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*Research Article*

# A Decision-Making Carbon Reinforced Material Selection Model for Composite Polymers in Pipeline Applications

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Pipes are manufactured primarily through the extrusion process. One of the material extrusion processes in recent digital manufacturing is additive manufacturing's fusion deposition modeling. Pipes are made from various materials such as metal and plastic/polymers, and the main challenge has been in selecting the pipe material for the customized application. For the creation of water-passing tubes, this research has chosen appropriate carbon-reinforced polymers that can be used with filament made of polyether ether ketone (PEEK) and polyethylene terephthalate glycol (PETG). For this goal, the analytical hierarchy process, also known as the AHP, is used to choose the best material based on factors such as cost, temperature resistance, printing speed, and mechanical properties of the material. The results revealed that PEEK-CF is a better material for the customized impeller application than PETG-CF. The PEEK-CF obtains the higher priority value of 0.6363, and the PETG-CF obtains 0.2791. This decision-making technique can be used to select other comparable customized applications.

## 1. Introduction

Researchers are still interested in carbon-fiber reinforced polymers (CFRPs), which are well-known for having high specific mechanical characteristics. However, due to the high degree of skill and substantial equipment expenditures needed, producing these composite materials is expensive. Cheaper manufacturing techniques are a crucial enabler technology for higher commercial acceptance of composites and quicker product development cycles since these decrease the growth of composite materials [1–3]. In recent decades, additive manufacturing methods have emerged, which use 3D printers to manufacture components layer by layer. Net-shaped parts can now be directly manufactured with more design freedom. The most common layer-by-layer technique is fused filament fabrication (FFF), also known as fused deposition modeling (FDM). Using this method, an object is constructed by depositing thermoplastic polymer material through a nozzle, a process also known as 3D printing. A relatively recent field of research [4–8] is the use of fiber-reinforced filament to produce composite parts using a completely automated method.

A hollow plastic cylinder or portion is known as a plastic pipe. It has a circular cross-section and is mostly used to move fluids, such as liquids and gases, slurries, powders, and masses of tiny materials. Polyvinyl chloride (PVC), a combination of plastic and vinyl, is the most commonly used material for polymer pipes. There is also CPVC (chlorinated polyvinyl chloride) piping, PERT (polyethylene-raised temperature) piping, and other options available [9–12].

Previous researchers explored different polymers for water-passing pipes/tube-based various applications instead of metals.

Supian et al. [13] wrote a review on the polymer composite materials in the energy absorption tube application. Based on this review, authors revealed that polymer replaces the metal application. Zhao et al. [14] investigated the 1D polymer material for the pipeline application and revealed that aerogels replace the liquid solvents with air to replace the solid interlaminar.

An amorphous thermoplastic polymer called ABS has been used to fabricate the pumps, rotor blades for drones, and rotary parts for the microorganic Rankine cycle (mORC) [15]. A semicrystalline thermoplastic polymer called PLA is made from sustainable resources like sugarcane or maize starch. One or more of the characteristics of this polymer is that it is biodegradable and compassable. When compared to other polymers, this polymer has a reasonable price, environmentally favorable biocompatibility, and acceptable physicomechanical properties. Impellers for pumps, compressors, and maritime applications have been made using PLA [16].

In order to examine the mechanical impact behavior of short carbon fiber reinforced PEEK composites and unfilled PEEK, Garcia-Gonzalez et al. [17] looked into the energy absorbed. In transverse, longitudinal, and unfilled fiber PEEK conditions, the tensile elastic modulus was 12.6, 24, and 3.6 GPa, respectively.

According to Alam et al.'s [18] investigation of carbon-reinforced PEEK for biomedical structural applications, the material recovers a sizable portion of the mechanical losses in strength and modulus brought on by sulfonation, in one instance increasing superior than (nonsulfonated) printed PEEK in terms of yield and final strengths (graphene nanoplatelets reinforcement).

