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Fabrication and Characterization of Untreated Waste Paper and Banana Fiber Reinforced Hybrid Composite

Nafsheen Reza Reedeka[*], *Kazi Afzalur Rahman, and Md Mustakim Ahmmad Hemel*

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

This research investigates the mechanical properties of epoxy-based hybrid composites reinforced with untreated waste paper and banana fibers. Three samples were fabricated using the hand layup method: one without fibers and two with banana fibers, while keeping resin content fixed at 80%. Different mechanical tests like Tensile, Hardness, Flexural, Impact, Water absorption and Density test were conducted for characterization of the composites. Among the three fabricated samples, the composite with the highest paper content (20%) demonstrated superior mechanical properties. This improvement can be attributed to better fiber–matrix bonding and a more uniform distribution of reinforcement within the resin. Specifically, this sample achieved a tensile strength of 21.82 MPa, hardness of 90 HRB, flexural strength of 10.37 MPa, the highest impact strength of 19,911.5 J/m², and the lowest water absorption rate of 2.58%. However, banana fiber was incorporated into both of the remaining samples, among which the specimen with a higher fiber-to-paper ratio (10% fiber + 10% paper) exhibited more favorable performance than the sample containing the lowest fiber proportion (5% fiber + 15% paper). This indicates that a balanced ratio of fiber and paper provides more favorable mechanical properties than an unbalanced composition with excessive paper and minimal fiber.

Keywords: Banana fiber, Waste Paper, Composite Materials and Hand-layup method.

1. Introduction

A preference for products made from recycled fibers and bio-composites made from plant fibers has been brought to light by the growing demand for sustainable materials in recent years. Because of their affordability, non-abrasiveness, abundance, biodegradability, and ease of disposal, natural fibers such as flax, jute, hemp, banana, and sisal are becoming viable substitutes for glass fibers in several industrial sectors. Their increased specific strength and stiffness are a direct result of their decreased specific weight. Reduced reliance on nonrenewable energy and material sources, lower emissions of pollutants and greenhouse gases, improved energy recovery, and component biodegradability at the end of their useful lives are all allegedly among the environmental benefits of biocomposites [1],[2],[3]. Because of their low cost, good performance, and eco-friendly attributes, waste paper from vegetal sources emerges as a potential substitute for (or combination with) synthetic fibers.

Specifically, the utilization of recycled lignocellulosic fibers, such as waste paper, waste wood, and agricultural residues, in the creation of composite materials is becoming more and more significant in both the scientific and industrial realms. This is because they provide a viable solution to preserving a sustainable development of economic and ecological appeal, particularly given the massive amount of waste paper and wood produced every day [4], [5].

The traditional recycling process of turning discarded paper into new paper is more costly. It emits more carbon dioxide than producing new paper, as it requires specific treatments that involve eliminating inks, dyes, sizing agents, binders, cleaning, refining, and reformation [6], [7].

Paper is made from cellulose, a natural polymer that is mainly taken from eucalyptus or Pinus. Printing, copying, packing, and hygiene are only a few of the many products and uses for paper. After being used, waste papers mostly office paper from printers, photocopiers, or drafts old newspapers, and sludge paper a byproduct of the paper industry can be recycled or dumped in landfills. However, a vast volume of waste paper (WP) is thrown away improperly or used insufficiently. The consumption of about 40.3% of this paper causes environmental issues worldwide [8].

