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THE INFLUENCE OF PIGMENTS ON THE MECHANICAL PROPERTIES OF HIGH DENSITY POLYETHYLENE (HDPE)

M J Lodeiro, P E Tomlins and A Pearce
Centre for Materials Measurement & Technology
National Physical Laboratory
Teddington
Middlesex TW11 0LW, UK

ABSTRACT

It is widely known that some organic pigments affect the crystallisation behaviour of polyethylene and polypropylene. These pigments appear to act as nucleating agents and produce marked changes in microstructure that can cause excessive shrinkage and warpage in mouldings manufactured from these materials. It is suspected that these changes in morphology may also influence the mechanical performance of pigmented mouldings. This is particularly important for closures containing tensioners where functionality is critically dependent on material performance.

This report presents the results from a study on the mechanical properties of injection moulded high-density polyethylene. The commonly used design parameters: Young's modulus, maximum yield stress, strain-to-failure and impact energy were used to characterise the effects of organic pigments (irgalite yellow and phthalocyanine blue) and processing conditions on performance.

The results show that the addition of organic pigments (in particular phthalocyanine blue) to high-density polyethylene does affect the principal mechanical characteristics. There is also evidence to suggest that the carrier and wetting agent used to manufacture masterbatches may play an important role in modifying the effects of pigments. The presence of small amounts of phthalocyanine blue causes an increase in ductility shown by a marked reduction in Young's modulus and yield stress and an increase in failure strain. These consequences can be attributed to morphological differences in levels of crystallisation, spherulite size and number. In addition, the increase in crystallisation temperature enhances the effects of processing variables, such as molecular orientation and skin-core ratio.

These results could be used by manufacturer's to allow for changes in pigmented mouldings in design or to counter the effects induced by pigmentation through modification of processing parameters in the production cycle.

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National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

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Head of Centre for Materials Measurement and Technology.

CONTENTS

1 INTRODUCTION

Environmental concerns and legislation regarding the use of heavy metal based inorganic pigments are responsible for the increased use of organic pigments as colorants in the plastics industry [1, 2]. Despite their low cost, excellent colouring ability and lightfastness, it is well known that some of these organic pigments can cause unacceptable levels of shrinkage and warpage in mouldings manufactured from polyolefins [3, 4].

We have previously demonstrated statistically significant links between different pigment types (phthalocyanine blue in particular) and both in- and out-of-plane shrinkage and warpage of a simple plate moulding [5, 6]. These pigments have been shown to affect the crystallisation behaviour of both polyethylene and polypropylene [7, 8]. Studies of crystallisation behaviour have shown that phthalocyanine blue acts as a nucleating agent raising the temperature at which crystallisation can occur and significantly reducing the size of the spherulites formed. These effects are more pronounced for polypropylene than for polyethylene. These changes in the morphology are likely to be reflected in the mechanical properties of mouldings. It is known that the fracture properties of filled polypropylene are affected both by spherulite size [9] and changes in the skin-core ratio that are attributable to differences in processing [10]. This issue is of particular importance to manufacturers of closures and snap-fittings, which contain tensioners and/or tamper-proof seals where the performance of the material is critical for functionality.

In this study, we assess how different types of pigment and processing conditions affect the mechanical properties of simple plate mouldings. The mouldings are characterised on the basis of the most commonly used design parameters:

- impact energy
- Young's modulus
- maximum yield stress
- strain to failure.

2 EXPERIMENTAL

The plates used in this study formed the basis of a previous investigation into dimensional stability of pigmented and un-pigmented high-density polyethylene (HDPE), moulded under a range of processing conditions.

There are potentially endless combinations of different processing conditions, pigment types, concentrations and masterbatch compositions possible. As a result, the number of pigments and processing variables considered were limited to those that have the most influence on shrinkage and warpage of mouldings [5, 6, 11]. These were established from trials and published literature. Further reductions were made through statistical sampling techniques (design of experiments). The range of each processing parameter investigated was defined by practical processing limitations.

The mould design, materials, processing windows and testing techniques are described briefly below.

2.1 MOULDING GEOMETRY

A simple edge-gated square plate mould was chosen to produce the mouldings. The detailed design is shown in Figure 1. The purpose of the domed region between the sprue and the weir gate is to ensure that a uniform flow front enters the mould cavity and hence that uniform filling occurs. This is achieved by ensuring that the flow path lengths between the sprue and gate are equal. This design was developed by the NPL to ensure maximum anisotropy of properties such as Young's modulus [12] and is based on predictions generated using the injection moulding simulation software package, Moldflow [13].