Siddikali et al. [19] investigated carbon-reinforced PETG for coating with an electroless metal layer application, and their findings show better mechanical properties. In a Pump-Jet Module application, the PETG impeller was studied by Odetti et al. [20]. Tests with a PETG impeller at 1200 rpm and 14 N of thrust revealed that it has the right characteristics for this application. A more advanced quasithermoplastic polymer is PEEK. This polymer exhibits exceptional thermal, mechanical, and chemical resistance qualities. Many academics are interested in the PEEK impeller found in centrifugal pumps because of its improved strength and dependability [21, 22]. Pumps have used PETG impellers. This polymer's good water resistance and biodegradability are reasons for using it in the manufacture of pump blades [23, 24]. The various types of polymers and applications are classified in Figure 1.

The manufacture of rotating components has been done using a variety of thermoplastic polymers, including ABS, PLA, polyethylene terephthalate glycol (PETG), PEEK, and polyphenylene sulfide (PPS) [26–29].

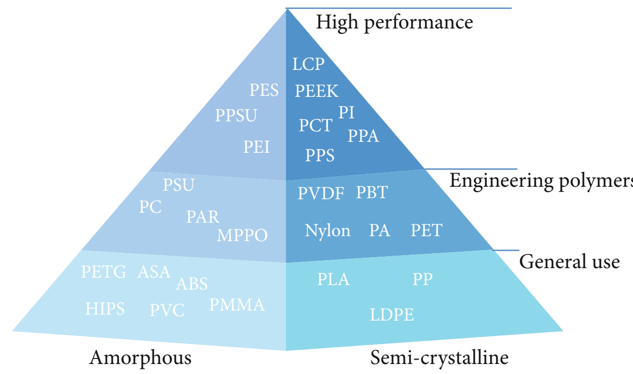



Figure 1: Various thermoplastic polymers and applications (open access article—Nader Zirak et al. [25]).

From this, previous literature has not done customized application material selection-based studies on carbon-reinforced polymer for water pipe making. Carbon-reinforced PEEK and PETG filaments are investigated in this study for use in the fabrication of customized water pipes. For obtaining this research objective, the detailed literature review has been carried out with MCDM methodology, particularly AHP procedures in the material selection problems as the first phase, and detailed materials and methods (how to apply) are discussed. The rest of the part elaborates on the result and discussion, and also, the conclusion shows research objective obtain or not.

## 2. Literature Review

*2.1. Multicriteria Decision-Making.* The act of choosing the best or appropriate option from a variety of options is known as decision-making. The primary goal of MCDM is to select the best alternative for a given situation including several criteria. The MCDM method makes use of criteria, options, and decision-makers' perspectives to determine the optimum course of action [30]. MCDM is a vital technique in operation research and can assist decision-makers when presented with a variety of options and requirements [31]. The MCDM contains a number of tools for making decisions, including AHP, FAHP, TOPSIS, and COPRAS, among others [32]. The FAHP, TOPSIS, and DEMATEL algorithms are frequently employed in the AM sector [33]. SCM [34], management science system engineering [35], sustainability [36], planning and product development assessment [37], and strategic management [38] all benefit from the application of MCDM. FTOPSIS and FMEA risk assessment have both been enhanced by MCDM [39].

*2.2. Analytical Hierarchy Process (AHP).* In this study, the AHP technique is covered first. The three primary techniques that make up the AHP approach's foundation are the hierarchy structure, priority examination, and consistency confirmation. This methodology was created to help with complex decision-making. The rational hierarchy is designed to enable a decision-maker or group of decision-

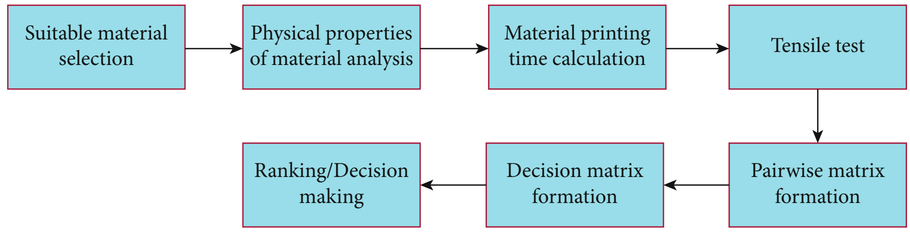



Figure 2: Research flow of the paper.

