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Evaluation of Precision Statements for Physio-mechanical Characterization Tests on GFRP Bars

Reference

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ABSTRACT

Glass fiber reinforced polymer (GFRP) bars are composite materials that, in the field of civil engineering, serve as an alternative for the internal steel reinforcement of concrete structures. The study and development of these material systems in construction are relatively new, requiring targeted research and development to achieve greater adoption. In this scenario, research and standardization play crucial roles. The development and publication of new test methods, material specifications, and other standards, as well as the improvement of the existing ones, allow for quality control, validation, and acceptance. One of these improvements is the evaluation of precision statements of the different ASTM standards related to the physical-mechanical and durability characterization of GFRP bars used as internal concrete reinforcement. Precision refers to how closely test results obtained under specific conditions agree with each other. A precision statement allows potential users to assess the test method's general suitability for their intended applications. It should provide guidance on the type of variation that can be expected between test results when the method is used in one or more competent laboratories. The present study aims to enhance the precision statements in ASTM standards pertaining to the geometric, material, mechanical, and physical properties required for GFRP bars in concrete reinforcement, including ASTM standards like ASTM D7205M-21, *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars*; ASTM D7617M-11(2017), *Standard Test Method for Transverse Shear Strength of Fiber-Reinforced Polymer Matrix Composite Bars*; and ASTM D7913M-14(2020), *Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing*, while in accordance with the statistical procedures and calculation methods outlined in ASTM Practices ASTM E177-20, *Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods*, and ASTM E691-22, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*.

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Keywords

GFRP bars, interlaboratory study, precision statistics, repeatability, reproducibility

Introduction

The construction industry ranks among the highest consumers of raw materials and contributes significantly to carbon dioxide emissions. Consequently, ensuring sustainability poses challenges in the design and construction of buildings and infrastructure. This involves the utilization of new materials that offer enhanced performance, affordability, public acceptance, and minimal environmental impact. These considerations apply not only to new constructions but also to existing structures. Accordingly, addressing infrastructure sustainability is a pressing research and practical concern today. Constructed facilities undergo degradation due to physical and environmental factors, leading to a shortfall in the expected service life of structural elements.[1,2]

When choosing the right material for a given application, it is crucial to understand its physical and mechanical properties. From this knowledge, it is possible to create products that meet certain performance, safety, and reliability requirements. Similarly, the physical and mechanical properties of a material influence how it can be processed and manufactured, allowing processes to be determined and optimized to obtain high-quality products.

The adoption of glass fiber reinforced polymer (GFRP) composites as internal reinforcement in concrete structures has emerged as a viable alternative to conventional steel reinforcement. This choice offers substantial benefits, especially corrosion resistance, ensuring enhanced durability and prolonging the structural lifespan.[3]

Because of these benefits, the fiber reinforced polymer (FRP) market has grown significantly in recent years and several products have already been implemented in different construction projects. In the early days, the absence of standards and specifications led to a diverse market, in which manufacturers developed FRP bar products with varying physical and mechanical characteristics.[4–6]

An important challenge impeding the incorporation of FRP composite materials into civil engineering lies in the lack of standardization for these materials. Nonstandard or proprietary materials necessitate validation for both short-term and long-term performance. This involves employing test methods and meeting criteria that may not be standardized either.[7] Currently, there are ASTM standard specifications related to the physical-mechanical and durability characterization of FRP bars used as internal concrete reinforcement such as ASTM D8505M-23, *Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement*, or D7957M-22, *Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement*, along with various standard test methods including ASTM D7617M-11, *Standard Test Method for Transverse Shear Strength of Fiber-Reinforced Polymer Matrix Composite Bars*; ASTM D7205M-21, *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars*; ASTM D7913M-14, *Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing*; ASTM E1356-08(2014), *Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry* (Withdrawn); ASTM E2160-04(2018), *Standard Test Method for Heat of Reaction of Thermally Reactive Materials by Differential Scanning Calorimetry*; ASTM E2584-18, *Standard Test Method for Ignition Loss of Cured Reinforced Resins*; ASTM D570-98(2018), *Standard Test Method for Water Absorption of Plastics*; and ASTM D792-20, *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*, among others. Because of applied research discoveries and the diversity of constituent materials and shapes driven by manufacturers pursuing improved performance with new generations of bars, the demand for testing methods and materials specifications has increased.[5,8]

ASTM D7957-M22[9] is the *Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement*. The bars covered by this specification must qualify through different test methods and meet the geometric, material, mechanical, and physical property requirements described in that document. In this way, it is possible to perform quality control and certification of the production for many of these bars.

Bias is a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. Precision, on the other hand, refers to the closeness of agreement between test results obtained under prescribed conditions.[10] The adoption of ASTM D7957M-22 has brought standardization to the GFRP bar industry, freeing designers and contractors from dependence on a specific manufacturer. This ensures traceability to production batch certifications, promoting safe and durable performance. However, the test methods referenced in ASTM D7957M-22, such as ASTM D7205M-21 or ASTM D7617M-11(2017) among others, currently lack bias and precision statements. Though the bias statement should describe the bias and methods employed to provide the corrected test results, the absence of universally accepted reference values for these test methods makes it infeasible to establish such statements at this time. However, precision can be estimated in accordance with the test program outlined in ASTM Practice E691-22, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*, by conducting an interlaboratory study to determine the precision of a test method, or through an equivalent interlaboratory test program.

