Evaluation of impact energy absorption in natural fiber composites

T B Andrade[1,2,*], R M Moreira[2], E P Eufrazio[2], T V Francisco[2,4] and E C Oliveira[1,3]

1 Pós MQI, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, 22453-900, Brazil
2 National Institute of Technology, Rio de Janeiro, 20081-312, Brazil
3 PETROBRAS S.A., Logistics, Operational Planning and Control, Measurement and Product Inventory Management, Rio de Janeiro 20231-030, Brazil
4 Graduate Program in Polymer Science and Technology, Federal University of Rio de Janeiro, Rio de Janeiro, 21941-598, Brazil

[*] Corresponding author: tatiandrade21@gmail.com

Abstract. In response to the increasing concerns about motorcyclists' safety and advancements in the motorcycle industry, this study investigated the potential of natural fibers as a sustainable means to enhance helmet protection. Leveraging statistical tools such as the Shapiro-Wilk test, Chauvenet's criterion, and the Interquartile Range, we compared the impact energy absorption of composites reinforced with natural fibers to that of expanded polyurethane (PU) prototypes. The results, assessed through confidence intervals, indicated that composites reinforced with 5 % sugarcane bagasse, 5 % and 10 % coconut, and 10 % and 15 % sisal demonstrated a notably superior impact absorption performance than pure PU. These insights emphasize the potential of natural fibers in enhancing helmet safety and suggest promising directions for future research into the ideal composite materials for motorcycle helmets a line of inquiry currently in progress.

Keywords: *impact absorption; motorcycle helmet; natural fiber; statistical analysis.*

1. Introduction

The motorcycle industry has grown at an unparalleled rate, as evidenced by an increase in the motorization rate, which shows the relationship between the number of registered vehicles and the population. Between 2000 and 2018, this rate climbed considerably, rising 456.2 % from 23.3 to 129.6 motorcycles per 100,000 inhabitants. The rate of motorization in 2019 was 134.1 [1].

With this expansion comes increased concern about motorbike riders' safety. In this context, the motorcycle helmet is the principal protective equipment worn by users of this mode of transportation. Wearing a helmet reduces the risk of death by 42 % and major injuries by 69 %, according to the Pan American Health Organization. These data highlight the device's critical efficacy in preventing fatalities and serious injuries in car accidents [2].

A motorcycle helmet is an important piece of safety equipment comprising numerous parts, including the shell, inner liner, comfort liner, chin strap, and visor, as depicted in Figure 1 [3]. This investigation will concentrate on the inner lining, often known as protective padding. This component is often composed of expanded polystyrene (EPS) because of its soft, cushioning features paired with a thick structure meant to decrease the impacts and the consequent injuries [4].

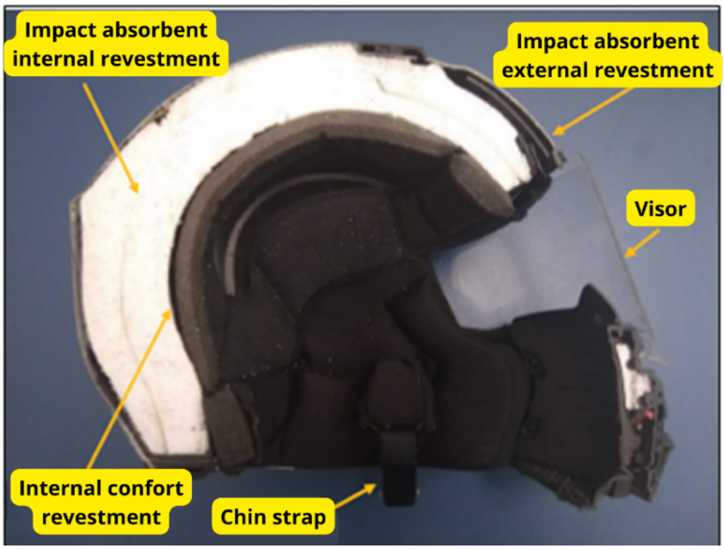

Figure 1: Adapted from Linhares, 2022.

However, ongoing technological advancement in tandem with a growth in global demand for resources, as well as consumer desires and expectations, has highlighted critical difficulties relating to material availability and environmental sustainability. There is an increasing interest in natural fibers in this context, as novel formulations and techniques are explored, developed, and applied consistently. This development demonstrates that natural fibers are becoming more viable as long-term alternatives capable of satisfying market demands [5].