De Rosa et al. [9] created many samples by using leftover office paper sheets that had not been treated and reinforced with woven jute fiber in an epoxy resin matrix. Five composite panels were created by altering the order in which waste paper sheets and woven jute fiber layers were stacked. The Hand Lay-up process was used to develop the laminates. To ascertain the specimens' mechanical properties, tensile and flexural tests were conducted. The material reinforced with waste paper demonstrated superior tensile and flexural strength in both situations compared to the composite made solely of jute fiber. Das et al. [10] investigated the mechanical properties of composite materials made by combining jute fiber and un-shredded waste paper in a polyester resin matrix. A total of four samples were made using two distinct stacking sequences. They conducted scanning electron microscopy (SEM) analysis in addition to testing the composites' mechanical properties in terms of tensile, flexural, and interlaminar shear stress. Compared to hybridized composites, the pure paper-based composite has lower tensile and flexural strength. Guan et al. [11] examined the best method for creating green layered composites out of waste newspaper and polypropylene film lamination. They also looked into how the qualities of the composites were affected by the hot-pressing temperature, time, and paper content. The findings demonstrated that the resulting composite material had a flexural strength of 126 MPa, a tensile strength of 95 MPa, an impact strength of 5.3 kJ/m^2, and a water absorption thickness expansion ratio of 3.2% when hot-pressed at 180 °C, compressed for 20 minutes, and contained 66.7% paper. Interestingly, it outperformed the original waste newspaper by 164% in terms of tensile strength. Stanescu et al. [12] utilized volume ratios of 60%, 70%, and 80% of Dammar natural resin, and waste paper-reinforced composite materials were prepared with an epoxy resin or hybrid resin matrix. SEM and tensile tests were performed on all the acquired samples. Measured properties included tensile strength, modulus of elasticity, elongation at break, tensile response, and fracture surface analysis. The damping vibration ability of the bars in hybrid resins and composite materials under investigation was also studied. The mechanical properties of the composite materials were compared to those of four other types of resins. Using cassava starch as a binder, Yusuf et al. [13] investigated a few features of composite samples made from waste paper in an equal mix-ratio with rice husk and bamboo stem fibers (BSF) independently without chemical pre-treatment. Rice husk composites are superior because of their higher compressive strength, lower water absorption rate, and lower thickness swelling rate. In contrast, the BSF composites are exceptional because of their lower density. In addition to other specific features of the composites, the impact strength does not seem to be significantly impacted by the material composition. Except for the samples' comparatively high thickness swelling and water absorption, all of them have characteristics that satisfy the requirements for composites. Adediran et al. [14] investigated the effect of a fixed waste paper-cement ratio with varying content of the wood sawdust and chicken feather fiber-reinforced materials; thus, their flexural properties and water absorption tendencies were tested for samples prepared from those mixes. These results showed that the flexural strength, modulus of rupture, and modulus of elasticity increased. At the same time, water absorption decreased with an increase in chicken feather fiber concentration and a decrease in wood saw dust percentage. Maximum flexural strength occurred at 4:1 of chicken feather fiber to wood saw dust. At the same time, modulus of rupture and modulus of elasticity attained the peak when the ratio was 3:2. It was observed that, in the case of most of the investigated attributes, the higher chicken feather fiber concentration (3–5%) was more effective than wood saw dust.

Most previous studies on natural fiber composites have focused on chemically treated reinforcements such as alkali-treated jute, sisal, and banana fibers to enhance adhesion with polymer matrices. However, limited research has explored the mechanical behavior of composites reinforced with untreated waste paper and banana fibers. Using untreated waste paper simplifies fabrication, reduces processing time, and minimizes chemical intervention while maintaining acceptable mechanical performance. This study aims to fill this research gap by investigating the combined effect of untreated waste paper and banana fibers in hybrid epoxy composites and determining the influence of varying fiber-to-paper ratios on mechanical and physical properties. The objectives of this study are to fabricate epoxy-based hybrid composites with varying proportions of waste paper and banana fibers using the hand lay-up method, characterize their mechanical and physical properties, and analyze the effect of reinforcement composition on overall performance.

2. Materials and Method

While conducting this study, we utilized waste paper and banana fiber as base material for the composite. Extracted from the pseudo-stem of the banana plant, banana fiber is a natural lignocellulosic fiber known for its strength, biodegradability, and moisture absorption capabilities. Chemical composition of banana fibers consists of Cellulose (60-65%), Hemicellulose (6-19%), Lignin (5-10%), Pectin (3-5%), Ash (1-3%), and Extractives (3-6%) [15]. Banana fiber was collected from a local craft store in Gojaria, Munshiganj as shown in figure 1(a). A total of 350 grams of raw fibers were soaked in a 5% sodium hydroxide (NaOH) solution, made by dissolving 350 grams of NaOH in 7 liters of water. This chemical treatment as shown in Fig. 1(b) helped remove non-cellulosic materials (hemicellulose, lignin, pectin, waxes), enhancing fiber surface roughness. Then, the fibers were thoroughly rinsed with distilled water multiple times until the water became clear, which ensures complete removal of residual chemicals. Following this step, the fibers were sun-dried over several days, with frequent turning to ensure even drying. Once thoroughly dried, the fibers were inspected for impurities, discoloration, and defects to ensure quality. The cleaned and defect-free fibers were then cut into approximately 1-foot lengths shown in Fig. 1(c) to facilitate uniform alignment and distribution within the epoxy resin matrix.