The mould cavity and cooling circuit are contained within a block of P20 steel of dimensions 296 mm * 496 mm * 168 mm. The dimensions of the square plate cavity are 150 mm x 150 mm x 4·4 mm. The cooling circuit maintains uniform cooling at both mould surfaces and a baffle insert positioned on the underside of the plate dissipates heat from the domed region of the cavity [11, 12].

2.2 MATERIALS

Pelletised masterbatches containing the components listed in Table 1 (supplied by Addcolour Plastics Ltd) were tumble mixed with pellets of HDPE (DSM Stamylan). These feedstocks were then used to injection mould 4 mm thick square plates with a pigment content of 0·13%. In order to determine the possible effect of some of the masterbatch components on the behaviour of the mouldings, an additional coloured feedstock was prepared. In this case the pellets of HDPE were tumble mixed directly with pigment powder and extruded. The concentration of pigment in the *direct* blend of phthalocyanine blue and pellet was 0·2 %.

	Masterbatch formulation			
Pigment	% Pigment	% Zinc Stearate	% Polyethylene Wax	% Linear Low Density Polyethylene (LLDPE)
Irgalite Yellow (yellow 62)	6·66	1	3	89·34
Phthalocyanine Blue	6·66	1	3	89·34

Table 1 - The composition of masterbatches.

Virgin HDPE was used to clean the barrel of the injection moulding equipment between successive colour changes. This procedure ensured that all traces of the previous colour were purged. When the processing conditions were stable (see section 2.3), six plates were produced for each set of conditions as listed in Appendix 1. These plates were removed from the machine immediately after ejection and placed on to the surface of a wooden table where they cooled to room temperature, approximately 18 ^{o}C. Five plates from each batch of six were used to manufacture test-pieces for mechanical testing.

2.3 PROCESSING CONDITIONS

The influence of a number of processing factors on the mouldings was considered. The range chosen in each case was based on the requirement to determine suitable processing windows that would produce acceptable mouldings for all combinations of factors. Several discrete levels were then chosen within each range as target values to be achieved for individual mouldings. These are given in Table 2.

Processing variable	Target values
Injection time (s)	1·5, 3·0, 4·5
Holding pressure (bar)	20, 40
Holding time (s)	20, 40
Melt temperature (°C)	190, 200, 215
Mould temperature (°C)	23, 40

Table 2 - Target values for the processing variables studied.

Unfortunately the practicalities of the injection moulding process mean that it is very difficult to ensure that the target values are actually met in the cavity. For example, lowering the holding time reduces the cycle time and causes the cavity wall temperature to rise as the cooling circuit attempts to dissipate a higher heat flux. Also, shear heating of the melt as it flows through the gate becomes increasingly significant with decreasing injection time, raising the melt temperature within the cavity above that measured at the nozzle tip. An additional complication arises with short injection times. These are associated with the rapid flow of melt into the cavity which results in melt compression. Decompression of the melt after the cavity is filled can cause backflow if insufficient holding pressure is applied. Alternatively, if the gate freezes before all the material within the cavity has solidified then the melt decompression can compensate, at least in part, for a lack of hold pressure. What happens in practice depends on the time taken for the material within the mould cavity to freeze and that, in turn, depends on both the effective melt and mould temperatures. Interactions of this type, between different factors, have been accounted for in the resultant moulding plan detailed in Appendix 1. Here it can be seen that the target and measured values are in close agreement (generally better than 5%).

The temperature of the melt was measured by inserting a platinum resistance thermocouple into the molten material after it had been extruded from the barrel (the barrel being positioned some distance from the mould). These measurements were made after several completed injection cycles, following changes to the temperatures of the barrel heaters.

A pressure transducer mounted behind one of the ejection pins was used to monitor cavity pressure. This transducer is centrally located within the cavity at a point near to the gate. It was apparent from the pressure time plots that the time over which the holding pressure is applied to the cavity is substantially shorter for the lower holding pressure, despite constant holding time settings being used for the machine. This shortfall is due to the gate freezing. Pressure traces provided by this transducer were used to assess machine “stability”.

For each batch of moulded plates, the injection-moulding machine was allowed to run through at least six moulding cycles before conditions were deemed to be sufficiently stable for moulding production.