As a reference for this type of analysis, Research Report D30-1003[11] from ASTM International was conducted to establish precision statistics for ASTM D3039M-14,[12] *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. The objective of the interlaboratory test program was to obtain precision measures, including repeatability and reproducibility, for several commonly used composite material systems using the ASTM D3039M-14 test method. In addition, the precision measures generated through the study were incorporated into the ASTM D3039M-14 precision statement.

To address part of this challenge in physio-mechanical characterization and durability test methods for GFRP bars, the present work aims to establish a precision statement that provides guidelines on the expected variability between test results when the test method is used in one or more laboratories. Offering measurable parameters of expected variability could empower laboratories and manufacturers to make more accurate decisions regarding the performance of materials. Similarly, it could assist in establishing standardized test protocols and contribute to more reliable and consistent results across various test environments.

Materials and Methods

GFRP BARS

FRP bars are composite materials composed of continuous longitudinal fibers embedded in a resin matrix. Commonly used fibers include glass, carbon, aramid, and basalt, whereas the matrices typically consist of thermosetting resins like epoxies, polyesters, and vinyl esters. Additionally, rebar surfaces may exhibit various textures and surface deformations, such as sand-coated, grooved, lugged, and others. These types of rebars are manufactured by the pultrusion process.

GFRP bars, in particular, are increasingly being used as an alternative for the internal steel reinforcement of concrete structures because of advantages including high tensile strength, low weight, and corrosion resistance. This extends the service life of structures and reduces maintenance costs.[13] The use of FRP composites within structures is closely tied to areas where the corrosion of conventional steel reinforcement poses significant economic and safety risks. The excellent mechanical capabilities, outstanding durability, and sustainability benefits (including reduced environmental impacts like global warming, photochemical oxidant generation, and acidification) of FRP composites make them highly suitable for such situations.[14]

TEST METHODS

To be used as reinforcement in concrete structures, GFRP bars must conform to standard specifications. ASTM D7957M-22[9] defines requirements for the geometrical, material, mechanical, and physical characteristics of GFRP bars. Additionally, the standard prescribes sampling protocols for bar qualification, quality control, and certification. To address the precision statistics of the required test methods in the GFRP bar specification (ASTM D7957M-22), these methods were categorized into two groups: mechanical properties and physical and durability properties. The first group includes the following properties:

- Tensile properties: ultimate tensile force, tensile modulus of elasticity and ultimate tensile strain (ASTM D7205M-21[15,16])

- Transverse shear strength (ASTM D7617M-11(2017)[17])
- Bond strength (ASTM D7913M-14(2020)[18])

The second group includes the following properties:

- Fiber mass content (ASTM D2584-18[19])
- Glass transition temperature (ASTM E1356-08(2014)[20])
- Degree of cure (ASTM E2160-04(2018)[21])
- Measured cross-sectional area (ASTM D7205M-21 and ASTM D792-20[15,22])
- Moisture absorption to saturation in 24 hours (ASTM D570-98(2018), *Standard Test Method for Water Absorption of Plastics*[23])

Some of these methods, such as ASTM D7913M-14 or ASTM D2584-18, include a partial statement of precision. However, others, such as ASTM D7205M-21 or ASTM D7617M-11(2017), do not include any statement and indicate that precision, defined as the degree of agreement between individual measurements, cannot be estimated because of an insufficient amount of data. It is worth noting that much of this data are available in laboratories conducting daily tests on these materials. Therefore, this work aims to complement these test methods by providing the necessary statistics. The Structures and Materials Laboratory (SML) at the University of Miami (an ISO 17025-certified laboratory) uses state-of-the-art equipment and modern instrumentation for experimental and analytical research of FRP materials, with a focus on their physio-mechanical and durability characterization. Over the past several years, a significant amount of experimental data have been collected and can be analyzed and processed for statistical studies aimed at reducing uncertainty.

To carry out this study, a database of physical and mechanical characterization tests performed during the last six years at the SML was collected. From this information, the guidelines, calculation methods, and statistical procedures of ASTM E177-20, *Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods*,[24] C670-15, *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*,[25] and ASTM E691-22, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*[26] standards were followed with some exceptions, explained hereafter:

Interlaboratory Study (ILS)

The design considered for the ILS is represented by a two-way classification table, with rows representing laboratories and columns representing materials. Each cell, at the intersection of a row and column, contains the test results from a specific laboratory on a particular material (see **Table 1**).

Laboratories

Although Standard Practice ASTM E691-22 requires a minimum of six laboratories for an ILS, this study was conducted in a single laboratory. It is important to note that the data collected in the study span tests conducted over several years, with different operators at different times. As a result, variations between operators, such as dexterity, reaction time, interpolation in scale reading, etc., contribute to the variability between test results that should be considered when calculating the reproducibility of the method for the statement of precision.

Given the limited number of laboratories, this variable was replaced by having different technicians perform the tests while using the same equipment. This decision was based on the primary goal of establishing preliminary precision statements for various physical-mechanical and durability tests required for GFRP bar specifications. As mentioned earlier, some of these tests do not even have a preliminary statement, and this study aims to provide that initial approach. Each year from 2018 to 2023 was treated as a "laboratory" in the study, with Laboratory 1 representing 2018 and Laboratory 6 corresponding to 2023.

