Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

Usefulness of a statistical analysis in the quality control of plastics for household appliances

C. Leone[1], V. Lopresto[1], G. Caprino[1], I. De Iorio[2]
[1]*Department of Materials and Production Engineering, University of Naples "Federico II", Italy*
[2]*Department of Space Science and Engineering, University of Naples "Federico II", Italy*

Abstract

In this work, the problem of quality control of plastics destined to household appliances is faced. The material is poly-propylene charged with mineral filler, drawn from two batches, each provided by a different producer. From each batch, dog-bone shaped specimens for tension testing were fabricated by injection moulding, using two different injection rates. The samples were tested in tension up to failure, and the tensile strength and Young's modulus were measured. In all, sixteen tests were carried out for each experimental condition. From the mean values of the Young's modulus and strength, the difference between the experimental conditions adopted could not be simply appreciated. However, the application of the analysis of variance (ANOVA) clearly revealed the effect of both the material producer and the process conditions, especially when the strength was adopted as a parameter. In order to model the strength and modulus distribution, a two-parameter Weibull curve was assumed for the mechanical properties measured. From the results, the Young's modulus and tensile strength reasonably follow a Weibull curve. Moreover, also the parameters of the curve proved to be capable to discriminate between both the different batches and the different process conditions.

Introduction

An efficient quality control of incoming materials is one of the topical aspects in industry, strongly contributing to assure repeatability in the properties of the final part.

Unfortunately, the importance of this task is often underestimated, and stringent procedures in the material control stage are seldom adopted, especially when small and medium enterprises are considered.

The evaluation of mechanical properties such as the elastic modulus and strength, easily obtainable by simple tensile tests, often provides the basis for a decision on the material suitability, according to predetermined requirements. However, when the material under concern is a polymer under form of pellets, an additional drawback in decision making is the process followed in fabricating the specimen destined to the mechanical characterisation. In fact, it is well known that the process parameters can strongly influence the response of a plastic component, D. D. Rosato [1], J. H. DuBois [2]. Therefore, the role played by the fabrication stage must be well understood, in order to interpret correctly the experimental results.

The previous considerations highlight the significance of this work, whose main scopes were: a) to assess the effect of the fabrication parameters on the Young's modulus and tensile strength of filled polymers for household applications; b) to verify the suitability of a statistical analysis to discriminate between materials nominally identical, except for the producer and the specimen fabrication process. To this aim, dog-bone shaped samples were fabricated by injection moulding, adopting two batches of pellets of a nominally identical polymer, provided by two different producers. In injecting the material into the mould, two different flow rates were set. The mean values of Young's modulus and strength measured in the mechanical characterisation tests were of limited usefulness in distinguishing between the different cases examined. However, the analysis of variance (ANOVA) was able to reliably reveal the differences. In an attempt to model the scatter in the mechanical properties, the effectiveness of a two-parameter Weibull curve was tested. The data generated showed that the Weibull distribution is in satisfactory agreement with both the modulus and strength results.

Materials and experimental procedures

The material considered in this work was polypropylene (PP) charged with a $CaCO_3$ mineral filler, under form of pellets. Two nominally identical batches, labelled in the following as "B" and "D", respectively, each one provided by a different producer, were studied. From the pellets, dog-bone specimens 13 mm in width, 3.2 mm in thickness, and 215 mm in overall length, were fabricated by injection moulding. During the injection process, all the parameters were held constant, except the flow rate, which was selected according to the specifications in Table 1.

The specimens were tested in tension up to failure using an Instron 4301 universal testing machine in stroke control. The cross-head speed was fixed at 5 mm/min. During each test, the strain was measured by a strain-gauge extensometer 25 mm in length, and the stress–strain curve was recorded. From the σ-ε curve, the Young's modulus and the tensile strength were evaluated. In all, 16 specimens (Table 1) were tested for each experimental condition.

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

Table 1: Matrix of the experimental tests.

Producer	Designation	Flow rate (Kg/h)	No. of samples
B	B800	800	16
	B1450	1450	16
D	D800	800	16
	D1400	1400	16

Results and discussion

In Tables 2 and 3, the usual statistical parameters relevant to the cases examined are collected for the Young's modulus and the tensile strength, respectively.
Looking at the mean values of the Young's modulus only, one could conclude that some difference exists between material B and D, whereas the flow rate does not sensibly influence the material behaviour. The differences between the experimental conditions adopted are even harder to discern on the basis of the mean strength, which seems to be quite insensitive to both the material producer and the flow rate.
The experimental data were statistically treated using ANOVA with the aim to better appreciate the influence of the parameters analysed. The ANOVA table (see Tables 4 and 5 for modulus and strength, respectively) decomposes the variability of the material properties into the contributions due to the various factors (A: Producer, B: Flow rate, AB: interaction Producer-Flow rate).