2.4 MECHANICAL TESTING

The test-pieces were machined from the same position in each plate and, in the case of the tensile specimens in the same orientation (parallel to the flow direction), to minimise sample-to-sample variations. The nominal dimensions and source locations of each test-piece are shown in Figure 2. All tests were carried out under standard laboratory conditions (23 °C, 50% RH).

2.4.1 Young's Modulus, Yield Stress and Tensile Failure Strain

Measurements were made in accordance with ISO 527 part 2 (specimen type 1B) [14]. Tensile dogbone specimens, nominally 145 mm long with length of 60 mm and width of 10 mm within the gauge section, were tested at a crosshead displacement rate of 2 mm/min on an Instron test machine. Load was measured using a 100 kN load cell and specimen strain was monitored using a pair of 50 mm gauge length extensometers. Averaging the output from these compensates for the straightening of any warpage within the test-piece during loading. Young's modulus was determined from a linear regression on the stress/strain curve over the range 0·05-0·25% strain and the maximum yield stress was determined from the first stress maximum. Just after the maximum yield point was reached, the specimens were tested at 100 mm/min to failure. The specimen elongation at failure was determined from the crosshead displacement and original gauge-length. This higher test rate ensured ultimate failure of the specimen within the machine limits and a reasonable time frame.

2.4.2 Impact Energy

Impact energy-to-failure measurements were made in accordance with ISO 6603-2 [15]. The tests were carried out on a Rosand instrumented falling weight impact machine. The disc specimens, 60 mm in diameter, were supported on a 40 mm diameter steel ring. These were impacted at the centre by a 10 mm diameter hemispherical steel striker mounted on a 5 kg mass. A drop height of 2 m, giving an impact velocity of 6 m/s, was used to ensure penetration of the discs. A transducer mounted immediately behind the striker was used to monitor the load changes during impact. An optical device measured the striker velocity immediately prior to impact. The fracture energy of the specimen was calculated from the area under the force-deflection trace.

2.5 DATA INTERPRETATION

The mechanical data are interpreted using several methods: (i) analysis of means, (ii) analysis of variance and (iii) correlation analysis. The analysis of means is used to rank the effect of pigment and processing variables on mechanical performance. The analysis of variance is a statistical technique which determines the significance of differences in population means, taking into account the scatter in the data, and provides a measure of confidence in the trends observed with the analysis of means approach. Further to these, correlation analysis assesses the strength of the association between populations. However, in all cases the factors are considered in isolation such that interactions between different factors are assumed to have no influence on the results.

2.5.1 Analysis of Means (ANOM)

This approach compares and ranks the mean mechanical property values at each level of a processing factor. The effect of injection time, for example, would be determined by dividing the mechanical property data into three groups representing injection times of 1·5, 3·0 and 4·4 s and evaluating the mean value of data within each group.

2.5.2 Analysis of Variance (ANOVA)

Each of the pigment and processing variables will affect the mechanical property data to different degrees. Some may have no more influence than might be expected through experimental/random scatter. The variance in the data both within and between populations are analysed to draw conclusions about differences in the group means and the probability that these differences are due to treatment effects. A factor is considered significant if the hypothesis that its effect on the data is attributable to chance can be rejected with at least 95% confidence.

2.5.3 Correlation Analysis (Pearson)

This measures the relationship (linear) between two populations to determine if changes in one set correlate to changes in the other. An association is considered significant if the assumption that no correlation exists can be rejected with at least 95% confidence. For statistically significant associations, relationships may be positive (values tend to increase with one another) or negative (as one parameter increases, the other decreases).

3 RESULTS AND DISCUSSION

The averages and standard deviations of all the batch test results are presented in Appendix 2 and Figure 4. It is clear from a cursory inspection that there are differences in the data associated with the different pigments, mixes and processing variables. ANOM, ANOVA and correlation statistical tools were employed in order to establish those factors that affect the mechanical properties.

Changes in the mechanical properties of the mouldings due to geometrical differences between samples are generally accounted for in test method calculations. However, the impact energy absorbed to failure was found to show a strong correlation with plate thickness (directly related to plate weight). This relationship is likely to be an artefact of the test method since, in this case, frictional loads and material yielding experienced as the striker passes through the plate are also included in the load measurement, and these are dependent on thickness. Thus the measured energy increases with increasing thickness/plate weight. As a result, the energy absorbed during the impact up to the peak in the force-displacement trace was taken as a more representative parameter of the intrinsic material properties, being less dependent on geometric factors.

The ANOM ranking results are presented in Figure 5. The influence of colour, in particular, is shown in Table 3.