The purpose of this research is to compare the impact absorption test on composites reinforced with natural fibers to expanded polyurethane (PU) foams. To accomplish this goal, the acquired data were subjected to a thorough statistical analysis. Initially, the normality test was used to validate the data distribution, to ensure the proper use of statistical tools. This statistical approach is required to ensure the robustness and reliability of the acquired findings. Statistical analysis was critical in interpreting the acquired data, allowing for an objective and grounded assessment of the effects of impact absorption in the various tested materials. Consequently, the use of statistics in this research gave a firm foundation for evaluating the data and making scientifically sound conclusions.

2. Experimental Method for Impact Absorption

2.1. The Manufacture of Composites

The polyurethane foams were created using a 1:1 mass ratio of polyol and isocyanate as specified by the manufacturer, both of which were acquired from the business AVIPOL®. Specific natural fibers (coconut, sugarcane bagasse, and sisal) were included during the foam creation process. The choice of these fibers was inspired by their widespread availability in Brazil and, in many cases, their improper disposal as solid waste, demonstrating the potential for the sustainable application of these resources [6].

The procedure for forming the composite, with the addition of natural fibers, initially involves chemical treatment of these fibers using a 10% sodium hydroxide solution (PA, VETEC®). This step takes place under controlled conditions of room temperature (25 ºC ± 5 ºC) and continuous agitation for a period of 15 minutes. Following this phase, the fibers are washed with distilled water until a state of neutrality is obtained and, later, they are dried in an oven at 70 °C for a period of 24 hours. Afterward, the fibers undergo a sieving process to homogenize the particle size. At the end of the process, the composites are then formulated with the proportions of 5 %, 10 %, and 15 % of the selected fibers. Because the study discovered specific limits on the use of higher volumes, these proportions were limited to a limit of 20 %. As a result, the volumes have been standardized to assure the dynamics and efficiency of the test body manufacturing [7, 8].

All stages of the composites' fabrication were carried out in a temperature-controlled environment (25 °C ± 5 °C), and a total healing time of 48 hours was observed as recommended by the manufacturer for subsequent impact absorption tests. The testing was carried out at the National Institute of Technology's Product Testing Laboratory (*Laboratório de Ensaios em Produtos)* (LAENP). Three authentic and true replicates of each chemical were created to assess variability. The standard thickness of the compounds was 10 mm, which corresponded to the thicker side filling of motorcycle helmets, representing the least thick and hence a significant criterion concerning thickness. A 100 mm diameter polyvinyl chloride (PVC) tube was utilized to standardize the molding.

2.2. Impact absorption test

The gravitational acceleration imposed on the test head, along with the helmet, during a guided free fall test is used to measure a helmet's impact absorption capabilities. During the test, the set including the helmet is dropped from particular elevations with impact speed of (7.00 ± 0.15) m/s on a flat surface and (6.00 ± 0.15) m/s on a hemispheric surface. In order to protect the user's safety, the ABNT standard NBR 7471:2015 regulates the maximum allowable acceleration. It is noteworthy that this maximum acceleration is expressed in multiples of "g," where "g" corresponds to 9.80665 m/s^2. These regulations include the requirement that acceleration does not exceed 300 "g" at any point and does not surpass 150 "g" for more than 5 ms [9].

The prototypes were randomized to undergo an impact test to establish adequate parameters for statistical analysis. The vertical machine for impact tests, model MAU 1006, produced by AD Engineering, was used to conduct this experimental research, as illustrated in Figure 2. This apparatus includes an integrated computer system capable of automatically displaying test findings, which comprise the helmet-head set acceleration, expressed in g, and the impact time interval, expressed in milliseconds (ms).

Figure 2: Impact Test Machine, 2023.
Source: Author

The test head with a circumference of 62 cm was employed for the process. This dimension was selected to reproduce the most severe impact conditions in mind, as it has the greatest radius and represents the greatest mass (6.1 ± 0.18 kg). The test was performed from a standard height, as is common in interlaboratory comparisons, equating to a drop of 50 centimeters (cm) starting from the P point of the test head, with an unchanged speed of 3.13 m/s. The acquired values were arranged and reported in Table 1, which highlights the findings of the impact absorption tests for each evaluated component.