Table 1: Saaty scale of relative alternative, [4].

| Saaty scale | |
|---|---|
| 2, 4, 6, and 8 | Intermittent values |
| 1/3, 1/5, 1/7, 1/9 | Inverted comparison values |
| 1 | Equal significance |
| 3 | Moderate significance |
| 5 | Strong significance |
| 7 | Extremely significance |
| 9 | Very extremely significance |

makers to pairwise compare criteria and the related alternatives, resulting in global weight syncing, and then use the results to decide on alternative priority. Additionally, one of the main contributions of AHP and what sets it apart from other MCDA methodologies is that it permits the evaluation of judgement consistency [40].

The top level of the AHP hierarchy structure may be the aim or objective, with criteria and/or subcriteria appearing at the intermediate level. Then, the possibilities that correlate can be pursued at the most basic level. To create numerical weights, all pairwise comparison matrices will be collected, assessed, and then normalized. However, given the existence of uncertain situations in the decision-making process, this work suggests the integrative AHP and fuzzy logic (i.e., FAHP), which can be further researched [41].

## 3. Methodology

The research flow of the manuscript is shown in Figure 2. The research objective is to select a suitable carbon-reinforced material for pipe application. For this, the physical properties of material analysis such as price, mechanical property, printing time, and temperature withstand. Then, the third criteria of time have been calculated during the printing.

Then, the printed samples were involved in the tensile test, and based on all the criteria results, the pairwise matrix formed. In this paper's research, the AHP is used for finding suitable materials from the selected carbon-reinforced materials. The AHP processes have the Saaty scale as shown in Table 1. The Saaty scale is used to evaluate the criteria and alternatives. Figure 3 expresses the methodology of the manuscript. The objective of the research is the selection of suitable materials based on criteria such as price, temperature, printing time, and mechanical property.

## 4. Fabrication and Testing

*4.1. Physical Properties of Material Analysis.* The physical properties of PEEK and PETG are analyzed using criteria such as price and temperature. As a consequence, the cost and temperature of both materials are as follows.

PEEK is a liquid crystalline thermoplastic with high-temperature chemical and mechanical resistance properties. PEEK CF is one of the most advanced thermoplastics ever created. It is employed in some of the most demanding applications in industries such as automobiles, aerospace, defense, semiconductors, and oil and gas. PEEK is used by engineers in applications where failure is not an option. With tensile strengths between 90 and 100 MPa and a Young's modulus of 3.6 GPa, PEEK is both stiff and powerful. Polyether ether ketone is also referred to as PEEK. It is a colorless organic thermoplastic polymer that produces some of the best results of any thermoplastic on the market. It belongs to the polyether ether ketone (PEEK) family of compounds. PEEK filament has a variety of distinct properties. PETG filament is a quasi-industrial strength material with excellent UV and impact resistance and a slightly softer surface. It is simple to postprocess to achieve the desired surface finish [42–45].

Their main distinctions are their properties, applications, and material costs. PETG is more durable and stronger than PLA. PLA, on the other hand, is commonly used as an FDM/FFF filament due to its superior melt and cooling properties. However, comparable materials, PETG and PEEK, have superior materials compared to PLA. PETG is more expensive than PLA in terms of cost. PETG CF is a material designed for users that need to create structural elements that are subjected to significant mechanical pressures. As a result, many disciplines of engineering, including medicine, utilize this material to create prototypes and final items.

PETG is mainly remembered for its strength and durability, and the plastic is resistant to high temperatures, UV rays, water, chemical solvents, and other environmental factors. All of this makes PETG an excellent filament material choice for printing parts that will be exposed to harsh environments or will be subjected to a high level of physical stress [46–49].