This study introduced additional variability from factors such as different operators and longer test times within a laboratory. Therefore, the precision must be designated as "intermediate precision" per the Form and Style for ASTM Standards[10] guidelines outlined in section A21.2.4. ASTM E456-13a(2022), *Standard*

TABLE 1
Ultimate tensile force ILS test result data (units in kN)

	Material			
Laboratory	A (#3)	B (#4)	C (#5)	D (#6)
1	86.55	146.53	228.49	309.78
	81.87	135.87	225.35	307.18
	86.30	144.29	230.99	284.23
	87.46	138.89	211.46	295.40
	84.33	124.25	228.97	292.37
2	83.41	134.42	239.8	313.29
	89.70	131.76	220.74	299.72
	86.75	128.36	217.52	310.66
	88.65	126.18	220.14	306.39
	86.01	138.34	222.81	289.62
3	85.91	135.23	220.68	318.98
	84.16	132.82	219.74	303.78
	88.31	134.12	205.06	279.35
	88.19	133.45	204.24	296.84
	86.04	140.60	212.12	306.10
4	80.51	133.45	202.39	301.14
	78.58	140.60	207.78	309.88
	76.76	152.84	214.84	308.66
	76.06	143.68	207.29	327.39
	84.90	135.98	194.20	319.28
5	84.59	136.69	226.43	305.35
	96.52	139.04	216.77	324.59
	83.77	133.22	218.16	323.80
	84.75	142.12	220.10	324.06
	86.30	131.14	217.08	323.21
6	85.45	135.97	213.32	320.56
	84.39	134.65	223.63	330.01
	85.81	137.39	233.52	327.41
	86.30	140.61	224.89	329.62
	85.17	140.63	209.17	321.06

Terminology Relating to Quality and Statistics,[27] further defines this term as the "precision of test results from tests conducted on identical material by the same test method in a single laboratory at the same or various times with one or more known sources of variability controlled at multiple levels." As a result, the outcomes of this study will be considered to demonstrate "intermediate precision" based on these criteria.

Materials

In this study, four materials (except for the results of ASTM D7913M-14(2020), which only considers three materials) were considered. Materials are represented by four diameter sizes of Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement. Recognizing the differences in form factors and surface enhancements among GFRP bars from various manufacturers, ASTM D7957M-22 introduces the concepts of 'nominal bar diameter' which corresponds to a standard diameter of a bar and 'size designation' which corresponds to an alphanumeric identifier of different bar sizes. The materials used in this study are listed below:

- Material A: GFRP bar No.3.
- Material B: GFRP bar No.4.
- Material C: GFRP bar No.5.
- Material D: GFRP bar No.6.

Number of Test Results per Material

In this study, a total of five (5) test results per material were specified. This sampling rate was chosen following the guidelines provided in Section 11 of ASTM practice E691-22. This section recommends a minimum of three test results per laboratory for chemical tests and three or four for physical or optical tests to obtain a reliable estimate of repeatability.

Calculation and Display of Statistics

According to ASTM practice E691-22, there are three main objectives in analyzing and interpreting the results of an ILS. The first objective is to assess the consistency of the collected data to establish a reliable test method precision statement. The second is to identify and address any inconsistent data. Lastly, the analysis aims to obtain the necessary precision statistics for formulating the precision statement, which is preliminary in this case study. The statistical analysis involves conducting a one-way analysis of variance for each level of the tested materials, separately considering the within-laboratory and between-laboratory variations. To provide a detailed explanation of the process, the following parameters were defined:

n, number of test results
p, number of laboratories
x, individual test result
$\bar{x}$, cell average
s, cell standard deviation
$\bar{\bar{x}}$, average of cell averages
d, cell deviation
$S_{\bar{x}}$, standard deviation of cell averages
S_r, repeatability standard deviation
S_L, between-laboratory standard deviation
S_R, reproducibility standard deviation
h, between-laboratory consistency
k, within-laboratory consistency

The terms above are used as specified in ASTM Practice E177-20 and standard E456-13a. To facilitate the calculations, a separate worksheet for each material was prepared using Table 2 of Practice E691-22 as a model. The test result data for each material, along with the calculated variables mentioned earlier, were entered on the same worksheet. This was done in accordance with the mathematical and statistical procedures outlined in Practice E691-22. Details of the display of results are presented below in the Results and Discussion section.

Results and Discussion

This section provides a general discussion of the results obtained for the two groups of properties studied and presents the precision statement for each of the tests analyzed in this study.

CRITICAL VALUES OF THE CONSISTENCY STATISTICS

The critical values of the consistency statistics h and k are defined for a significance of 0.5 %. The critical values for h depend on p, whereas the critical values for k depend both on p and n. Therefore, as provided in figure 1 and figure 2, for the evaluated physio-mechanical parameters $p = 6$, $n = 5$ the resultant critical values are: $h = 1.92$ and $k = 1.75$. All critical values were calculated based on the Student's t distribution with $p - 2$ degrees of freedom.

MECHANICAL PROPERTIES DISCUSSION ILS

Based on the results of figures 1 and 2, no significant h and k values were noted for the ultimate tensile strain and Transverse Shear Strength data, whereas a few were noted for the ultimate tensile force, modulus of elasticity

FIG. 1 *h*-materials between labs: (*A*) ultimate tensile force, (*B*) modulus of elasticity, (*C*) ultimate tensile strain, (*D*) transverse shear strength, (*E*) bond strength, (*F*) fiber mass content, (*G*) glass transition temperature, (*H*) degree of cure, (*I*) measured cross-sectional area, (*J*) moisture absorption to saturation, and (*K*) moisture absorption in 24 h.