Table 2: Statistical parameters measured from the tensile tests. Young's modulus.

Material	Mean (MPa)	Stand. Dev. (MPa)	Coeff. of Var. (%)
B800	4173	146	3.50
B1450	4155	134	3.23
D800	4482	152	3.40
D1400	4374	94	1.24

Table 3: Statistical parameters measured from the tensile tests. Tensile strength.

Material	Mean (MPa)	Stand. Dev. (MPa)	Coeff. of Var. (%)
B800	26.66	0.102	0.381
B1450	25.08	0.220	0.877
D800	25.62	0.126	0.492
D1400	25.46	0.118	0.465

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

In the ANOVA table, the Sum of Squares (SS) indicates the contribution of each of the factors considered when the effects of all other factors are removed. Df is the degree of freedom, that is defined to be 1 less than the number of levels for the variables. The Mean Square (MS) is the SS/Df ratio: it has a similar meaning to the Sum of Squares, but show in amplified manner the variable effect. The F-ratio is the ratio MS_{factor}/MS_{error}; this parameter is used to compare the variance due to the factor to the variance due to the experimental error. The P-values gives the statistical significance of each of the factors. When the P-value is less than 0.05, the factor has a statistically significant effect on the material property at the 95 % confidence level, D. C. Montgomery [3], E. O. Doebelin [4].
From Table 4, the Young's modulus is significantly influenced uniquely by the producer (SS_A = 972951.0, P-value < 0.05), whereas this property is substantially insensitive to the variation in the flow rate set during the specimen fabrication.
Looking at the tensile strength (Table 5), both the variables, Producer and Flow rate, exhibit a significant Sum of Squares, a comparable F-ratio and a P-value that is less than 0.05. Therefore, the tensile strength is significantly affected by both the parameters taken into account. In particular, the influence of the flow rate is more pronounced than that of the producer, as the F-ratio signals clearly.
The previous conclusions indicate that the choice of the elastic modulus could be more appropriate in performing acceptability tests on incoming materials. This should allow the fabrication of specimens under less stringent process conditions. On the contrary, the tensile strength could be used when the scope of the test is to draw information on the parameters actually adopted during an industrial fabrication process.

Table 4: Results of ANOVA. Young's modulus.

Source	Sum of square	Df	Mean Square	F-ratio	P-Value
Producer (A)	972951.0	1	972951.0	58.67	0.0000
Flow rate (B)	35181.8	1	35181.8	2.11	0.1530
Interaction AB	15344.3	1	15344.3	0.92	0.3424
Residual	800868.0	49	16684.8		
Total	1.84482E6	52			

Table 5: Results of ANOVA. Tensile strength.

Source	Sum of square	Df	Mean Square	F-ratio	P-Value
Producer (A)	1.41322	1	1.41322	62.17	0.0000
Flow rate (B)	9.87836	1	9.87836	434.55	0.0000
Interaction AB	6.57268	1	6.57268	289.13	0.0000
Residual	1.09115	48	0.0227323		
Total	19.3392	51			

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

Although not explicitly shown in this paper, it was verified that conclusions similar to those previously discussed could be drawn by a t-Test, comparing one to one the four populations. Of course, in using the t-Test some information, as the importance of each single variable on the mechanical response, is loosen.
It is well known, D. C. Montgomery [3], E. O. Doebelin [4], M. R. Spiegel [5], that the knowledge of the mean and standard deviation implicitly yields a complete information on the overall material behaviour. In particular, if the property distribution follows a Student or a Gaussian curve, from mean and standard deviation the probability P to find a modulus (strength) value lower than an assigned value x can be obtained theoretically. Unfortunately, when the previous distributions are assumed to represent the data scatter, a closed form formula cannot be used to calculate P, and the solution is only available in tabular form. Due to this drawback, in the last decades the possibility to describe P by a closed-form, two-parameter Weibull curve:

$$P = 1 - \exp[-(x/\alpha)^{\beta}] \qquad 1)$$

has been successfully tested in many application fields concerning materials similar to those considered here, W. Hwang, [6], M. R. Wisnom [7].
In equation (1), α and β are two constants to be experimentally determined, labelled as "scale parameter" (or "characteristic value") and "shape parameter", respectively. Of course, α physically represents the x value in correspondence of which P = 0.63, whereas β is correlated to the data scatter, being the lower, the larger the scatter is.
From equation (1), the following relationship is easily obtained:

$$-\ln(1 - P) = (x/\alpha)^{\beta} \qquad (2)$$

Therefore, plotting the term on the left of equation (2) versus x on a log-log scale should result in a straight line having slope β and intercept ($-\beta\log\alpha$). This provides a simple tool to evaluate the constants of the Weibull distribution from the experimental results.
To calculate the experimental distribution P for each of the cases examined (Table 1), the specimens of each group were numbered in ascending order on the basis of the property concerned (elastic modulus or strength). Then, the following formula was utilised:

$$P = \frac{m_i}{m + 1} \qquad (3)$$

where m is the total number of specimens of the group, and m_i the order number. The results are represented by the symbols in Figures 1 to 2 and Figures 3 to 4, regarding the Young's modulus and tensile strength, respectively.

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

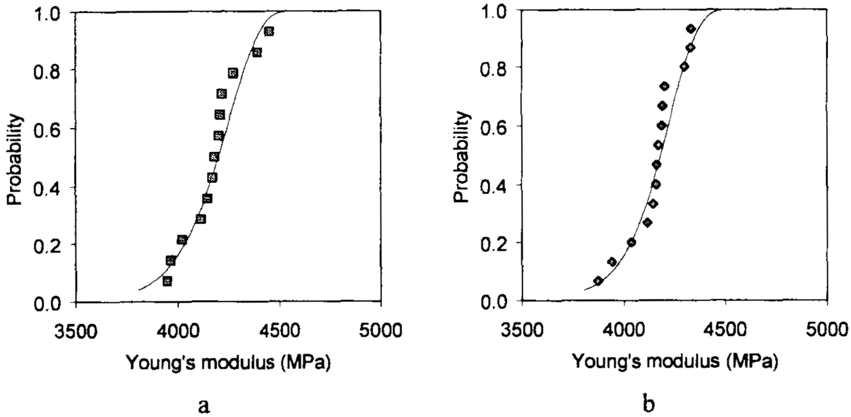


Figure 1: Young's modulus distribution for a) B800; b) B1450

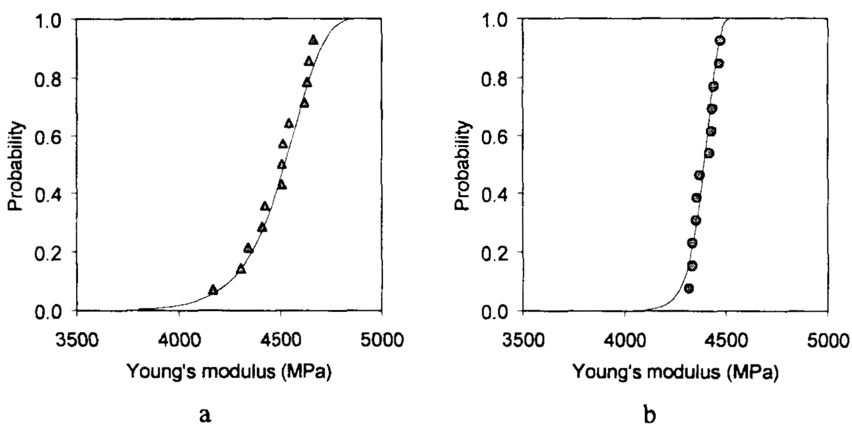
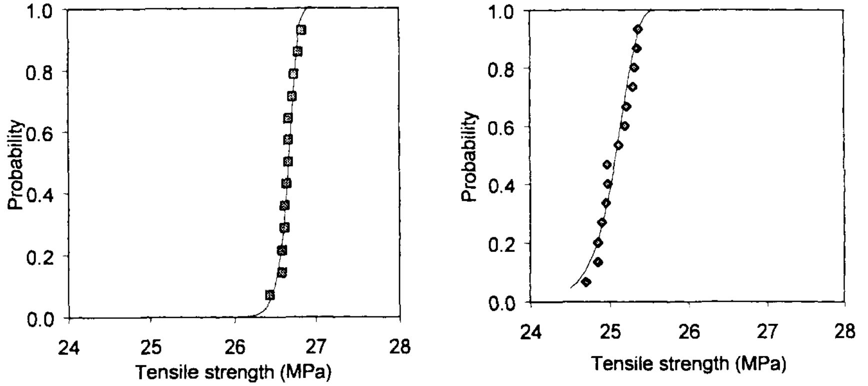