	Modulus (GPa)	Yield stress (MPa)	Failure strain (%)	Impact energy (peak) (J)
high	Yellow	Yellow	MB blue	Virgin
↑	Virgin	Virgin	DB blue	DB blue
↑	MB blue	MB blue	Virgin	Yellow
low	DB blue	DB blue	Yellow	MB blue

Table 3 - ANOM ranking of the influence of pigment type and mix on mechanical performance (direct blend and masterbatch blue labelled DB and MB blue respectively).

It is apparent that Young's modulus and yield stress are similarly affected by pigmentation and it is particularly interesting to note that mouldings produced using irgalite yellow have properties that exceed those of virgin material. In contrast, phthalocyanine blue reduces these properties (of the order of 2·5 - 5%) with respect to the virgin material, regardless of the method of pigment mixing. However, there is a large difference between the two blue mixes that is unlikely to be attributable to the small increase in pigment concentration in the direct blend as compared to the masterbatch mix. Comparison of the modulus and yield stress rankings with those of shrinkage and warpage measurements carried out parallel to the flow direction on the moulded plates show a similar trend, as can be seen in Table 4. Failure strain shows almost the exact opposite trend. Note that there is an inverse ranking relationship between the different pigments and shrinkage, such that greater shrinkage perpendicular to the flow direction is commensurate with less shrinkage parallel to the flow direction. The ranking of the pigments with peak impact energy is different and seemingly unrelated to that observed between colour and either modulus, yield stress or failure strain.

	Shrinkage/Warpage parallel to flow ($S_{\parallel}$)	Shrinkage/Warpage perpendicular to flow ($S_{\perp}$)
high	Yellow	DB blue
↑	Virgin	MB blue
↑	MB blue	Yellow
low	DB blue	Virgin

Table 4 - ANOM ranking of the influence of pigment type and mix on plate shrinkage [5].

The ANOVA results presented in Table 5 indicate that some of the differences identified by the ANOM rankings are highly significant. These indicate that colour and mould temperature have the most influence on the overall mechanical performance of the mouldings.

	Young's Modulus (GPa)	Maximum Yield Stress (MPa)	Failure Strain (%)	Impact Energy (peak) (J)
Colour	***	***	***	***
Injection time			***	*
Holding Pressure	*	***		
Melt temperature			*	
Holding time	*	*	*	*
Mould temperature	***	***	***	***

Table 5 - ANOVA results showing statistical significance of the mechanical property differences due to pigment and processing parameters (symbols relate to probabilities, values of less than 0·1% are highly significant).

KEY: *blank:* $P \geq 5\%$

*: $1\% \leq P < 5\%$

**: $0{\cdot}1\% \leq P < 1\%$

***: $P < 0{\cdot}1\%$

Table 6 shows statistically significant linear relationships between processing variables and mechanical performance determined using correlation analysis.

	Young's Modulus (GPa)	Maximum Yield Stress (MPa)	Failure Strain (%)	Impact Energy (peak) (J)
Injection time			***(+)	*(+)
Holding pressure	*(+)	***(+)		
Melt temperature				
Holding time	***(–)	***(–)		*(–)
Mould temperature	***(+)	***(+)	***(–)	***(–)
$S_{\perp}$	*(+)	***(+)		
$S_{\parallel}$	***(–)	***(–)		
Thickness	**(+)	***(+)		

Table 6 - Correlation results showing the nature of associations between mechanical properties and processing parameters, (+ : indicates direct proportionality, – : indicates inverse proportionality, other symbols and key as for Table 5).

Variations in thickness and shrinkage behaviour imply that there are significant differences in the morphology of the mouldings. The degree of crystallinity and the size and arrangement of crystallites can have a profound effect on physical and mechanical properties. Phthalocyanine blue has a significant influence on the microstructure of HDPE mouldings. There is a substantial reduction in the size of spherulites, secondary infilling lamellae are not seen and there is an increased number of crystalline structures. We have previously shown that the addition of phthalocyanine blue to HDPE (as a masterbatch) reduces the overall level of crystallinity from approximately 69% to 64%, despite the increased density of crystalline structure. In contrast irgalite yellow has much less influence on the morphology of HDPE, affecting only the detailed structure of spherulites. This is reflected in the overall level of crystallinity remaining unchanged from that of the virgin material.