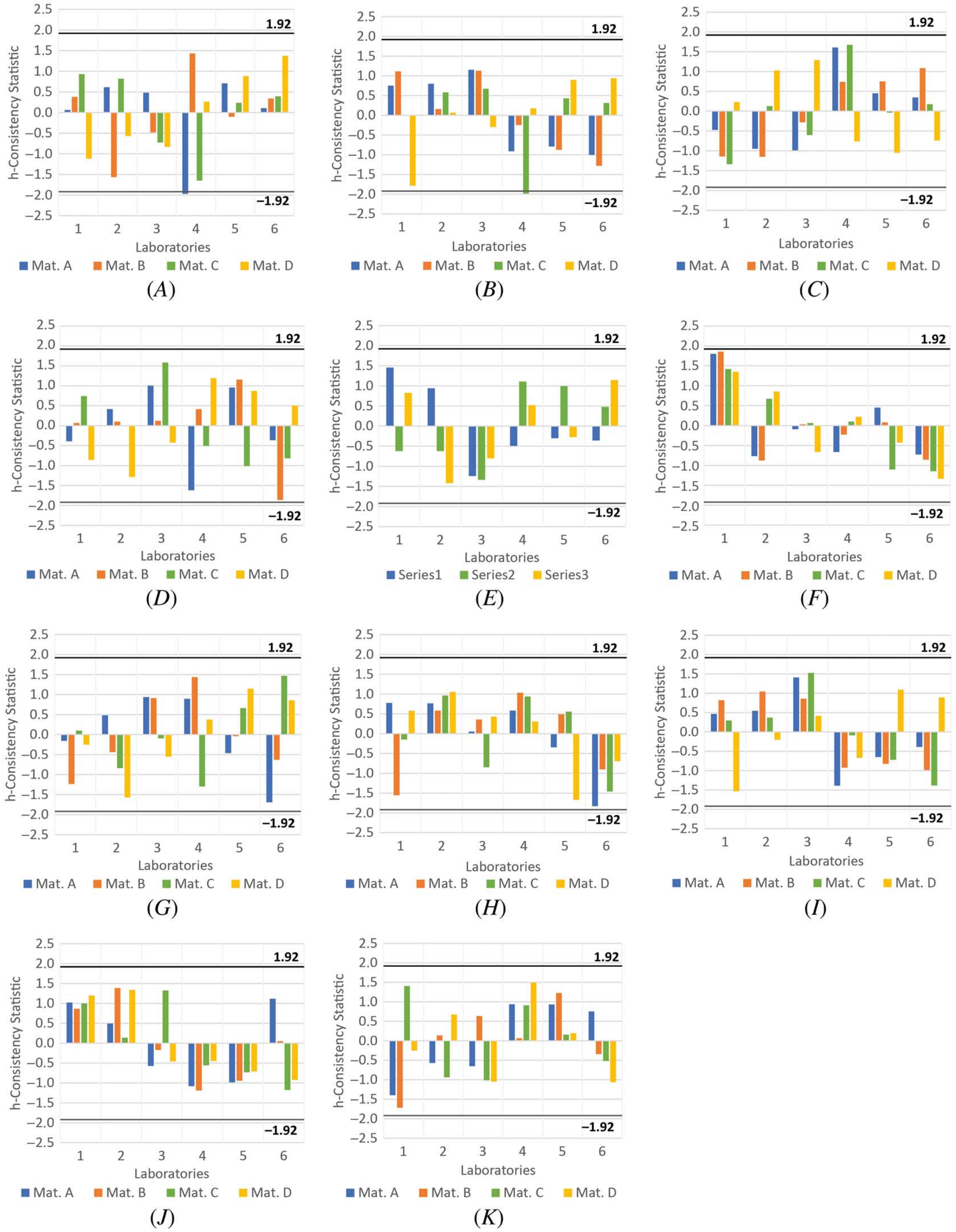
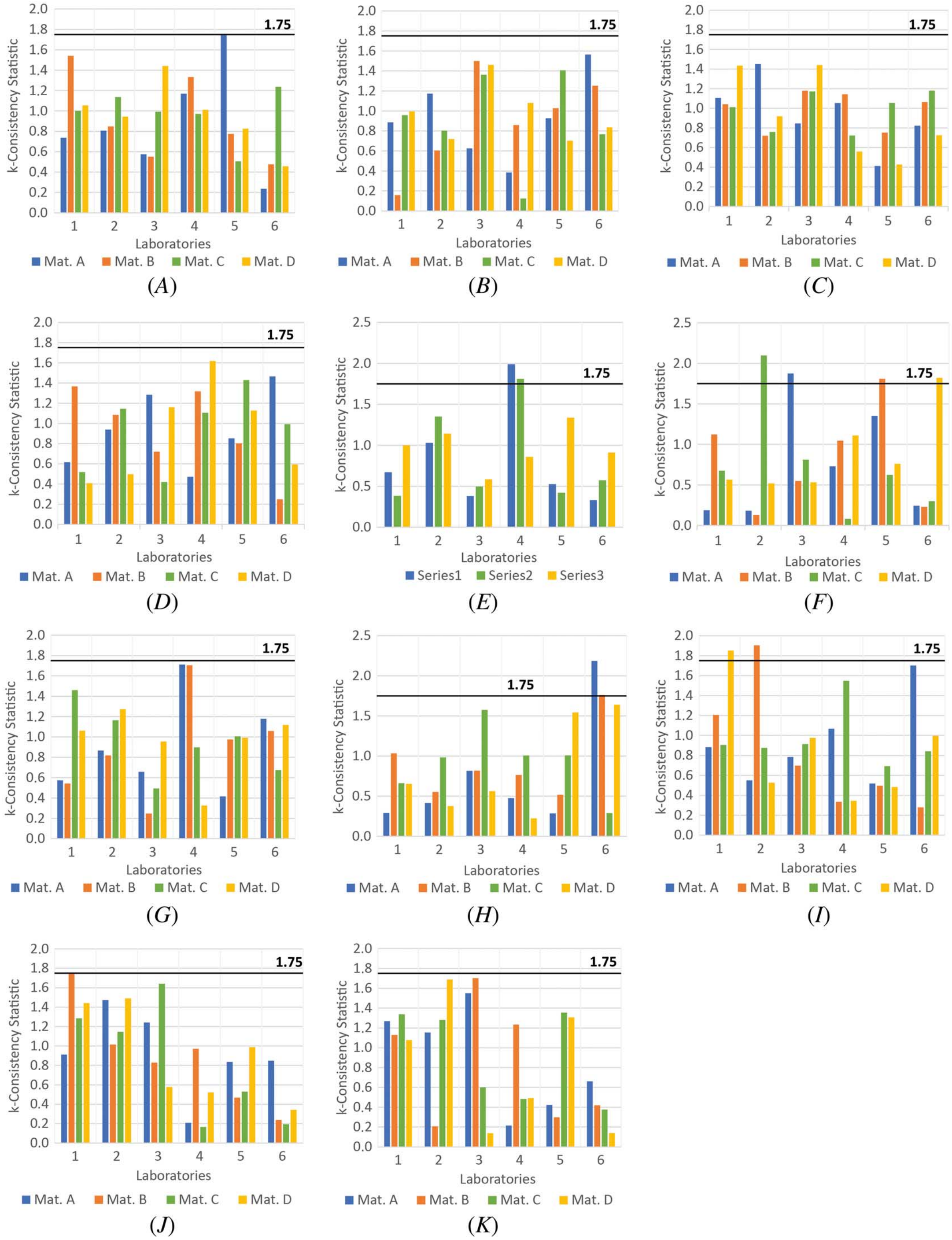


