Abstract
This study considers the effect of prepreg properties on the manual layup process. Commercial prepregs were characterised in terms of shear behaviour, tack and flexural rigidity. The materials were then laid up by professional laminators on a series of increasingly challenging moulds, and the time taken to lay up each material was used as a metric of layup performance. It was found that there is a positive correlation between shear angle and layup time. Considerable differences (up to a factor of 2) in time taken to lay up different materials were also seen. The measured properties were used as predictors in a linear model to determine layup time, where it was found that shear energy and tack are significant. Lastly, some implications for the design and manufacture of composite components are discussed.

1 Introduction
The manual layup of pre-impregnated (prepreg) plies is a well-established manufacturing method for advanced composite components, and is widely used for the manufacture of complex and high performance products in the aerospace industry [1]. Despite its widespread use and long history, the process of hand-lamination remains largely unchanged since it was first used.

Even though it is broadly accepted knowledge that most prepreg has been designed for hand layup [1], there is little evidence in the literature of any design for manufacture research or any work which aims to improve the quality, consistency or ease of manufacture through a consideration of human aspects and material properties.

Lamination is considered highly skilled labour, and has been referred to as a “black art” [2], [3], perhaps as a result of having received little attention from research as regards the science behind it. Rules of thumb prevail and in many cases, laminators appear to be given freedom to splice plies, heat up the material and even use their own forming tools.

This work seeks to examine the role of material choice on the hand layup process. It attempts to identify the key aspects of a material which contribute to the ease or difficulty of manufacturing parts with relatively complex geometry. Focus is on the use of prepregs with a woven reinforcement, as these are known to have better “handling” characteristics than unidirectional (UD) reinforcements [4], [5].

2 Background
2.1 Drapability/Formability
The behaviour of woven cloth is well understood, and a large portion of this knowledge was developed in the field of textiles [6]. As early as 1956, and before the invention of carbon fibre, Mack and Taylor [7] proposed the pin-jointed net model for the fitting of woven cloth to surfaces. An orthogonally woven cloth of inextensible fibres will act as if pin-jointed at the warp and weft crossover points, such that if the cloth is stretched in a direction at 45° to the weave, it will tend to rotate about the crossover points, as indicated in Fig. 1, producing an in-plane shear deformation.

The deformation achievable in this mode is considerable, but reaches a limit when the warp and weft tows interact and lock. The included angle between warp and weft becomes so small that warp and weft tows begin to interact, the angle achievable is limited due to the finite width of these tows. This is referred to as the "locking angle".
However, there are other deformation modes and effects which are considered secondary and often neglected, and these include: fibre/tow slip, fibre/tow straightening (crimp interchange) and fibre stretching [8].

Previous work investigating the role of material properties on formability has generally been limited to automated processes and usually involve forming over a hemispherical geometry [9]. In woven cloths, the principal deformation mode which allows them to be fitted to complex (doubly-curved) geometries is in-plane shear and it is this response, if any, which is measured and evaluated for manufacture [10]. Traditionally, the adaptability of the human has been invoked as a reason to overlook the effect of material properties and variability on the process [11].

It is proposed herein that even without any evidence of deliberate efforts from manufacturers, some prepregs are deemed by laminators to be significantly easier to work with than others. Furthermore, it is possible to reduce manufacturing times considerably by choosing one material over another. That different materials can affect layup time has been noted in the past [12], but the aim of this work is to develop the understanding of which properties are significant in causing these outcomes and to clarify the mechanisms involved.

### 2.2 Drape in the textiles industry

In the textile industry, there exists a very active field known as “Fabric Objective Measurement” (FOM), which was originated by the work of Kawabata in Japan in the early 1970s.

The FOM requirement has been phrased by Postle [13] as “that a necessary and sufficient set of instrumental measurements be made on fabrics in order to specify and control the quality, tailorableity, and ultimate performance of apparel fabric”. However, researchers have since concluded that it is necessary to establish reliable methods for quantifying subjective judgements, such as the concept of fabric “hand” or “handle”, which is an assessment of a personal reaction to a fabric including a component of sight and touch, among other physical, physiological and even social factors [14], [15].