Figure 2: Young's modulus distribution for a) D800; b) D1400

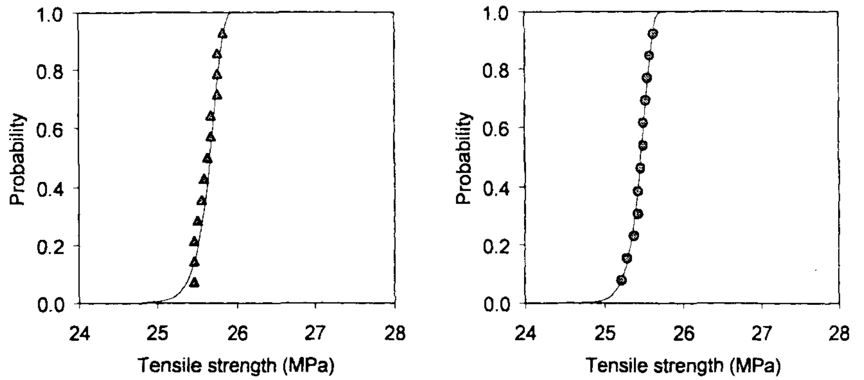
It is noted from the figures that each group consists of less than sixteen points. This depends on the fact that, after mechanical testing, the visual observation of the fracture surfaces revealed a critical porosity in some of the specimens, which were excluded from all the statistical analyses discussed in this work.
Using equation (2), the parameters of the Weibull curve were calculated by the best-fit method, and collected in Table 6. Figures 5a and 5b are two examples of the diagrams used to evaluate α and β. It can be noted that linear, instead of logarithmic scales, have been adopted in these figures, in order to better evidence the fitting of the theoretical curves (continuous lines) to the experimental data.

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6



a b

Figure 3: Tensile strength distribution for a) B800; b) B1450



a b

Figure 4: Tensile strength distribution for a) D800; b) D1400

The continuous lines in Figures 1 to 4 are the Weibull distributions calculated from equation (1) using the constants in Table 6. In general, the agreement between equation (1) and the experimental data is quite satisfying, despite some fluctuations in Figures 1a and 1b, anticipated from the small sample size. Therefore, it is concluded that a Weibull curve is suitable to analytically model both the Young's modulus and strength of the materials studied.

All the theoretical curves in Figures 1 to 2 and in Figures 3 to 4 are collected in Figures 6 and 7, respectively, for a quick comparison.

From Figure 6, the following main conclusions can be drawn with reference to the elastic modulus: a) for a fixed fabrication process, material B exhibits a Young's modulus lower than material D; b) increasing the flow rate during

fabrication results in a decrease in both the elastic modulus and scatter; c) material D is more sensitive to the process conditions than material B; the latter seems to be quite insensitive to the flow rate. This is in agreement with what observed in the ANOVA analysis.
The tensile strength (Figure 7) is adversely affected by an increase in the flow rate. This occurs irrespective of the material considered. However, when the strength is considered, material B is more sensitive to the flow rate than material D, exhibiting a far larger decrease in strength for an analogous increase in flow rate.

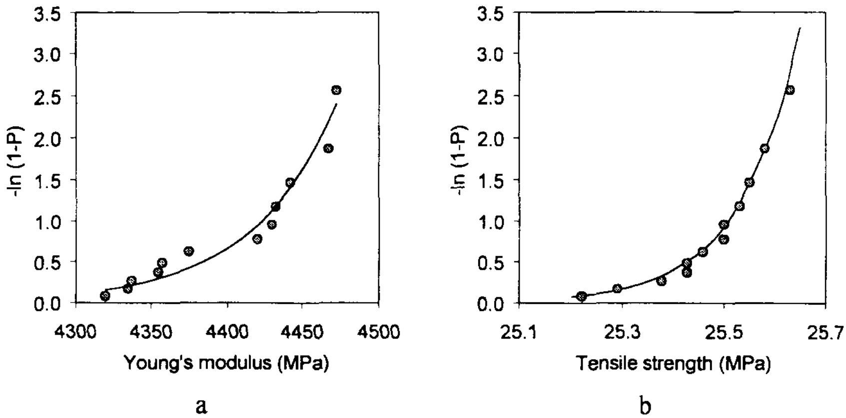


Figure 5: Graph for the evaluation of the constants α, β for the D1400 material, a) Young' modulus and b) Tensile strength.