The price of PETG carbon fiber filament starts onwards (Indian rupee) INR.1150 and PEEK carbon fiber filament price INR 4800 onwards, as shown in Figure 4. PETG has a significant melting point of 210°C and a fairly low temperature for glass transition of about 85°C. This means that, while the printing process necessitates hotter temperatures,

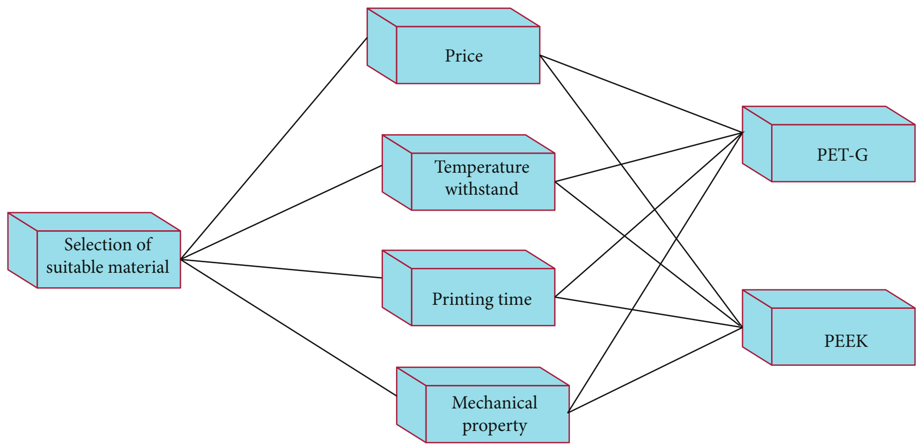



Figure 3: Methodology.

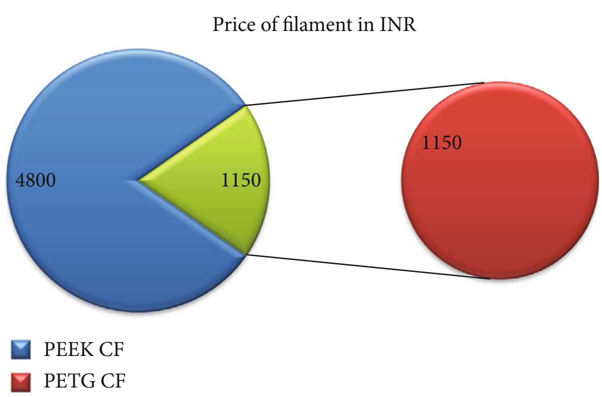



Figure 4: Comparison of the price of filaments.

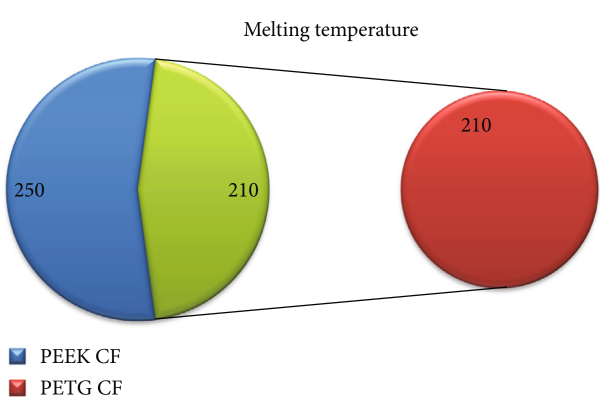



Figure 5: Comparison of the melting temperature of filaments.

PETG components are not well-known for their thermal properties. PEEK has a roughly 143°C (289°F) transition temperature and a roughly 250°C (662°F) melting temperature, and the comparison between the two selected polymers is shown in Figure 5 [44, 50, 51].