(a) (b) (c)

Fig. 1 (a) Untreated Banana Fiber, (b) Alkali Treatment of banana fiber, and (c) Extracted banana fiber

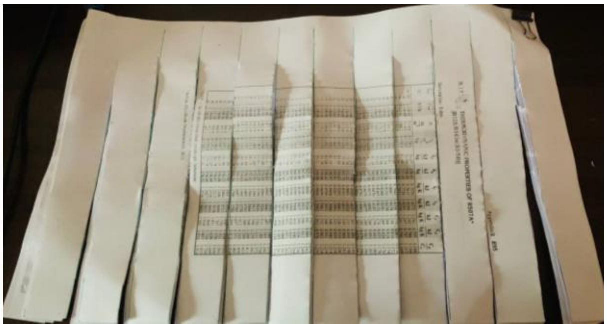

Fig. 2 Shredded Paper

For this study, we gathered paper waste from old notes, printed handouts, and study papers that were used in school. We sorted the papers to remove items like staples and glue that could make them dirty. The paper was shredded into smaller pieces after cleaning to facilitate easier handling and more even addition to the composite. Each A4 sheet was cut into strips that were 1 inch wide to increase the surface area and help the fibers spread out better in the epoxy matrix shown in Fig. 2. This made the bond between the paper and resin stronger. The paper strips were then kept dry until they were ready to be mixed. Epoxy resin is the most commonly used thermoset material in polymer matrix composites due to its superior moisture and chemical resistance, low shrinkage during curing, impact resistance, long shelf life, and strong electrical insulating properties [15]. When mixed with a hardener, a chemical reaction occurs, generating heat and causing the resin to solidify. A 10:1 resin-to-hardener ratio was used in this study.

2.1 Hand Layup Method

Suitable for small-scale work and offering control over fiber distribution, the hand lay-up method was used to fabricate composites in this study. The paper waste was collected from leftover academic papers, cut into approximately 1-inch strips, dried thoroughly, and then mixed evenly with the epoxy resin in every sample. The resin content was 350 grams, making up 80% of the composite weight. Each composite specimen weighed 437.5 grams with the remaining 20% consisting of varying proportions of paper waste and banana fibers. Three types of samples were prepared:

1. Fully Paper-Based Composite (20% Paper Waste): This sample contained only shredded paper waste as reinforcement, comprising 20% by weight (87.5 grams) of the total composite. The paper weight corresponded to approximately 23 standard A4 sheets.
2. Hybrid Composite (10% Banana Fiber + 10% Paper Waste): This sample consisted of equal proportions of banana fiber and paper waste, each contributing 10% of the total composite weight (43.75 grams each). Alkali-treated banana fibers, cut into 1-foot lengths, were layered with shredded paper strips and thoroughly mixed with epoxy resin.
3. Hybrid Composite (5% Banana Fiber + 15% Paper Waste): This sample contained 15% paper waste (65.625 grams) and 5% banana fiber (21.875 grams), designed to study the effect of varying ratios on composite performance.

For each sample, the epoxy resin and hardener were measured and mixed thoroughly in a 10:1 ratio before gradually adding the reinforcing materials. The mixture was poured into a flat mold and compressed manually with a flat plate to eliminate air pockets and ensure even thickness inside the composite. The composites were cured under 50 kg load for 24 hours at room temperature (25 ± 2°C) and conditioned for an additional 48 hours before testing. After curing, the composites were removed from the mold. We made about two samples for each type of specimens as shown in Fig. 3 and cut them into standardized specimen shapes.

2.2 Characterization of Composites

To assess the characteristics of the composite, we conducted several mechanical tests, including tensile, hardness, and impact tests. Along with these mechanical tests, we also tested the composite for water absorption percentage and density. For the tensile test, a Controls Universal Testing Machine was used and the specimens were prepared according to the ASTM D638 standards shown in Fig 4(a).