The majority of the research was conducted in the mid 1980s and early 90s, and has since advanced through the technology readiness levels, reaching industrial implementation in the form of the Kawabata Evaluation System (KES-F) and Fabric Assurance by Simple Testing (FAST) [16] systems, among other instruments generically known as ‘drapemeters’, which use a series of measurements, such as those in [17] to provide a ‘drape coefficient’ value. The most notable example is the KES-F system, which consists of four test instruments: tensile and shear tester, bending tester, compression tester and surface friction tester. The tests were designed to measure properties which could be used objectively to match a group of experts’ definition of fabric handle through regression analysis [14].

### 2.3 Drape in composites

In composites, the problem is slightly simplified by the (theoretically) reduced role of aesthetic considerations and other sensory observations relating to comfort/fabric-skin interactions (e.g. thermal, smoothness) which have been reported as key in the fabric industry.

Nevertheless, the aforementioned KES-F system has been used to characterise dry carbon preforms [9], but not extensively, perhaps due to the high cost and scarcity of the equipment [18]. Another reason is that the KES-F system is designed to test apparel fabrics at “very low load levels” [19]. For example, in the shear test, a load of 1.96N is used to shear a specimen up to a maximum of 8° [18]. By contrast, the woven reinforcements used in advanced composites are capable of shear deformations several times greater. Furthermore, in prepregs, the loads involved are also considerably higher due to the presence of resin. This equipment is therefore unsuitable for the purposes of this study; the tests used are outlined in section 3.1. There is, however, no accepted way of translating a set of material properties into a ‘formability’ measurement.

During this study it became clear from interactions with laminators that there is a subjective element to hand layup, and that a laminator is able to express,
to varying degrees, his or her perception of the material’s performance in terms of its ability to conform to the mould.

It is a generally accepted in the ergonomics field that measures of task duration can be related to task difficulty and operators’ perception thereof [20]. It follows, then, that a laminator’s assessment of “ease of layup” should correlate strongly with the time taken to lay up a part. In a productivity oriented environment perceptions may well be altered by material deposition rates, assuming quality can be maintained.

Since the outcome metric should be end-use/application specific, it seems reasonable to consider time taken to lay up and quality in the case of composites, as opposed to one of the many possible appearance/comfort related criteria seen in textiles.

3 Experimental approach

This work follows a two-part experimental approach: firstly, commercial prepregs (Table 1) were characterised by a selection of tests deemed to be relevant to hand layup scenarios. Secondly, the same materials were laid up by professional laminators over a series of representative moulds.

3.1 Material characterisation

At present, there is no standard methodology for the evaluation of prepreg with regard to its layup performance. As mentioned previously, the shear stiffness and/or locking angle are used to give an indication of a material’s ability to conform to geometries. The shear response is usually characterised using either a picture frame test or a bias-extension test. Although neither test is recognised in standards, they are widely used in research. A comprehensive description and comparison of the picture frame test and bias-extension tests is given in [21].

The properties relevant to hand layup are assumed, at this stage, to be some measurement of:

- Flexural rigidity
- Tack
- In-plane shear response

To measure these properties, ASTM D1388 [22], ASTM D3167 [23] and a bias extension test were used, respectively (see Fig. 2). The tests were selected from a variety of contexts from within both the textile and pressure-sensitive adhesives industries.

Due to the viscoelastic nature of prepreg, its behaviour is highly dependent on time/rate and temperature. As a result, the tests were carried out in a temperature and humidity controlled composites clean room under modified test parameters to represent the forces and rates the materials might undergo in the hands of a laminator. Relevant literature [24] and experimental values for the forces exerted in grasps and while applying pressure were used to inform the choice of test settings. For example in the bias extension test, rather than testing at extension rates of 1mm/min, values closer to 200 mm/min were chosen. However the response of the material may vary significantly at other rates, as shown in [25].