*4.2. Printing the Samples.* FDM has risen in popularity among additive manufacturing techniques because of its accessibility and material adaptability. This technique has been used over the years to generate a variety of materials

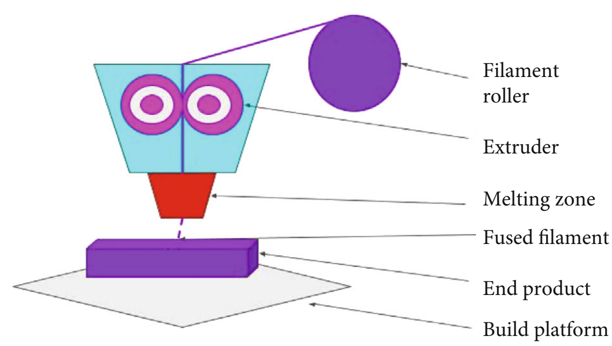


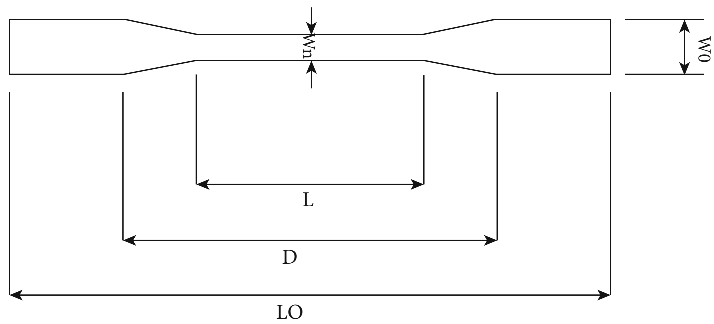

Figure 6: FDM components.

Table 2: Time recorded for printing ASTM D638 samples.

| PETG-CF | Time taken in "min" | PEEK-CF | Time taken in "min" |
|---|---|---|---|
| Sample 1 | 9 | Sample 1 | 15 |
| Sample 2 | 10 | Sample 2 | 15 |
| Sample 3 | 9 | Sample 3 | 16 |
| Total | 28 | Total | 46 |
| Average | 9.33 | Average | 15.33 |

for application in the aerospace [52], medical [53], and automotive industries, including plastics, powder, ceramics, and composites [54]. This procedure involves layering a partially built object with semisolid filament material that has been extruded through a heated nozzle. The process uses a build platform, print bed, liquefier head, and build material spool, as shown in Figure 6. The geometry development program is used to create the STL (standard triangular language) file format for the manufactured part model. It is then entered into the software and split into thin, two-dimensional layers.

This two-dimensional contour information is used to produce the tool path motion. The movement of the liquefier head is controlled by a 3-axis mechanism. It moves in the $X$-$Y$ plane in accordance with the tool path of the




ASTM D638
TYPE-V

| | |
|---|---|
| LO | 63.5 mm |
| D | 25.4 mm |
| L | 9.53 mm |
| Wo | 19 mm |
| Wn | 3.18 mm |

Figure 7: Geometrical standard of ASTM D638 type V [45].

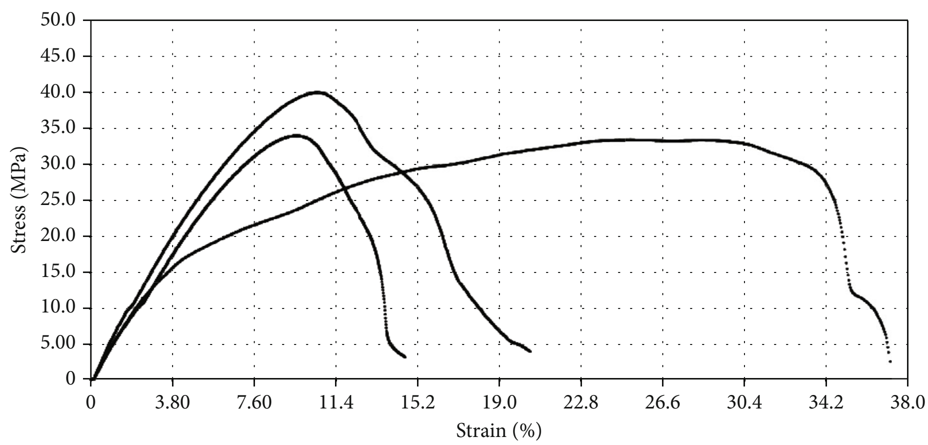



Figure 8: Stress and strain diagram for PEEK-CF.