Lower values of Young's modulus are associated with lower levels of crystallinity, due to the inherent high stiffness of crystalline material. Reductions in the overall level of crystallinity are also likely to have a negative influence on yield stress, as there is a greater proportion of amorphous material allowing crystalline regions to deform relative to one another. A similar argument will apply for the change in crystalline structure, where smaller crystals in larger numbers, each surrounded by amorphous material, are able to deform readily and lead to a reduced yield stress. A positive association between the Young's modulus and yield stress further confirms this finding.

Following this argument, the data shown in Table 3 and Figure 5 suggest that there is a significant difference in the level of crystallinity between phthalocyanine blue when added as a direct blend rather than a masterbatch. This difference is larger than would be expected due to the increase in pigment concentration (0·13-0·2%). This finding implies that the carrier LLDPE and/or the wetting agent constrain the distribution of pigment particles within the HDPE matrix. This hypothesis has yet to be tested by calorimetric measurements.

The reduction in both Young's modulus and yield stress leads to predictions of increased ductility for HDPE containing phthalocyanine blue. This is observed in practice with yield stress and failure strain showing a negative correlation. It is also possible that molecular orientation affects the relative differences in failure strain between moulding batches, as a material that is largely oriented in the direction of loading will have little remaining deformation available to it prior to rupture (distortion of the crystalline structure occurring by crystallite elongation and eventual unfolding). Evidence of this can be seen in the dependence of failure strain on injection time and mould temperature in Tables 5 and 6 and Figure 5. The ranking of shrinkage parallel to the flow with colour also suggests an orientation effect, with lower shrinkage indicating an increasing degree of preferred orientation in this direction and being linked to a higher modulus and yield stress and a lower failure strain as shown in Tables 3 and 4.

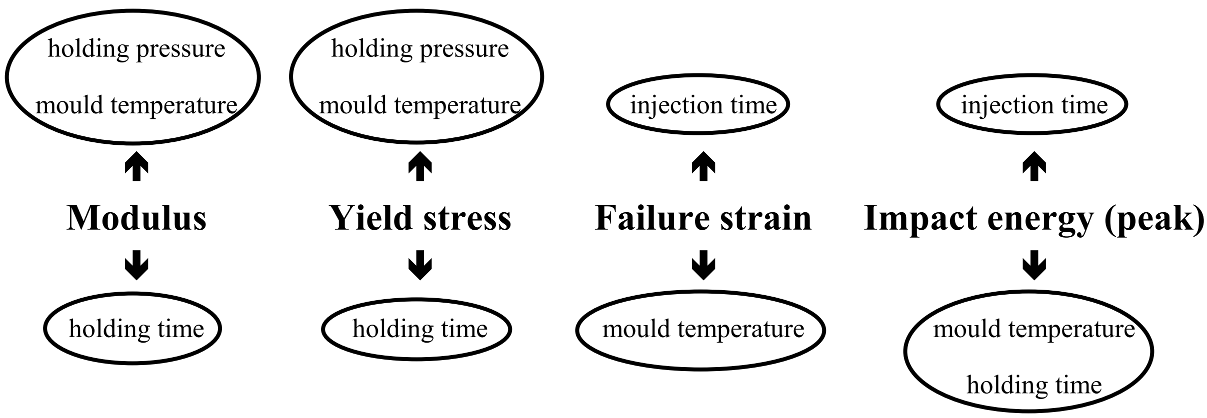
Understanding the link between impact energy and colour/processing parameters is more complex. The impact test is inherently more complex than the simple uniaxial tensile test, determining the global response of the moulded material with multi-directional loads being experienced. Thus the properties perpendicular to the flow direction may have a considerable influence. Factors other than variations in the level of crystallinity and spherulite morphology will of course affect mechanical performance of injection mouldings. Changes in mould temperature (cooling rate) and injection time (shear stress-induced orientation) will no doubt affect the degree of molecular orientation (and possibly preferred alignment of crystals) remaining in the plates after ejection and the ratio of oriented skin to amorphous core. Evidence of these effects can be seen in two indicators of peak impact energy: the peak load and deflection. The peak impact load is related to the modulus and yield stress, which are strongly affected by global crystallinity and would suggest a similar colour ranking for impact energy. However, the deflection at peak increases with injection time and decreases with increasing mould temperature, which indicates a strong influence of orientation and skin-core ratio on the flexural response of the material. The situation is further complicated by the nucleating action of the phthalocyanine blue which raises the temperature at which crystallisation occurs, perhaps enabling more molecular orientation to be frozen in during the cooling phase of the moulding cycle.