There appears to be only one precedent of the combined use of these tests on prepreg [26], where the authors vary the level of cure and monitor the effect this has on “handling characteristics” as measured by the tests. However, no evidence is provided to support that the tests actually do measure handling characteristics. They conclude with a qualitative appraisal of the prepreg’s performance in layup, which was deemed to have an acceptable balance of properties when laid up over an undescribed tool.

3.2 Layup trials

To test the hypothesis that some materials are easier to work with than others, a series of moulds of increasing complexity were designed to challenge both materials and laminators (Fig. 3). The geometry is similar to what might be seen in aerospace secondary structures with a machined honeycomb core.

The tool consists of a base, into which the mould insert is placed and secured. The overall tool shape remains unchanged, but the difficulty is increased by varying the insert ramp angle (from 20° to 70°), in increments which create a linear increase in the
shear angle the cloth would have to undergo in order to be successfully draped over the tool. The moulds are made from epoxy tooling block and finished with release wax.

Three professional laminators, all with experience of more than one high performance industry were tasked with laying up a single ply of each of the prepregs over each mould, starting with the 20° mould and progressing towards the more complex ones. The ply dimensions were 25 x 25 cm.

By specifying datum lines, the drape/shear pattern was constrained in order to guarantee that the ply was laid up consistently each time. A drape simulation output, (produced using Virtual Fabric Placement, an in-house kinematic drape modeller) is shown in Fig. 4. The laminators were also briefed on quality requirements:
- Datums must be followed
- No wrinkling allowed
- No bridging allowed

These were assessed visually after each layup by both laminators and the lead author.

A full test consisted of a single ply of each material, laid up over each mould (total of 40 plies per laminator). The trials were performed in a temperature and humidity controlled clean room, to match the conditions under which the material characterisation took place. Laminators were allowed to use dibber tools, but the use of heat guns was not permitted.

Each layup was recorded using a video camera and the time taken was extracted from the recordings in later analysis. The subjects were also asked to rate the overall satisfaction with the ply after each one had been laid down, with a score out of 10, which includes an assessment of how easily it draped as well as an evaluation of quality. The assumption was that plies which take longer to lay up are perceived to be more difficult, providing the layup quality is acceptable.

4 Results
4.1 Material characterisation

A summary of results can be seen in Table 2. Values for flexural rigidity and peel strength were obtained according to the notes in the pertinent ASTM standards [22], [23].

The shear angle of the fabric was obtained from the bias extension test using a video extensometer. The values are plotted against force per unit width to give the curves in Fig. 5.

Since prepreg behaviour is highly non-linear, it is difficult to obtain a single value for shear stiffness. Consequently, the integral of the curves in Fig. 5 is computed using the trapezoidal rule to give a measure of the “shear energy” required to reach the deformation at various mould angles.

4.2 Layup times

The layup times were extracted from video files by observation, and any non-layup time discounted. The times were independently extracted by two of the authors and found to be within 5% of each other. The average time taken to lay up each material over the moulds is shown in Table 3.

5 Analysis and discussion
5.1 Layup times: the effect of mould geometry

From Fig. 6, it can be seen that there is a noticeable variation in the time taken by each laminator. Even though they are all professionals, there are differences in laminating style and techniques used, as each laminator will have their own way of approaching layup. For example, laminator 3 tended to deform the cloth globally, rather than working feature by feature, which is the style of laminator 2.

Nevertheless, Fig. 6 suggests that there is a trend between mould angle and layup time. The relationship appears to be fairly linear, especially up to around 60°, the point at which some materials begin to approach their locking angle, causing difficulty in layup and the appearance of some defects. In summary, the time taken to layup a mould is dependent on the amount of shear that must be introduced in the material.
5.2 The effect of material

Fig. 7 shows a comparison of the average layup time for each material for an average of all three laminators. The results suggest that some prepregs take significantly longer than others. For example, material 5 takes approximately twice as long as materials 2 and 4 to be laid up. The difference is especially noticeable in the latter moulds where greater levels of manipulation are required. However, to reduce complexity, this work does not take into account the variability within each roll, which is a known issue with prepreg [27].