FIG. 2 *k*-materials within labs: (*A*) ultimate tensile force, (*B*) modulus of elasticity, (*C*) ultimate tensile strain, (*D*) transverse shear strength, (*E*) bond strength, (*F*) fiber mass content, (*G*) glass transition temperature, (*H*) degree of cure, (*I*) measured cross-sectional area, (*J*) moisture absorption to saturation, and (*K*) moisture absorption in 24 h.



and Bond Strength. Regarding the h-statistic consistency for ultimate tensile force, only laboratory 4 stands out with a large value for Material A (Bar #3). However, if this laboratory is reviewed in more detail, there is a pattern in which the h-values for low levels of properties are of one sign (−1.97, for Material A), and for high levels of properties are of the opposite sign (0.26, for Material D). This may require further investigation of the results of laboratory 4. In terms of the k-statistic consistency, no significant k values were observed for the ultimate tensile force test, suggesting minimal within-laboratory imprecision. Only the data obtained for material A (Bar #3) from laboratory 5 approached but did not exceed the limit. This behavior can be attributed to the unusually high value of 96.52 kN reported in one of the results.

For modulus of elasticity, data obtained from laboratory 4 for material C (Bar #5) was found to provide an h value which exceeded the limit. Similarly, bond strength data obtained from laboratory 4 for materials A (Bar #3), and C (Bar #5) were found to provide a k-value which exceeded the limit. The fact that all the suspicious values were generated by laboratory 4 indicates that there might be a problem with the method used by that laboratory to test the specimens or to collect or analyze the data.

In the ultimate tensile strain data, a pattern is observed where the h-values have one sign for low property levels and the opposite sign for high property levels. This pattern may necessitate further investigation across all laboratories; in some cases, the mean results for each material are lower than the overall mean, whereas in others, they are higher.

The graph shown in **figure 3**, based on S_r and S_R values, helps illustrate whether there is a variation in the precision statistics with the level of property. For tests where there is no variability in the result when changing the diameter of the bars, the expected performance will be scattered without any trend. However, in the presence of variability, a linear trend is expected. As can be seen in **figure 3**, this latter condition only applies to the ultimate tensile force and bond strength tests. For modulus of elasticity, ultimate tensile strain, and transverse shear strength tests, little variation is observed. In **figure 3*A***, there is a noticeable trend of increased statistical precision variation as the property level increases, with S_r values ranging from 3.03 kN for material A (Bar #3) to 10.07 kN for material D (Bar #6). This indicates that for the specific case of the ultimate tensile force test, the larger the diameter of the bar, the greater the established range of statistical precision in the test. Similarly, for properties with consistent results, this behavior indicates that the statistical precision tends to remain the same regardless of the bar's diameter. Therefore, the repeatability and reproducibility standard deviation provided herein are within expected performance.

