"The authors declare no conflict of interest."

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