Table 1. Impact absorption test results

Free fall (g)											
0 %	**5 %**			**10 %**			**15 %**				
Pure PU	Sugarcane bagasse	Coconut	Agave sisalana	Sugarcane bagasse	Coconut	Agave sisalana	Sugarcane bagasse	Coconut	Agave sisalana		
65.99	51.86	52.19	68.02	64.12	48.70	53.82	65.36	66.45	68.22	58.33	62.97
65.30	61.72	64.27	69.50	58.81	64.74	75.40	62.66	63.81	56.90	49.84	56.60
56.72	59.04	54.94	65.28	58.00	58.44	56.12	67.15	71.30	59.72	71.82	74.92
65.47	58.41	61.16	70.08	62.77	63.93	62.24	71.70	61.55	71.68	83.20	57.35
76.79	59.86	58.73	63.10	65.99	65.53	55.24	64.87	77.42	60.70	63.78	58.82
86.44	64.61	55.47	80.45	60.14	60.11	57.41	61.42	75.61	77.52	64.17	65.42
65.72	66.71	61.81	63.86	67.00	58.65	62.12	63.07	57.08	54.73	67.39	57.41
78.86	60.81	49.59	61.28	62.00	59.49	59.87	61.74	66.72	54.78	64.78	52.19
78.50	58.26	59.13	61.28	69.22	54.78	61.05	57.90	57.11	52.35	59.62	68.14
73.78	56.35	61.54	68.11	63.29	54.23	56.85	96.53	65.24	53.72	65.65	58.10

The statistics in Table 1 indicate that the samples investigated in the study are independent and not paired. This attribute is extremely important in identifying the best statistical procedures. The normality of the data is examined in this context to determine if parametric or nonparametric tests are appropriate for carrying out the analysis. The data are given to the normality test, guiding the decision between a parametrical or nonparametric analysis.

3. Experimental Method for Impact Absorption

The methodologies for statistically analyzing the impact energy absorption test findings are discussed in this section. The steps needed to verify the data's normality, and the tests used to identify any outliers, will be discussed. This part is critical in understanding the methodologies used for data analysis, allowing for a thorough and correct review of the results collected.

3.1. Shapiro-Wilk test

The Shapiro-Wilk test, introduced in 1965, stands out among the different statistical procedures for testing the normality of data, particularly when working with sample sizes of less than fifty [10]. Because of its usefulness, this test has become extensively recognized and employed, garnering recognition for its robustness and strong statistical power qualities. When we examine an ordered random sample, indicated by $x_1 \leq x_2 \leq \cdots \leq x_n$, the statistics associated with the Shapiro-Wilk test are expressed as follows:

$$W = \frac{(\sum_{i=1}^{n} aixi)^2}{\sum(xi-\bar{x})^2} \quad (1)$$

The i-third statistical order is represented by xi in this formula, and the sample average is represented by $\bar{x}$. Furthermore, the sequence is defined as $a-(a1,\ldots,an)-\frac{m^T V^{-1}}{(m^T V^{-1} m)^{1/2}}$ where m denotes the expected values of order statistics obtained from independent random variables and distributed identically according to the standard normal distribution. The matrix V, in turn, corresponds to the order statistics' covariance matrix. This metric has been shown to be effective in detecting normalcy deviations in a variety of datasets [11].

3.2. Parametric test for outliers: Chauvenet's criterion

The Chauvenet criterion is a frequently used statistical strategy for identifying outliers in data sets. Based on this criterion, a measure should be rejected if $|dj| = |y_j - \bar{y}| > d_{ch}$, where d_{ch} is Chauvenet's limit, defined as:

$$Po = \int_{-\infty}^{-d_{ch}} G(n)d_n + \int_{+d_{ch}}^{+\infty} G(n)d_n = \int_{-d_{ch}}^{+d_{ch}} G(n)d_n = \frac{1}{2n} \quad (2)$$

The integral of the Gaussian function in two symmetrical intervals yields the probability, *Po*. simplifying the integral yields the formula $Po = 1/(2n)$, where n is the number of samples. In other words, a measurement can be ruled out if the likelihood of obtaining a deviation as large or greater than the observed deviation from the average is less than $1/(2n)$. This criterion states that if the r value determined by: $r = \frac{|y_i - \bar{y}|}{S(X)}$, is greater than the critical value for the relevant degrees of freedom, a measure, yi, should be eliminated [12].