PHYSICAL AND DURABILITY PROPERTIES DISCUSSION ILS

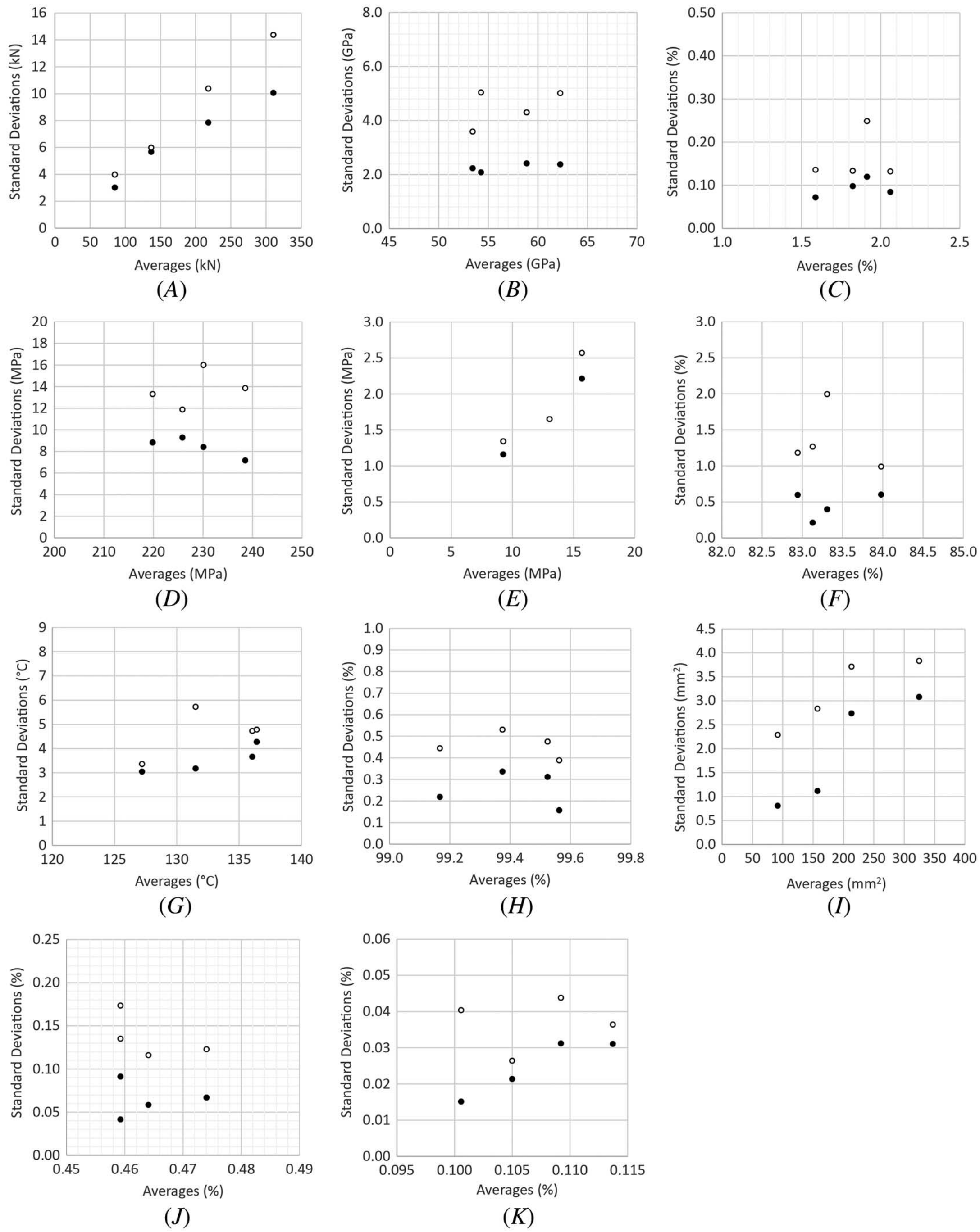
Regarding the group of physical and durability properties, no significant *h* and *k* values were noted for the glass transition and moisture absorption to saturation and in 24 h data whereas a few were noted for the fiber mass content, degree of cure and measured cross-sectional area. In the case of the latter, it was observed that data obtained from a few laboratories provided a *k*-value that exceeded the limit, indicating within-laboratory imprecision for these specific cases.

Similarly, in the results for fiber content, degree of cure, cross-sectional area, and moisture absorption to saturation, a trend is observed where some laboratories have positive h-values for all their materials whereas others have negative h-values. This indicates that the results from some laboratories are consistently below the general average, and those from other laboratories are consistently above it. Finally, like what was found in the mechanical properties group, for most of the physical and durability properties (except for cross-sectional area), the trend indicates that the statistical precision remains consistent irrespective of the bar diameter.

Investigation, Task Group Actions

Because the data used for the development of this study corresponds to results already processed and reported during the past six years by The SML at the University of Miami, an investigation into clerical errors, sampling, or procedural errors was not conducted. Therefore, all data, including any unusual results, were retained when determining the precision statistics for each test.

FIG. 3 Standard deviations of reproducibility (*O*) and repeatability (•) versus average: (*A*) ultimate tensile force, (*B*) modulus of elasticity, (*C*) ultimate tensile strain, (*D*) transverse shear strength, (*E*) bond strength, (*F*) fiber mass content, (*G*) glass transition temperature, (*H*) degree of cure, (*I*) measured cross-sectional area, (*J*) moisture absorption to saturation, and (*K*) moisture absorption in 24 h.



PRECISION STATEMENTS

From the statistics calculated in the previous sections, the calculation of repeatability (r) and reproducibility (R) limits according to the following equations is presented below:

$$r = 2.8S_r \quad R = 2.8S_R$$

In accordance with ASTM Practice E177-20 and C670-15, the precision statement is presented as follows:

Test Result

The precision information provided below, measured in the indicated units, is calculated in accordance with Practice ASTM E691-22. This study involves four materials (except for the results of ASTM D7913M-14 (2020), which only considers three materials) represented by four diameter sizes of Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement. The testing was conducted by a single laboratory over several years and by different operators. The terms "repeatability limit (r)" and "reproducibility limit (R)" are used as specified in Practice ASTM E177. The results are divided into two groups: mechanical properties and physical and durability properties.