Additionally, the hardness of the specimens was tested using a Rockwell hardness tester. The hardness number (HRB) was measured with a 5 mm diameter indenter and a 60 Kgf load. Moreover, we used a pendulum impact tester for measuring impact strength. This test is known as Charpy Impact Test. A hammer weighing 2.5 kg and having an arm length of 0.345 m hit the specimen from an initial height h_1. After the hammer struck the specimen, it reached a height h_2, which helped us calculate the impact strength.

$$\text{Impact strength} = \frac{mg(h_1-h_2)}{A} = \frac{mgR(\cos\beta-\cos\alpha)}{A} \tag{1}$$

Fig.3 Samples 1, 2, and 3 after curing

(a) (b)

Fig.4 (a) Tensile test specimen, (b) Tensile test specimen after failure

For the water absorption test, 1-inch square specimens were prepared and immersed in distilled water for 24 hours. The water absorption percentage was then calculated using the following equation:

$$M(t) = \left(\frac{w_t-w_0}{w_0}\right) \times 100\% \tag{2}$$

The flexural test was conducted on specimens measuring 165 mm in length and 25 mm in width, following ASTM D790 standards. Samples were placed on a flexural testing apparatus using either a three-point or four-point bending setup for accurate alignment. The machine was calibrated and zeroed before testing.

A digital precision weighing scale was used to quantify the specimens' mass, and digital slide calipers were used to measure their volume to calculate their density.

3. RESULTS AND DISCUSSION

Table 1 contains a comprehensive summary of the outcomes from the mechanical tests conducted. Detailed descriptions of these findings are discussed further in the following subsections 3.1 - 3.6.

Table 1: Mechanical Properties of the Specimens

Specimen Type	Only Paper (20% Paper)	10% Fiber+ 10% Paper	5% Fiber+15% Paper
Tensile Strength (MPa)	21.82	11.27	10.72
Hardness (HRB)	90	79.5	69.5
Impact strength (J/m^2)	19911.5	13969.6	11895.2
Water Absorption (%)	2.58%	5.67%	9.13%
Flexural Stress (MPa)	10.3675	7.674	6.8595
Density (g/cm^3)	1.0585	1.11	1.047

3.1 Tensile Strength

From Fig. 5, the results revealed that the 20% paper composite exhibited the highest tensile strength of 21.82 MPa, followed by the sample 2 at 11.27 MPa, and the sample 3 at 10.72 MPa. The superior performance of the paper-only composite can be attributed to better fiber–matrix bonding and uniform dispersion of paper fibers within the epoxy resin, which allowed more efficient stress transfer during loading. In contrast, the inclusion of banana fibers slightly reduced tensile strength, likely due to imperfect interfacial adhesion between the fibers and the matrix and increased void formation at higher fiber contents. The results indicate that increasing paper content up to an optimal level enhances tensile behavior, while excessive fiber incorporation without proper bonding leads to reduced strength [9].

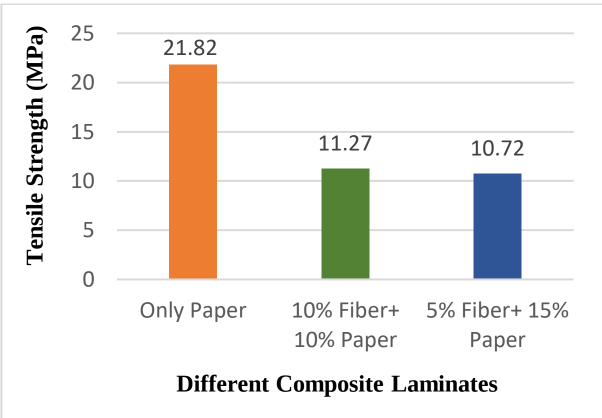

Fig. 5 Comparison of Tensile strength

3.2 Hardness

The Only Paper sample showed the highest hardness, as paper particles form dense areas resistant to indentation. Higher fiber content (10% and 5%) reduced hardness despite chemical treatment, since fiber softness remains. The 5% Fiber + 15% Paper sample had the lowest hardness due to soft fibers and possible voids, while the 10% Fiber + 10% Paper sample exhibited moderate hardness. Overall, increasing paper content improves hardness and tensile strength, but excessive fiber can reduce mechanical performance, highlighting the need to optimize the fiber-to-paper ratio.