3.3. A nonparametric test for outliers: Interquartile range (IQR)

We chose a technique based on interquartile amplitude (IQR) within the framework of statistical analysis for outliers' identification, which differs from traditional practice, which frequently employs standard

deviation in parametric testing. Based on quartile principles, this approach identifies outliers as points that exceed 1.5 times the IQR, either below or above this limit.
The IQR is defined as the difference between the third and first quartiles, which correspond to the 75th and 25th percentiles, respectively. As a result, when we employ this technique, data that falls outside the bounds provided by equations (3) and (4) are labeled as potential outliers:

$$Q_1 - 1.5\ x\ (Q3 - Q1) \tag{3}$$
$$Q_3 + 1.5\ x\ (Q3 - Q1) \tag{4}$$

It is vital to emphasize the impact of x, a multiplicative factor that influences sensitivity in outlier detection, in this context. This criterion was chosen to find locations that depart significantly from the center trend of data distribution, indicating potential contradictions that should be investigated further [13].

4. Results and discussion

The data acquired from the impact energy absorption test was subjected to the Shapiro-Wilk test to determine the normalcy of polyurethane foam (PU) and composites reinforced with natural fibers prototypes. The hypothesis testing was run using the R-Studio software, a tool widely utilized for statistical analyses. To determine the normality of the distribution, the p-values obtained were taken into consideration. The distribution is deemed normal when the p-value exceeds 0.05.

The following hypotheses were developed to assess the data conjunctions:
H0: There is statistical evidence that the data is distributed normally.
H1: There is no statistical evidence that the data is distributed normally.

Table 2 displays the test findings, which provide information on the adequacy of the data distribution to the normalcy assumption.

Table 2. Shapiro-wilk for free fall results.

Type and quantity of fiber	P-value	Conclusion
PU 0 %	0.575	There is no evidence to reject the null hypothesis
Sugarcane bagasse 5 %	0.929	There is no evidence to reject the null hypothesis
Coconut 5 %	0.655	There is no evidence to reject the null hypothesis
Agave sisalana 5 %	0.086	There is no evidence to reject the null hypothesis
Sugarcane bagasse 10 %	0.940	There is no evidence to reject the null hypothesis
Coconut 10 %	0.605	There is no evidence to reject the null hypothesis
Agave sisalana 10 %	0.018	We have evidence to reject the null hypothesis
Sugarcane bagasse 15 %	0.238	There is no evidence to reject the null hypothesis
Coconut 15 %	0.588	There is no evidence to reject the null hypothesis
Agave sisalana 15 %	0.238	There is no evidence to reject the null hypothesis

Table 2 results were evaluated at a 95 % level of significance. The null hypothesis*,* H0, was found to be rejected for the 10 % sisal data set, showing that this data set does not follow a normal distribution. The null hypothesis was not rejected for the other data sets, indicating they may be approaching a normal distribution.

Outliers were treated based on these findings. The Chauvenet criterion was applied to data sets that resembled a normal distribution; on the other hand, IQR was used for the data set in which the null hypothesis was rejected. Tables 3 and 4 show the outcomes of these analyses.

Table 3. Chauvenet's test for free fall results

	Free fall (g)

	0 %	5 %			10 %		15 %		
	Pure PU	Sugarcane bagasse	Coconut	Agave sisalana	Sugarcane bagasse	Coconut	Sugarcane bagasse	Coconut	Agave sisalana
Mean	71.36	59.76	57.88	67.10	63.13	58.86	67.24	66.23	62.36
Standard deviation	8.92	4.16	4.69	5.70	3.60	5.25	10.94	6.95	7.99
Outlier	-	-	-	80.45	-	-	-	-	83.20

According to the results shown in Table 3, upon applying the Chauvenet criterion, it was possible to identify the presence of outliers in the sisal sample sets with 5% and 15% concentrations. These outliers were excluded from the analysis, as their presence could adversely affect the results and hinder the proper interpretation of the data.

Table 4. The interquartile range for free fall results

10 % Agave sisalana (g)	
1st Quartile (Q1)	56.30
3rd. Quartile (Q3)	61.85
IQR (Q3-Q1)	5.55
Upper limit (Q3+1,5 x IRQ)	70.18
Lower limit (Q1-1,5 x IRQ)	47.98
Outlier	75.40

The Interquartile Range (IQR) is the difference between the third quartile (Q3) and the first quartile (Q1), acting as a measure of dispersion for the central half of the observed data. Using the IQR, we established lower and upper thresholds for accurate outlier detection. As delineated in Table 4, an outlier was detected in the dataset containing 10% Agave sisalana, with a value of 75.40. This atypical value was swiftly excluded from subsequent analyses to ensure accurate interpretation and conclusions regarding the results. Following the exclusion of this outlier, the modified dataset underwent the Shapiro-Wilk test to evaluate its normality. This step was initiated due to concerns that the outlier might have skewed our understanding of the data's distribution. We used a 95% significance level for this test, and the evaluated hypotheses were:

H0: There is statistical evidence that the data is distributed normally.