Precision Results for Mechanical Properties

TABLE 2
Precision statistics for mechanical properties

Material	$\bar{\bar{x}}$	$s_{\bar{x}}$	s_r	s_R	r	R
Ultimate tensile force (kN) (ASTM D7205M-21)						
A	85.117	2.9221	3.0316	3.9863	8.49	11.16
B	136.770	3.1693	5.6828	5.9899	15.91	16.77
C	217.923	7.6486	7.8589	10.3880	22.01	29.09
D	310.324	11.2093	10.0670	14.3779	28.19	40.26
Tensile modulus of elasticity (GPa) (ASTM D7205M-21)						
A	54.260	4.6855	2.0868	5.0436	5.84	14.12
B	53.418	2.9836	2.2376	3.5927	6.27	10.06
C	58.874	3.7216	2.4144	4.3027	6.76	12.05
D	62.255	4.5421	2.3788	5.0157	6.66	14.04
Ultimate tensile strain (%) (ASTM D7205M-21)						
A	2.061	0.1085	0.0845	0.1322	0.24	0.37
B	1.914	0.2247	0.1199	0.2490	0.34	0.70
C	1.824	0.1007	0.0981	0.1335	0.27	0.37
D	1.588	0.1198	0.0720	0.1360	0.20	0.38
Transverse shear strength (MPa) (ASTM D7617M-11(2017))						
A	230.099	14.1289	8.4098	16.0065	23.55	44.82
B	238.527	12.3001	7.1782	13.8749	20.10	38.85
C	219.838	10.7108	8.8406	13.3134	24.75	37.28
D	225.872	8.4986	9.2907	11.8862	26.01	33.28
Bond strength (MPa) (ASTM D7913M-14(2020))						
A	15.677	1.6395	2.2125	2.5698	6.19	7.20
C	13.023	0.5384	1.6505	1.6505	4.62	4.62
D	9.248	0.8501	1.1599	1.3413	3.25	3.76

Precision Results for Physical and Durability Properties

TABLE 3
Precision statistics for physical and durability properties

Material	$\bar{\bar{x}}$	$s_{\bar{x}}$	s_r	s_R	r	R
			Fiber mass content (%) (ASTM D2584-18)			
A	82.943	1.0548	0.5970	1.1823	1.67	3.31
B	83.128	1.2523	0.2125	1.2667	0.60	3.55
C	83.307	1.9643	0.3970	1.9961	1.11	5.59
D	83.979	0.8309	0.6019	0.9901	1.69	2.77
			Glass transition temperature (°C) (ASTM E1356-08(2014))			
A	136.051	3.4148	3.6605	4.7308	10.25	13.25
B	131.500	4.9700	3.1750	5.7241	8.89	16.03
C	127.208	1.9680	3.0450	3.3601	8.53	9.41
D	136.407	2.8758	4.2742	4.7838	11.97	13.39
			Degree of cure (%) (ASTM E2160-04(2018))			
A	99.375	0.4373	0.3363	0.5307	0.94	1.49
B	99.167	0.3988	0.2187	0.4441	0.61	1.24
C	99.563	0.3623	0.1565	0.3884	0.44	1.09
D	99.524	0.3852	0.3114	0.4754	0.87	1.33
			Measured cross-sectional area (mm^2) (ASTM D7205M-21 and D792-20)			
A	91.679	2.1717	0.8090	2.2891	2.27	6.41
B	157.073	2.6529	1.1202	2.8358	3.14	7.94
C	213.215	2.7916	2.7395	3.7144	7.67	10.40
D	324.477	2.6656	3.0802	3.8334	8.62	10.73
			Moisture absorption to saturation (%) (ASTM D570-98(2018))			
A	0.464	0.1036	0.0585	0.1161	0.164	0.325
B	0.474	0.1075	0.0669	0.1230	0.187	0.344
C	0.459	0.1077	0.0913	0.1351	0.256	0.378
D	0.459	0.1696	0.0416	0.1737	0.116	0.486
			Moisture absorption in 24 h (%) (ASTM D570-98(2018))			
A	0.105	0.0183	0.0214	0.0264	0.060	0.074
B	0.114	0.0236	0.0311	0.0364	0.087	0.102
C	0.101	0.0381	0.0151	0.0404	0.042	0.113
D	0.109	0.0338	0.0312	0.0438	0.087	0.123

Conclusions

This research has effectively determined precision estimates for Physio-Mechanical Characterization Tests on GFRP bars. These estimations cover both the consistency of results within-laboratory (repeatability) and to some extent, the consistency of results between-laboratories (reproducibility). These precision estimates have been formulated based primarily on standard deviations and the acceptable range between two test measurements (critical values).

These results do not aim to establish definitive and universal statements of precision. Instead, our goal is to attempt to narrow the existing gap in the standards. The explanation of "*r*" and "*R*" is provided to offer a meaningful way of considering the approximate precision of this test method. The data in Tables 2 and 3 should not be used for the acceptance or rejection of materials; they apply only to the materials tested in the round-robin. Users of this test method should apply the principles outlined in Practice E691-22 to generate data specific to their materials and laboratory (or between specific laboratories).