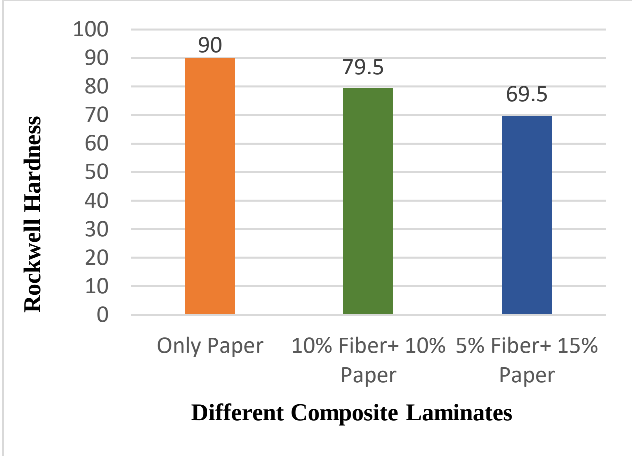

Fig. 6 Comparison of hardness

3.3 Impact Strength

Fig. 7 shows that the Only Paper (80% Resin + 20% Paper) sample had the highest impact strength (19,911.5 J/m²), likely due to better crack-bridging and stress distribution. The 10% Fiber + 10% Paper sample had a moderate impact strength (13,969.6 J/m²), while the 5% Fiber + 15% Paper sample showed the lowest value (11,895.2 J/m²), possibly due to poor fiber dispersion causing stress concentrations.

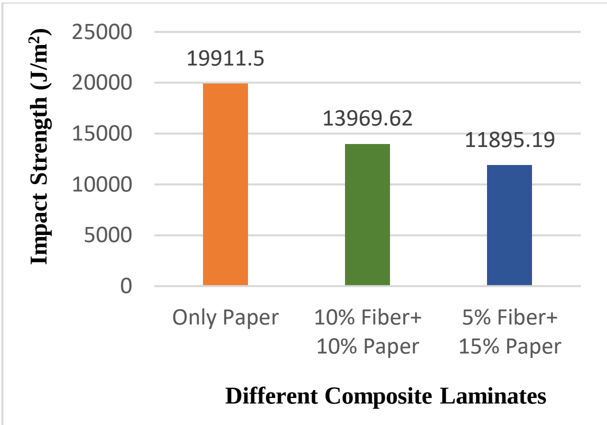

Fig. 7 Comparison of impact strength

3.4 Water Absorption

For the water absorption test, the three samples of each type were weighed first and then immersed in water for 24 hours and then weighed again. This test shows that the composite with only paper reinforcement (20% paper) absorbed the least water at 2.58%, indicating better moisture resistance. The higher absorption in the 5% fiber + 15% paper sample can be attributed to its greater paper content and lower fiber proportion, which resulted in more hydrophilic cellulose exposure and increased porosity within the matrix. In contrast, the 10% fiber +10% paper composite showed slightly lower absorption because the treated banana fibers created better resin bonding and less capillary void space for water penetration.