Furthermore, laminators found it very difficult to work with materials 5 and 3 at higher shear angles. This was observed from the dialogue during layup and is backed up by the subjective scores. This not only suggests that some materials are ‘quicker’ than others, but that certain materials are perceived to be easier to work with, and that this perception correlates strongly with the time taken to lay up.

5.3 The effect of material properties

While there seems to be a general relationship between shear angle and time, this section attempts to identify the origin of the differences between the materials.

To do this, multiple linear regression was used to model the relationship between the dependent variable (time) and the explanatory variables (material properties), based on the ordinary least squares approach. The assumption is that time is dependent on a linear combination of shear energy, tack and flexural rigidity and the regression coefficients assigned to these.

Two models were considered. The first considers only shear behaviour (in this case, shear energy) as this is the classic metric associated with drape. The results are shown in Table 4 and plotted in Fig. 8.

A second model was set up to include all properties, in the form:

\[ t = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \]

Where:

- \( t \) is the time taken to lay up
- \( \alpha \) is a constant (intercept) term
- \( x_1, x_2 \) and \( x_3 \) are the explanatory variables:
  - shear energy
  - tack
  - flexural rigidity
- \( \beta \) terms are the regression coefficients for the explanatory variables

The models will be compared in terms of their statistical significance as well as physical meaning. In this study, the purpose of the linear regression is two-fold. Firstly, it is used as a tool with which to assess the relationship of each property on the independent variable. The regression will also be considered for use as a predictive model to determine layup times from a knowledge of material properties.

5.3.1 Shear only

The regression statistics are shown in Table 4 and the regression is plotted Fig. 8.

Fig. 8 suggests a trend between the actual layup time and the time predicted by the model. The statistics strongly support that \( x_1 \) (shear energy) has an effect on layup times, which can be seen by the very low p-value. The readers are reminded of one of the many interpretations of this statistic, i.e. in this case, there is a < 0.0000005 chance that the result would occur if it is assumed that \( x_1 \) does not have an effect. P<0.05 is considered as the significance level at which we reject the null hypothesis, which is by default that the variable does not have an effect. The \( R^2 \) value of 0.55 is probably too low to be useful as a predictive model.

5.3.2 All properties

If all properties are considered together, the correlation and hence \( R^2 \) value for the model increase considerably, which is evident from a visual inspection of Fig. 9. As for the importance of each predictor, it can be seen that p <0.005 for shear energy and tack (see Table 5), which suggests that they are highly relevant. On the other hand, flexural rigidity does not appear to be statistically significant in this model. This result is perhaps counter-intuitive, but may be as a consequence of the way in which this property is measured. Despite this, the results do not put forward a case to discard the role
of flexural rigidity in hand layup. However, the $R^2$ value of 0.72 is closer to what is required from a predictive tool. At this stage it is worth mentioning there are inherent difficulties in predicting human behaviour, and for this reason, numerical values of what might be considered a “strong correlation” are likely to be lower than in other fields.

The $\beta$ coefficients can be interpreted as the effect a particular predictor has on the dependent variable (time taken) if all other variables are held constant. Hence, the magnitude of the coefficient together with its sign are important. However, it must be noted that the predictors have different units, so care must be taken in comparisons. For example, according to the model in Table 5, increasing tack by one ‘unit’ (1N/m) would decrease layup time by 0.72 seconds, assuming other properties are not changed. It does not seem unreasonable to suggest that increasing tack would decrease layup times in this experiment, as the moulds demand a good level of tack. Likewise, decreasing shear stiffness has the effect of reducing layup times, which also makes sense. Clearly, this relationship is not universal and must be bounded by an upper and lower level of tack, since it is possible to reach a level where the material is too tacky, making layup very difficult. One such case is reported in [28].