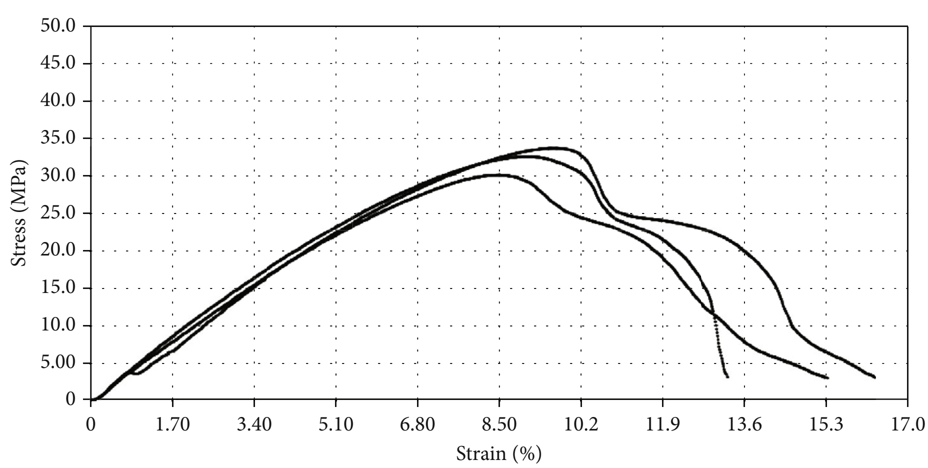



Figure 9: Stress and strain diagram for PETG-CF.

Table 3: Tensile test results for carbon-reinforced PETG AND PEEK.

| PETG-CF | UTS in "MPa" | PEEK-CF | UTS in "MPa" |
|---|---|---|---|
| Sample 1 | 39.9 | Sample 1 | 79.8 |
| Sample 2 | 33.9 | Sample 2 | 81.2 |
| Sample 3 | 33.3 | Sample 3 | 84.5 |
| Total | 107.1 | Total | 245.5 |
| Average | 35.7 | Average | 81.83 |

software and deposits the first layer while doing so. The recently added layer and the recently deposited layer are joined. Until the entire section is finished, the material will be deposited in successive layers.

After completion, the structure can be manually or chemically removed from the print platform by destroying the support structure [25, 55–57]. Fused deposition modeling (FDM) or material extrusion additive manufacturing are other names for this process that are permissible in

Table 4: Pairwise matrixes for analyzing criteria.

| Based on aim | Price | Printing time | Temperature withstand | Mechanical property |
|---|---|---|---|---|
| Price | 1 | 3 | 4 | 6 |
| Printing time | 1/3 | 1 | 1/2 | 3 |
| Temperature withstand | 1/4 | 2 | 1 | 3 |
| Mechanical property | 1/6 | 1/3 | 1/3 | 1 |

Table 5: Decision matrix with criteria.

| Criteria weight | 0.56 Priority-1 | 0.18 Priority-2 | 0.24 Priority-3 | 0.07028 Priority-4 |
|---|---|---|---|---|
| PEEK-CF | 0.613 | 0.667 | 0.643 | 0.641 |
| PETG-CF | 0.095 | 0.107 | 0.072 | 0.136 |

Table 6: Final decision matrix.

| | Total rows | Priority value | Rank |
|---|---|---|---|
| PEEK-CF | 0.337 + 0.112 + 0.143 + 0.0452 | 0.6363 | I |
| PETG-CF | 0.165 + 0.032 + 0.063 + 0.0158 | 0.2791 | II |

ASTM F42 (additive manufacturing technologies) (AM). The FDM components and operation are shown in Figure 1.

*4.3. Printing Time Calculation.* Based on the printing time, carbon-reinforced PETG had 15 minutes, and PEEK took 19 minutes. Table 2 expresses the time recorded for printing the tensile samples.