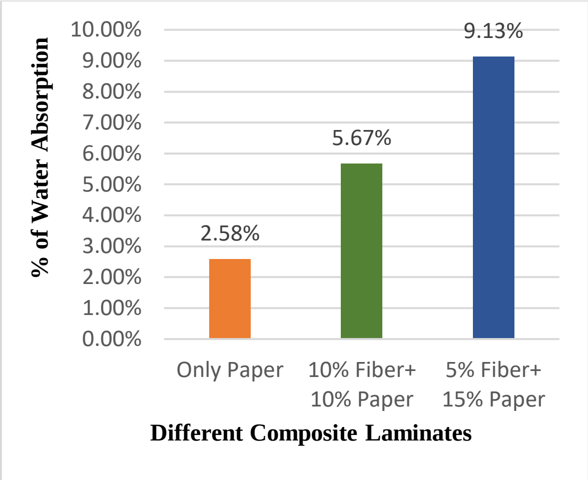

Fig. 8 Comparison of water absorption

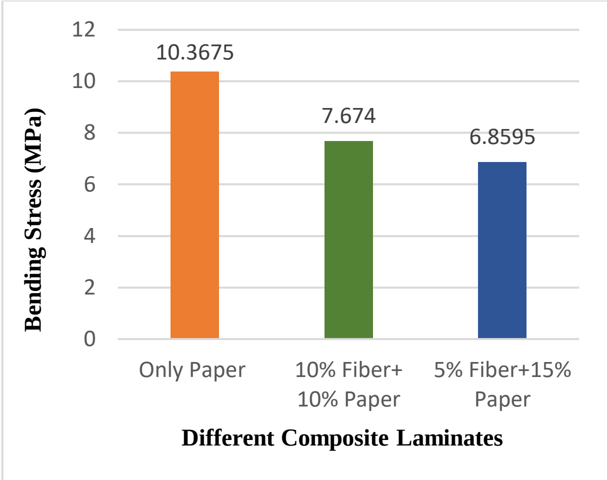

Fig. 10 Comparison of Flexural stress

3.5 Density

The composite with 10% fiber and 10% paper reinforcement has the highest density (1.11 g/cm2), according to the density results. This indicates a more compact structure as a result of improved packing and interaction between the fiber and paper within the resin matrix. The sample with only 20% paper is in the middle, which shows an optimum distribution of reinforcement. The composite with 5% fiber and 15% paper has the lowest density (1.047 g/cm³), which could mean that it is more porous or that the packing is less effective.

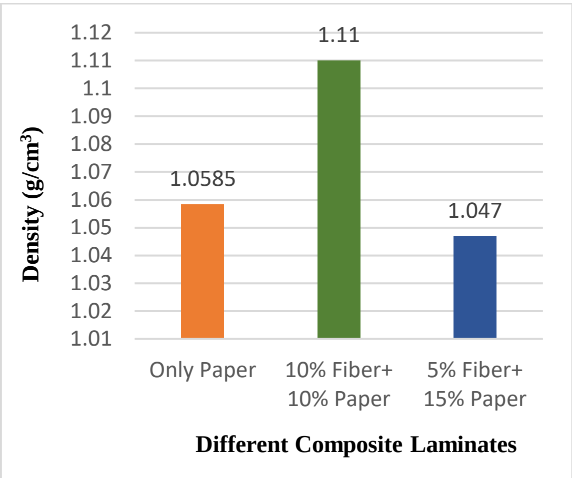

Fig. 9 Comparison of density

3.6 Flexural Stress

The Only Paper composite (80% resin + 20% paper) showed the highest flexural stress (10.37 MPa) because paper fibers provide strong bonding and uniform stress distribution, improving crack resistance during bending.
Although banana fibers were treated, adding them reduced flexural strength due to lower stiffness, imperfect bonding, and possible voids. The 10% Fiber + 10% Paper sample performed better than the 5% Fiber + 15% Paper one because its balanced fiber-to-paper ratio ensured better load transfer and fewer defects, while excess paper in the latter caused weaker bonding and higher porosity.

4. Conclusion

This study successfully demonstrates the development of hybrid composites using untreated waste paper reinforced with natural fibers, specifically banana fiber. The paper-only composite exhibited the highest overall mechanical performance, including tensile strength, impact strength, flexural stress and hardness, due to the higher fiber content and better load transfer within the matrix. Among the hybrid samples, the 10% Fiber + 10% Paper composite outperformed the 5% Fiber + 15% Paper composite, indicating that a balanced fiber-to-paper ratio is critical for optimizing strength and durability.
Key findings and implications of this study include:

- Mechanical properties such as tensile strength (21.82 MPa), impact strength (19,911.5 J/m²), and hardness (90 HRB) were highest in the paper-only composite, emphasizing the role of fiber content in load-bearing capacity.
- Hybrid composites with balanced fiber-paper ratios, such as the 10% Fiber + 10% Paper sample, provide a good compromise between strength and processability.
- Composites with higher paper content but lower fiber fractions (5% Fiber + 15% Paper) exhibited reduced mechanical performance, highlighting the importance of optimizing fiber-to-matrix ratios.

The findings of this study underscore the novelty of using untreated waste paper combined with banana fibers to produce hybrid composites. Future work can explore optimizing fiber-to-paper ratios, incorporating additional natural fillers, and investigating other properties such as thermal stability, acoustic damping, and long-term durability, paving the way for practical applications in lightweight structures, packaging, and construction materials.

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Nomenclature

Symbol	Meaning	Unit
m	Mass	(Kg)
G	Gravitational acceleration	(ms^{-2})
h_1	Initial height of the hammer	(m)
h_2	Final height of the hammer	(m)
R	Length of the hammer arm	(m)
α	Initial angle of the hammer	(degree)
β	Final angle of the hammer	(degree)
A	Cross-sectional area	(m^2)
W_0	Weight of the specimen before soaking	(gm)
W_t	Weight of the specimen after soaking	(gm)