4 CONCLUSIONS

The addition of organic pigments to HDPE has been shown to affect Young's modulus, yield stress, failure strain and impact energy. There is also evidence to suggest that the carrier and wetting agent used to manufacture masterbatches may play an important role in modifying the effects of pigments. Results show significant differences in the mechanical properties of HDPE when coloured with phthalocyanine blue added as a masterbatch or directly.

The presence of small amounts of phthalocyanine blue is sufficient to cause a reduction in Young's modulus of up to 10%. This is consistent with previous observations that phthalocyanine blue reduces the overall level of crystallisation by 5% or more. The morphology of HDPE containing phthalocyanine blue is substantially different from that of the virgin material. The spherulites are smaller and more numerous in the coloured material. Such morphological differences are likely to be responsible for the increased ductility of HDPE in the presence of phthalocyanine blue as indicated by a higher failure strain and lower yield stress. By acting as a nucleating agent phthalocyanine blue can influence the extent of molecular orientation by limiting the time available for the extended chains to recover during melt cooling. This is expected to influence both failure strain and impact energy. These properties have been shown to correlate with both injection time and mould temperature, processing conditions that can influence molecular orientation and the skin-core ratio.

The relationships we have identified between different processing conditions and mechanical performance could be used to counter the effects induced by pigmentation. These relationships are presented below showing those factors which cause an increase ↑ or decrease ↓ in the specified mechanical property.



The extent of the effects of pigmentation on mechanical performance is likely to be dependent on the grade of material, the type of polyolefin or the specific ‘active’ pigment used (including any masterbatch additives), since these factors will influence both the nature and degree of change in the crystallisation behaviour (e.g. level of crystallinity, crystal size and shape, ratio of crystalline phases - primary to secondary in HDPE and α to β in polypropylene) which have been shown to affect mechanical properties.