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References

1. Y. J. Kim, "State of the Practice of FRP Composites in Highway Bridges," *Engineering Structures* 179 (2019): 1–8, https://doi.org/10.1016/j.engstruct.2018.10.067
2. H. B. Mayya, D. Pai, V. M. Kini, and N. H. Padmaraj, "Effect of Marine Environmental Conditions on Physical and Mechanical Properties of Fiber-Reinforced Composites—A Review," *Journal of the Institution of Engineers (India): Series C* 102, no. 3 (June 2021): 843–849, https://doi.org/10.1007/s40032-021-00676-w
3. G. G. Claure, "Non-traditional Shape GFRP Rebars for Concrete Reinforcement" (PhD diss., University of Miami, 2015).
4. F. Ceroni, E. Cosenza, M. Gaetano, and M. Pecce, "Durability Issues of FRP Rebars in Reinforced Concrete Members," *Cement and Concrete Composites* 28, no. 10 (November 2006): 857–868, https://doi.org/10.1016/j.cemconcomp.2006.07.004
5. B. Benmokrane, S. Mousa, K. Mohamed, and M. Sayed-Ahmed, "Physical, Mechanical, and Durability Characteristics of Newly Developed Thermoplastic GFRP Bars for Reinforcing Concrete Structures," *Construction and Building Materials* 276 (2021): 122200, https://doi.org/10.1016/j.conbuildmat.2020.122200
6. B. Benmokrane, S. Mehany, C. Shield, A. Nanni, and V. Brown, "Physical Properties, Longitudinal Tensile Properties, and Bond Strength of the New Generation of GFRP Bars," *Journal of Composites for Construction* 27, no. 6 (December 2023): 04023056, https://doi.org/10.1061/JCCOF2.CCENG-4300
7. A. Ruiz Emparanza, R. Kampman-n, and F. De Caso y Basalo, "State-of-the-Practice of Global Manufacturing of FRP Rebar and Specifications," *ACI Symposium Publication* 327 (2018): 45.1–45.14, https://doi.org/10.14359/51713366
8. F. Elgabbas, E. A. Ahmed, and B. Benmokrane, "Physical and Mechanical Characteristics of New Basalt-FRP Bars for Reinforcing Concrete Structures," *Construction and Building Materials* 95 (2015): 623–635, https://doi.org/10.1016/j.conbuildmat.2015.07.036
9. *Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement*, ASTM D7957/D7957M-22 (West Conshohocken, PA: ASTM International, approved February 1, 2022), https://doi.org/10.1520/D7957_D7957M-22.
10. ASTM International, *Form and Style for ASTM Standards* (West Conshohocken, PA: ASTM International, 2023).
11. *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, ASTM D3039/D3039M-14 (West Conshohocken, PA: ASTM International, approved May 15, 2014), https://doi.org/10.1520/D3039_D3039M-14
12. *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, ASTM D3039/D3039M-17 (West Conshohocken, PA: ASTM International, approved October 15, 2017), https://doi.org/10.1520/D3039_D3039M-17
13. A. Nanni, A. De Luca, and H. J. Zadeh, *Reinforced Concrete with FRP Bars: Mechanics and Design* (Boca Raton, FL: CRC Press, 2014).
14. J. D. Ortiz, S. S. Khedmatgozar Dolati, P. Malla, A. Nanni, and A. Mehrabi, "FRP-Reinforced/Strengthened Concrete: State-of-the-Art Review on Durability and Mechanical Effects," *Materials* 16, no. 5 (March 2023): 1990, https://doi.org/10.3390/ma16051990
15. *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars*, ASTM D7205/D7205M-21 (West Conshohocken, PA: ASTM International, approved May 15, 2021), https://doi.org/10.1520/D7205_D7205M-21
16. B. Benmokrane, C. Nazair, X. Seynave, and A. Manalo, "Comparison between ASTM D7205 and CSA S806 Tensile-Testing Methods for Glass Fiber-Reinforced Polymer Bars," *Journal of Composites for Construction* 21, no. 5 (October 2017): 04017038, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000819
17. *Standard Test Method for Transverse Shear Strength of Fiber-Reinforced Polymer Matrix Composite Bars*, ASTM D7617/D7617M-11(2017) (West Conshohocken, PA: ASTM International, approved August 1, 2017), https://doi.org/10.1520/D7617_D7617M-11R17
18. *Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing*, ASTM D7913/D7913M-14(2020) (West Conshohocken, PA: ASTM International, approved February 1, 2020), https://doi.org/10.1520/D7913_D7913M-14R20
19. *Standard Test Method for Ignition Loss of Cured Reinforced Resins*, ASTM D2584-18 (West Conshohocken, PA: ASTM International, approved September 15, 2018), https://doi.org/10.1520/D2584-18

20. *Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry (Withdrawn)*, ASTM E1356-08(2014) (West Conshohocken, PA: ASTM International, approved March 15, 2014), https://doi.org/10.1520/E1356-08R14
21. *Standard Test Method for Heat of Reaction of Thermally Reactive Materials by Differential Scanning Calorimetry*, ASTM E2160-04(2018) (West Conshohocken, PA: ASTM International, approved April 1, 2018), https://doi.org/10.1520/E2160-04R18
22. *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*, ASTM D792-20 (West Conshohocken, PA: ASTM International, approved July 1, 2020), https://doi.org/10.1520/D0792-20
23. *Standard Test Method for Water Absorption of Plastics*, ASTM D570-98(2018) (West Conshohocken, PA: ASTM International, approved August 1, 2018), https://doi.org/10.1520/D0570-98R18
24. *Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods*, ASTM E177-20 (West Conshohocken, PA: ASTM International, approved October 1, 2020), https://doi.org/10.1520/E0177-20
25. *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials*, ASTM C670-15 (West Conshohocken, PA: ASTM International, approved June 15, 2015), https://doi.org/10.1520/C0670-15
26. *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*, ASTM E691-22 (West Conshohocken, PA: ASTM International, approved May 15, 2022), https://doi.org/10.1520/E0691-22
27. *Standard Terminology Relating to Quality and Statistics*, ASTM E456-13a(2022) (West Conshohocken, PA: ASTM International, approved April 1, 2022), https://doi.org/10.1520/E0456-13AR22