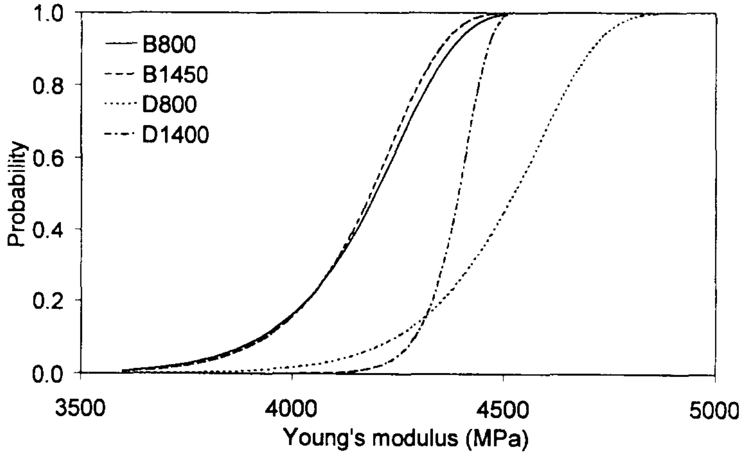


Figure 6: Weibull curves calculated for the different materials. Elastic modulus.

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

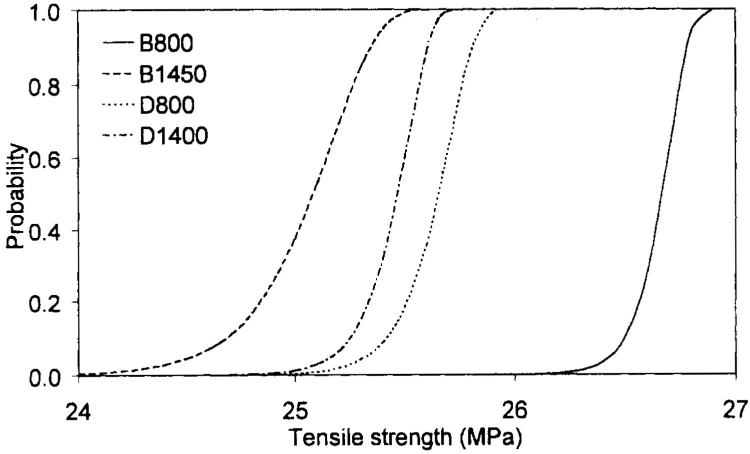


Figure 7: Weibull curves calculated for the different materials. Tensile strength.

Table 6: Calculated constants of the Weibull distribution of the Young's modulus and of the tensile strength for the materials considered.

Material	Young's modulus		Tensile strength	
	α (MPa)	β	α (MPa)	β
B800	4251	28.7	26.71	290
B1450	4234	31.2	25.21	100
D800	4578	30.0	25.69	201
D1400	4415	79.03*	25.51	230

Conclusions

In this work, tensile tests were carried out on ABS specimens fabricated by injection moulding from pellets provided by two different producers. During the fabrication process, two different flow rates were adopted. From the analysis of the elastic modulus and tensile strength, the following main conclusions were drawn:

- the effect of both the variable, material producer and the flow rate, can be quantitatively appreciated performing the ANOVA test;
- the Young's modulus of the material is mainly affected by the producer, being quite insensitive to the flow rate; on the contrary, the tensile strength is influenced by both the producer and flow rate;
- the distribution of both the Young's modulus and the tensile strength is well described by a two-parameter Weibull curve; therefore, the latter can be

Paper from: *High Performance Structures and Composites*, CA Brebbia and WP de Wilde (Editors).
ISBN 1-85312-904-6

used to evaluate the probability for the material modulus to be lower than a fixed value, or the probability of failure under an assigned load.

Acknowledgements

Electrolux-Zanussi is gratefully acknowledged for providing the specimens and economic support to develop the present research work.

References

[1] D.D. Rosato, *"Injection Moulding Handbook"*, The complete Moulding Operation, Van Nostran Reinhold Pub. New York, 1986.
[2] J.H. DuBois, W. I. Pribble, *"Plastic Mould Engineering Handbook"*, Van Nostran Reinhold Pub. New York, 1987.
[3] Duglas C. Montgomery *"Introduction to statistical quality control 3rd edition"* John Wiley & Son Pub Inc., 1996.
[4] Ernest O. Doebelin "*Engineering Experimentation, Planning, Execution, Reporting*" McGraw Hill Pub. Inc., New York, 1995.
[5] M. R. Spiegel, *"Statistics"*, McGraw-Hill Publ., New York, 1961. M. R. Spiegel, Statistics, McGraw-Hill Publ., New York, 1961.
[6] W. Hwang and K. S. Han, *"Statistical Study of Strength and Fatigue Life of Composite Materials"*, Composites, Vol. 18, No 1, pp. 47-53, 1987.
[7] M. R Wisnom., "*Relationship Between Strength Variability and Size Effect in Unidirectional Carbon Fibre/Epoxy*", Composites, Vol. 22, No. 1, pp. 47-52, 1991.