It is important to note that although the differences in mechanical properties due to pigmentation are small, when combined with the shrinkage effects of phthalocyanine blue, they may be sufficient to cause a loss of functionality in components with tight tolerances moulded from polyolefins.

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Appendix 1

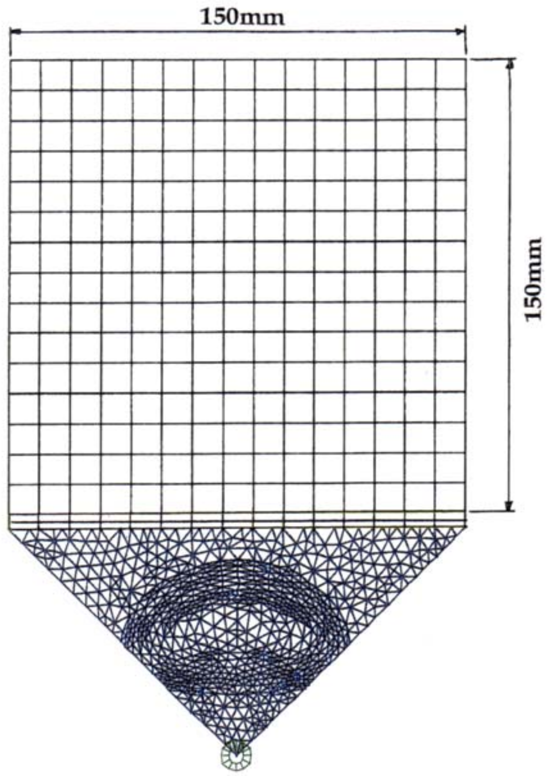
Colour (Identity code)	Injection time (s)	Holding pressure (bar)	Melt temperature (°C)	Holding time (s)	Mould temperature (± 1.5 °C)
Virgin (0000)	4.4	20	188.5 ± 3.5	20	23
Virgin (0001)	4.4	20	203.0 ± 3.0	20	23
Virgin (0002)	4.4	20	214.5 ± 1.5	20	23
Virgin (0010)	4.4	40	188.5 ± 3.5	20	23
Virgin (0012)	4.4	40	214.5 ± 1.5	20	23
Virgin (0100)	3.1	20	188.5 ± 3.5	20	23
Virgin (0102)	2.9	20	214.5 ± 1.5	20	23
Virgin (0111)	2.9	40	203.0 ± 3.0	20	23
Virgin (0200)	1.4	20	190.0 ± 2.0	20	40
Virgin (0211)	1.5	40	191.5 ± 3.5	20	40
DB Blue (1000)	4.4	20	188.5 ± 3.5	40	23
DB Blue (1001)	4.4	20	203.0 ± 3.0	40	23
DB Blue (1012)	4.3	40	210.0 ± 3.5	40	23
DB Blue (1100)	3.1	20	188.5 ± 3.5	40	23
DB Blue (1101)	3.1	20	203.0 ± 3.0	40	23
DB Blue (1110)	3.1	40	188.5 ± 3.5	40	23
DB Blue (1112)	2.9	40	210.0 ± 3.5	40	23
DB Blue (1200)	3.0	20	190.0 ± 2.0	40	40
DB Blue (1201)	1.5	20	191.5 ± 3.5	40	40
DB Blue (1202)	1.5	20	210.0 ± 3.5	20	40
DB Blue (1211)	1.5	40	191.5 ± 3.5	40	40
DB Blue (1212)	1.5	40	210.0 ± 3.5	40	40
Yellow (2000)	4.4	20	190.0 ± 2.0	40	40
Yellow (2002)	4.4	20	214.5 ± 1.5	40	40
Yellow (2011)	4.4	40	191.5 ± 3.5	40	40
Yellow (2012)	4.4	40	214.5 ± 1.5	40	40
Yellow (2101)	2.9	20	191.5 ± 3.5	40	40
Yellow (2102)	2.9	20	214.5 ± 1.5	40	40
Yellow (2111)	2.9	40	191.5 ± 3.5	40	40
Yellow (2112)	2.9	40	214.5 ± 1.5	40	40
Yellow (2201)	1.5	20	203.0 ± 3.0	40	23
Yellow (2210)	1.5	40	190.5 ± 2.5	40	23
Yellow (2212)	1.5	40	214.5 ± 1.5	40	23
MB blue (3001)	4.4	20	191.5 ± 3.5	20	40
MB blue (3002)	4.4	20	209.5 ± 3.5	20	40
MB blue (3010)	2.9	40	190.0 ± 2.0	20	40
MB blue (3011)	4.4	40	191.5 ± 3.5	20	40
MB blue (3102)	2.9	20	209.5 ± 3.5	20	40
MB blue (3110)	1.5	40	190.0 ± 2.0	20	40
MB blue (3202)	1.5	20	210.0 ± 3.5	20	23
MB blue (3211)	1.5	40	203.0 ± 3.0	20	23