Each tensile sample of PETG carbon fiber takes a minimum of 9 minutes and a maximum of 10 min for printing the ASTM D638. Similarly, the PEEK carbon fiber samples take a minimum of 15 minutes and a maximum of 16 minutes. The average time of PETG carbon fiber is better than that of PEEK carbon fiber.

*4.4. Tensile Test.* The tensile test has been prepared from 3 out of 6 samples for PETG-CF and the rest of 3 out of 6 samples for PEEK-CF. The polymer tensile specimen standard ASTMD638 type V has been used for the experiment, and its geometrical size is shown in Figure 7.

The stress-strain curves of carbon-reinforced PEEK polymer are depicted in Figure 8, and PETG polymer is depicted in Figure 9.

Table 3 expresses the ultimate tensile strength values of carbon-reinforced PETG and PEEK. From the result, the PEEK carbon-reinforced polymer has a much superior tensile mechanical property.

Based on the tensile strength, the carbon-reinforced PETG has 35.7 MPa, and PEEK has 81.83 MPa. The tensile test was carried out by Instron machine, and the maximum load of 10000 N is applied to the specimen at the strain rate of 1 mm/min.

## 5. Result and Discussion

According to time, PETG-CF takes 9.33 minutes, and PEEK-CF takes 15.33 minutes. PETGCF compare to PEEK-CF takes less time. Based on tensile test results, PETG-CF has less strength compared to PEEK-CF. The other parameter comparison is discussed in detail in section 4.0. The pairwise matrix shown below has been created based on the discussion of the criteria and the Saaty scale. The pairwise matrixes formed in the first row indicated that price is considered equally important for both alternatives. Then, column 3 compares the price versus printing time; it takes 3 which means moderate importance. Column 4, in the first row, compares the price versus temperature withstands of material; it takes 4 which means intermediate of moderate and strong importance. Finally, column 5 compares the price versus mechanical property; it takes 6 which means intermediate between strong and very strong importance. Table 4 shows the pairwise matrix for the selected criteria.

Consistency index,

$$\text{C.I} = \frac{\lambda\text{max} - n}{n - 1.} \tag{1}$$

where: $\lambda$max = (Sum of ratio of weight sum value and criteria weight)/(number of criteria) and $n$ is the number of criteria.

Based on the consistency ratio verification,

$$\text{C.R} = 0.05 < 0.10 \tag{2}$$

As a result, the criteria are acceptable, and the consistency ratio is reasonable. If the consistency is less than one, it means that the created pairwise matrix is acceptable.

Table 5 shows the four criteria with priority values to form the decision matrix. Table 6 expresses that the PEEK-CF has been the most suitable material for the pipe-making customized application. The PEEK-CF material has the highest priority value of 0.6363, and the PETG-CF materials have the lowest priority value of 0.2791.

## 6. Conclusion

The purpose of this research is to select suitable materials from two different carbon-reinforced materials for manufacturing customized pipes. For this, a technique called AHP has been used in the mathematical programming technique of multicriteria decision-making. In this, both materials are evaluated based on the common criteria of time, temperature resistance, printing time, and tensile strength which are mechanical properties. In terms of price, PETG carbon fiber is slightly less when compared to PEEK-CF. And in terms of temperature, PEEK-CF is considered superior to PETG carbon fiber. Then, in terms of time, it is found that PETG carbon fiber can produce products in slightly less time when compared to PEEK-CF. Finally, PEEK carbon fiber is known to be stronger than PETG carbon fiber in terms of mechanical properties. Based on these four criteria, the pairwise matrix is generated with the help of Saaty scale. And through it, the consistency index is found, and the criteria are evaluated. Accordingly, this research indicates that PEEK carbon fiber is more suitable for pipe application than PETG carbon fiber. This research will be useful for future researchers to choose customized materials and equipment problems.

## Data Availability

The article contains all the data required to back up the investigation's conclusions. The author in question can provide more details upon request if necessary.

## Conflicts of Interest

The authors declare that they have no conflict of interest.

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