H1: There is no statistical evidence that the data is distributed normally.

The result of this test is presented in Table 5.

Table 5. Shapiro-Wilk: 10% Agave Sisalana (Without Outliers)

Type and quantity of fiber	P-value	Conclusion
Agave sisalana 10 %	0.9245	There is no evidence to reject the null hypothesis

The analysis confirmed that all data sets adhere to a normal distribution. In comparing the various composites to the Polyurethane prototype, we utilized the confidence interval method at a 95% significance level. This method facilitated the assessment of the accuracy of sample means. With a number of samples of fewer than 30 in each set and an assumed normal distribution, we employed the Student's t-distribution to determine critical values. The standard error (SE) was computed from the sample standard deviation, adjusted for the number of samples, as described by the following formula: SE=$\sigma/\sqrt{n}$. The CI is defined by the expression $\bar{x} \pm t * SE$.

Table 6 provides the results for each dataset.

Table 6. Confidence Interval Results for the Different Prototypes

Prototype	Mean	Standard deviation	samples	Confidence Interval
PU 0%	71.36	8.92	10	6.38
Sugarcane Bagasse 5%	59.76	4.16	10	2.97
Coconut 5%	57.88	4.69	10	3.36
Agave sisalana 5%	65.61	3.43	9	2.64
Sugarcane bagasse 10%	63.13	3.59	10	2.57
Coconut 10%	58.86	5.25	10	3.76
Agave sisalana 10%	58.30	3.11	9	2.39
Sugarcane bagasse 15%	63.99	3.93	9	3.02
Coconut 15%	66.23	6.95	10	4.97
Agave sisalana 15%	61.64	7.07	29	2.69

Figure 3 illustrates the confidence intervals for each composite group, enabling a visual comparison of the variations between the materials under investigation.

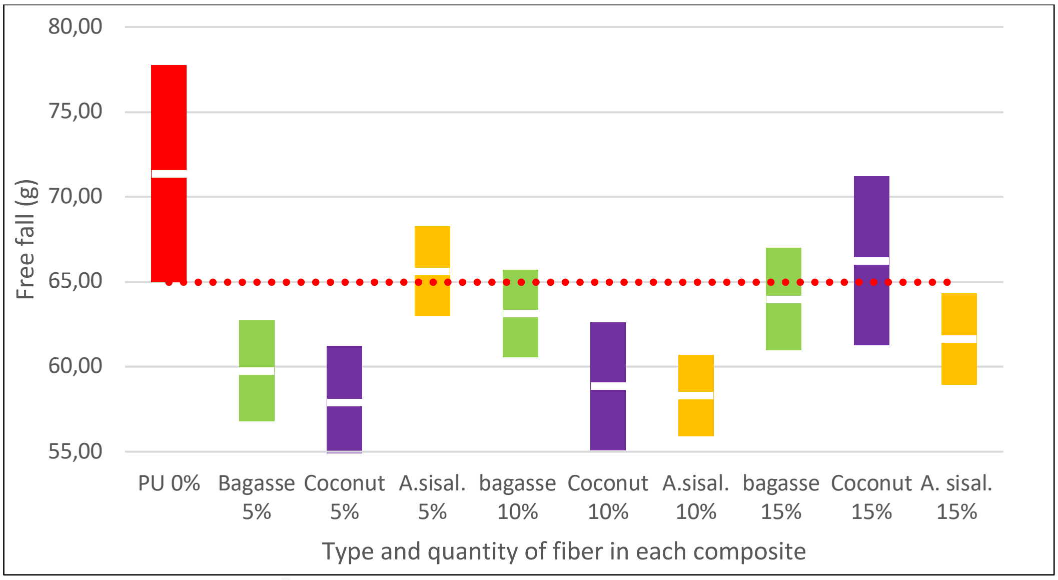

Figure 3: Confidence interval for free fall by composite type.

The analysis conducted highlighted a significant difference when comparing the performance of the pure polyurethane (PU) prototype to the composites reinforced with natural fibers. It's crucial to underscore that composite with added natural fibers exhibited superior performance compared to pure PU. Moreover, the findings showcased the exceptional performance of the various fibers employed. Sugarcane bagasse stood out at a 5 % ratio, coconut excelled at 5 % and 10 % ratios, and sisal shone at the 10 % and 15 % ratios. This finding demonstrates that the introduction of natural fibers improved the characteristics and performance of composites, showing their potential as a promising alternative to the reference material.