Although the results strongly suggest that the material properties considered have a direct and measurable influence on layup times, it is possible that a better fit could be found if other explanatory variables are used. Future work will consider using model selection criteria such as stepwise regressions to add, remove and combine predictors from a broader list in order to arrive, potentially, at a more accurate model.

6 Implications

It is recognised that composites design and manufacture is mostly dominated by structural performance requirements, however, the benefits of a deeper understanding of manufacturing considerations are undeniable. For example, demonstrating that simply changing a material can so noticeably affect layup times makes material selection a worthwhile consideration from a costing point of view. Increasing output without any capital expenditure is an attractive concept since the demand for composite components is rapidly rising, yet there is an expectation for costs to follow and opposite trend. This cannot be supported by the present status of technology.

Indeed, the role of tool geometry is also critical. The results suggest that decisions in the design stage, such as reducing the severity of a feature (in this case, the ramp angle), can lead to large savings in layup time. For example, it is shown in Fig. 6 that changing the ramp angle from 45° to 37.5° almost halves the time taken to lay up the part.

Although this study has not explicitly considered cured material properties, which are of course a primary consideration, it seems that the properties which affect layup time are not necessarily linked to those which deliver final, as cured performance. For instance, layup times for materials 4 and 2 are separated by an average of a few seconds, the former is glass-reinforced while the latter is a high performance carbon prepreg.

Furthermore, while primary structural components often have rigorously prescribed materials (due to certification reasons) manufacturers of secondary structures may be presented with a choice of prepregs to use [29]. At this point, the findings of this study are of value. If in addition to lower layup times, a different material also has a lower purchase price and/or reduced processing costs, then there is potential for considerable savings.

This research paves the way for establishing a layup relevant definition of drapability. It also opens up possibilities for the design of optimised prepreg for a specific application, if the material properties can be translated in to raw material and process requirements at the prepreg manufacturing stage.

Lastly, the issue of quality has not been approached quantitatively, but slower times in this study have been associated with quality issues, as most of the time was spent fixing wrinkles and generating the shear pattern. Thus, it seems that choosing materials which take less time to lay up may be indirectly linked to improved quality metrics, but this requires further study.
7 Conclusion

This study presents, for the first time, an approach with which the effect of prepreg properties on hand layup speed can be quantified. The results provide evidence to support the heuristics which are common in industry; it may seem intuitive that tack, shear and bending behaviours do affect layup, but this has not been substantiated in the literature. The role of these properties has been determined by layup trials involving professional laminators, where it was found that shear and tack are significant.

Furthermore, the relationships have been established using standard tests, and it may be possible to obtain higher fidelity models by designing custom tests which more accurately simulate what is happening in layup.

It appears that simply changing the material used can result in substantial time savings, without commensurate changes in cured material properties. Mould geometry and feature severity also have a quantifiable effect on task time. It is likely that further benefits exist in terms of quality, as longer layup times are indicative of the appearance of defects such as wrinkling and bridging. These outcomes can be translated into cost savings. Other implications are that if an ideal material property set is known, then this can be scientifically applied to the design and manufacture of prepreg.

In summary, the present work makes a contribution to the relatively unexplored composite design for manufacture field, demonstrating that simple changes and considerations can result in significant time, quality and ultimately cost improvements.

Acknowledgements

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References

Fig. 1: Schematic of the pin-jointed net model, tows may rotate about the crossover points (circles)

Fig. 2: Schematic of the tests used to characterise prepregs

Fig. 3: Layup test moulds

Fig. 4: Mould showing datum lines (red) and shear pattern of the draped ply. Ramp angle shown as $\theta$
Fig. 5: Force against shear angle plot obtained from the bias-extension test, for materials 1-5

Fig. 6: Time taken to lay up as a function of mould angle, average of 5 materials
Fig. 7: Average time to lay up over all moulds, sorted by material (numbers correspond to the material code given in Table 3). Error bars show standard deviation from the mean of all laminators.

Fig. 8: Plot showing observed times vs. the times predicted from the model using shear energy only.
Fig. 9: Plot showing observed times vs. the times predicted from the model using all material properties

Table 1: Materials characterised

<table>
<thead>
<tr>
<th>Material</th>
<th>Resin</th>
<th>Fibre</th>
<th>Weave</th>
<th>Manufacturer</th>
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<tbody>
<tr>
<td>1</td>
<td>MTM49-3</td>
<td>Carbon</td>
<td>2x1 Twill</td>
<td>Umeco</td>
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<tr>
<td>2</td>
<td>977-2A</td>
<td>Carbon</td>
<td>2x2 Twill</td>
<td>Cytec</td>
</tr>
<tr>
<td>3</td>
<td>MTM44-1</td>
<td>Carbon</td>
<td>2x2 Twill</td>
<td>Umeco</td>
</tr>
<tr>
<td>4</td>
<td>913</td>
<td>Glass</td>
<td>8 HS</td>
<td>Hexcel</td>
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<tr>
<td>5</td>
<td>913</td>
<td>Carbon</td>
<td>Plain</td>
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Table 2: summary of material properties. The flexural rigidity value is an average of the 0/90° and ±45° directions. The peel force value corresponds to the side of the prepreg which was laid down on the tool.

<table>
<thead>
<tr>
<th>Mould angle [°]</th>
<th>Material</th>
<th>Flexural rigidity [µJ/m]</th>
<th>Peel force [N/m]</th>
<th>Shear energy [J/m²] x10^4</th>
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<tr>
<td>37</td>
<td>1</td>
<td>3963.8</td>
<td>298.1</td>
<td>0.25</td>
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<td>45</td>
<td>2</td>
<td>2786.3</td>
<td>323.1</td>
<td>0.27</td>
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<td>50</td>
<td>3</td>
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<td>217.1</td>
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<td>55</td>
<td>4</td>
<td>1534.7</td>
<td>359.8</td>
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<tr>
<td>60</td>
<td>5</td>
<td>3229.2</td>
<td>247.8</td>
<td>0.34</td>
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</table>

Table 3: Time to lay up a single ply of each material over the moulds. Average of 3 laminators.

<table>
<thead>
<tr>
<th>Mould angle [°]</th>
<th>Material</th>
<th>37</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>63</th>
<th>70</th>
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<tr>
<td>Time [s]</td>
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<td>108.7</td>
<td>142.3</td>
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<td>291.7</td>
<td>211.3</td>
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<td>2</td>
<td>76.0</td>
<td>166.0</td>
<td>146.0</td>
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<td>3</td>
<td>128.0</td>
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<td>4</td>
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<td>121.7</td>
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<td>5</td>
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<td>291.3</td>
<td>428.0</td>
<td>406.3</td>
<td>409.0</td>
<td>476.3</td>
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Table 4: Regression statistics for the model considering shear only

<table>
<thead>
<tr>
<th>Variable</th>
<th>β (coeff.)</th>
<th>Std. Error</th>
<th>tStat</th>
<th>p-Value</th>
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<tbody>
<tr>
<td>Intercept</td>
<td>100.310</td>
<td>22.672</td>
<td>4.42</td>
<td>9.95 x 10^-05</td>
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<tr>
<td>x1</td>
<td>0.009</td>
<td>0.001</td>
<td>6.29</td>
<td>4.08 x 10^-07</td>
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</table>

$R^2$ Value = 0.55, p-Value for model = 4.08 x 10^-07

Table 5: Regression statistics for model considering all material properties

<table>
<thead>
<tr>
<th>Variable</th>
<th>β (coeff.)</th>
<th>Std. Error</th>
<th>tStat</th>
<th>p-Value</th>
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<tr>
<td>Intercept</td>
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<td>3.17</td>
<td>3.45 x 10^-3</td>
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<tr>
<td>x1</td>
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<td>0.00</td>
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<tr>
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<td>-3.35</td>
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<td>x3</td>
<td>0.009</td>
<td>0.01</td>
<td>0.65</td>
<td>5.22 x 10^-1</td>
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$R^2$ Value = 0.72, p-Value for model = 1.4 x 10^-08