5. Conclusions

The purpose of this study was to look at the effect of an impact absorption trial on compounds reinforced with natural fibers. We conclude that there are statistically significant variations in impact absorption between pure polyurethane (PU) prototypes and compounds supplemented with natural fibers based on the data obtained. Furthermore, the study emphasizes that the presence of fibers results in superior impact absorption performance, corroborating previous research.

The results obtained are important for the ongoing research, which utilizes multivariate analysis to identify the most suitable component to replace EPS in the fabrication of protective linings for motorcycle helmets for their users.

The findings of this study contribute to the growth of knowledge in the field of natural fiber-reinforced composites and their use in increasing impact absorption in protective equipment such as motorcycle helmets. The findings emphasize the need to produce compounds with varying proportions and types of natural fibers to achieve optimal impact absorption performance.

However, it is critical to stress that additional research is required to enhance knowledge in this sector. Future research may investigate additional aspects of compounds, such as mechanical strength and durability, as well as the impact of processing and overall material characteristics. These new studies will provide a more thorough and enhanced understanding of natural fiber-enriched substances and their uses in protective equipment.

6. References

[1] Abramet, Associação Brasileira de Medicina de Tráfego et al 2021 *A motocicleta no Brasil do século XXI*. ABRAMET.

[2] OPAS, Organização Pan-Americana da Saúde 2023 Segurança no Trânsito. [Online]. Available: Segurança no trânsito - OPAS/OMS | Organização Pan-Americana da Saúde (paho.org). [Accessed: 14/06/2023].

[3] Linhares, L 2022 *Análise da performance de capacetes para motociclistas: Influência da temperatura em ensaios de impacto*. Trabalho de conclusão de curso (Graduação em Engenharia Mecânica) – Departamento de Ensino Superior do CEFET/RJ, Rio de Janeiro.

[4] Ferreira, R 2013 *Estudo comparativo do desempenho mecânico de capacetes fabricados com diferentes materiais atuando na segurança do motociclista*. Trabalho de conclusão de curso (Graduação em Engenharia de Materiais) - Centro Federal de Educação Tecnológica de Minas Gerais, Minas Gerais.

[5] Faruk O, Bledzki A, Fink H and Sain M 2012 Biocomposites reinforced with natural fibers: 2000–2010. *Progress in polymer science* **37** (11) 1552-1596.

[6] Singh M, Singh P and Brar, G 2019 Natural Fiber Reinforced Polyurethane Composite. *Journal of Emerging Technologies and Innovative Research* **6** (5) 399-401.

[7] El-shekeil Y, Sapuan S, Khalina A, Zainudin E and Al-Shuja'a O 2012 Effect of alkali treatment on mechanical and thermal properties of Kenaf fiber-reinforced thermoplastic polyurethane composite. *Journal of Thermal Analysis and Calorimetry* **109** (3) 1435-1443.

[8] Sonnenschein M 2021 *Polyurethanes: science, technology, markets, and trends*. John Wiley & Sons.

[9] ABNT 2015 *NBR 7471:2015. Veículos rodoviários automotores — Capacete e viseiras para condutores e passageiros de motocicletas e veículos similares — Requisitos de desempenho e métodos de ensaio*. Rio de Janeiro: ABNT.

[10] Shaphiro S and Wilk M 1965. An analysis of variance test for normality. *Biometrika* **52** (3) 591-611.

[11] Razali N and Wah Y 2011 Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors

and anderson-darling tests. *Journal of statistical modeling and analytics* **2** (1) 21-33.

[12] de Oliveira E, de Faro A, dos Santos A and de Oliveira C 2016 Comparison of different approaches for detection and treatment of outliers in meter proving factors determination. *Flow Measurement and Instrumentation* **48** 29-35.

[13] Zou M, and Djokic S 2020 A review of approaches for the detection and treatment of outliers in processing wind turbine and wind farm measurements. *Energies* **13** (16) 4228.

Acknowledgments

We want to thank the Laboratory Technicians, Rubem Samuel Silva dos Santos, Valcemar de Oliveira Junior, and Agemar de Paula Filho, for their help during the impact tests. We also thank Vitoria Maria da Silva Garcia, the production engineer, for her assistance in quality management, and Leonardo de Farias Linhares, the mechanical engineer, and manager of the Product Testing Laboratory, for his leadership and advice to the technicians in this effort.

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brazil) under finance code 001, as well as the Brazilian agency CNPq (305479/2021-0) for providing a scholarship.

Special thanks are also extended to MCTI and FAPERJ for their significant assistance.