Design matrix for HDPE moulded plates, listing the values for processing parameters. Holding pressures and times are machine set, all other quantities are measured (direct blend and masterbatch blue labelled DB and MB blue respectively).

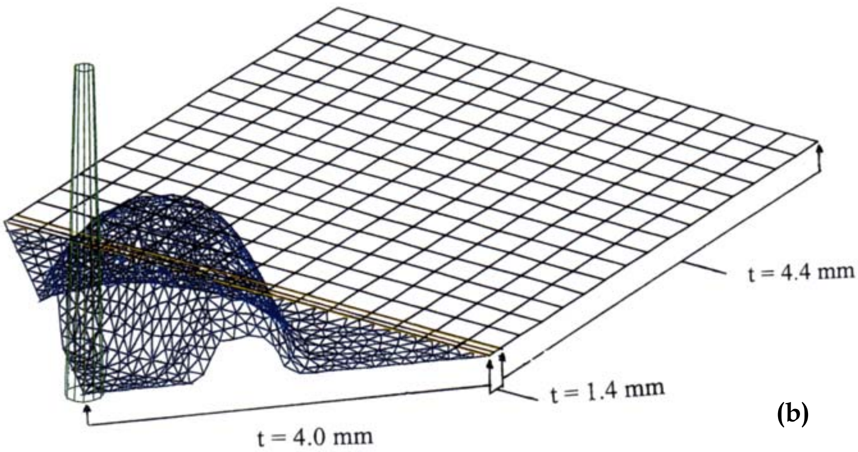
Appendix 2

Colour (Identity code)	Young's modulus (GPa)	Maximum yield stress (MPa)	Failure strain (%)	Impact energy (failure) (J)	Impact energy (peak) (J)	Plate thickness (± 0 01 mm)
Virgin (0000)	1.31 ± 0.05	20.37 ± 0.09	115 ± 42	20.96 ± 0.58	15.19 ± 0.36	3.84
Virgin (0001)	1.32 ± 0.06	20.48 ± 0.03	97 ± 26	20.83 ± 0.13	14.79 ± 0.05	3.83
Virgin (0002)	1.35 ± 0.03	20.59 ± 0.05	138 ± 35	20.82 ± 0.20	15.44 ± 0.59	3.82
Virgin (0010)	1.33 ± 0.02	20.46 ± 0.06	106 ± 40	21.23 ± 0.31	15.12 ± 1.17	3.93
Virgin (0012)	1.32 ± 0.02	20.21 ± 0.04	130 ± 44	21.53 ± 0.26	16.00 ± 0.32	3.99
Virgin (0100)	1.36 ± 0.03	20.59 ± 0.05	123 ± 39	20.67 ± 0.31	15.54 ± 0.38	3.83
Virgin (0102)	1.29 ± 0.04	20.18 ± 0.07	105 ± 27	20.43	14.75	3.84
Virgin (0111)	1.34 ± 0.01	20.26 ± 0.05	137 ± 30	21.28 ± 0.16	15.37 ± 0.22	3.95
Virgin (0200)	1.40 ± 0.04	20.86 ± 0.12	77 ± 5	21.12 ± 0.20	14.62 ± 0.97	3.83
Virgin (0211)	1.36 ± 0.02	20.82 ± 0.07	75 ± 6	21.62	15.08	3.95
DB Blue (1000)	1.15 ± 0.04	19.47 ± 0.05	145 ± 42	20.51 ± 0.18	14.23 ± 0.45	3.82
DB Blue (1001)	1.23 ± 0.05	19.64 ± 0.03	164 ± 44	20.80 ± 0.25	13.67 ± 0.47	3.82
DB Blue (1012)	1.21 ± 0.04	19.68 ± 0.07	127 ± 27	21.15 ± 0.22	14.51 ± 1.42	3.95
DB Blue (1100)	1.23 ± 0.09	19.36 ± 0.03	132 ± 35	21.44 ± 1.49	13.55 ± 0.93	3.83
DB Blue (1101)	1.19 ± 0.05	19.52 ± 0.07	158 ± 30	20.38 ± 0.18	14.58 ± 0.13	3.82
DB Blue (1110)	1.22 ± 0.02	19.78 ± 0.01	115 ± 53	20.39 ± 0.19	14.43 ± 0.68	3.91
DB Blue (1112)	1.20 ± 0.02	19.58 ± 0.04	154 ± 65	21.14 ± 0.36	15.07 ± 0.79	3.94
DB Blue (1200)	1.19 ± 0.09	19.79 ± 0.06	79 ± 12	20.83 ± 0.47	14.46 ± 0.35	3.82
DB Blue (1201)	1.21 ± 0.06	19.34 ± 0.05	82 ± 7	20.41 ± 0.26	14.57 ± 0.24	3.85
DB Blue (1202)	1.22 ± 0.02	19.85 ± 0.06	83 ± 3	20.89 ± 0.31	14.38 ± 0.43	3.86
DB Blue (1211)	1.23 ± 0.02	20.23 ± 0.09	79 ± 6	20.74 ± 0.27	14.73 ± 0.77	3.93
DB Blue (1212)	1.25 ± 0.02	19.87 ± 0.02	105 ± 50	21.75	13.70	3.99
Yellow (2000)	1.35 ± 0.06	20.59 ± 0.10	82 ± 8	20.59	14.75	3.83
Yellow (2002)	1.37 ± 0.06	20.42 ± 0.08	99 ± 36	20.50	14.26	3.83
Yellow (2011)	1.41 ± 0.02	21.00 ± 0.05	78 ± 13	21.35	13.93	3.93
Yellow (2012)	1.38 ± 0.01	20.79 ± 0.08	93 ± 20	21.00	14.55	3.97
Yellow (2101)	1.32 ± 0.07	20.40 ± 0.09	80 ± 5	21.07	12.85	3.84
Yellow (2102)	1.32 ± 0.06	20.50 ± 0.10	85 ± 14	20.52	13.21	3.83
Yellow (2111)	1.35 ± 0.02	20.65 ± 0.06	105 ± 55	21.08	13.94	3.96
Yellow (2112)	1.38 ± 0.03	20.84 ± 0.05	81 ± 5	21.16	14.16	3.97
Yellow (2201)	1.38 ± 0.03	20.38 ± 0.03	75 ± 5	20.41	14.07	3.84
Yellow (2210)	1.36 ± 0.01	20.41 ± 0.07	83 ± 9	20.92	14.02	3.93
Yellow (2212)	1.36 ± 0.01	20.59 ± 0.04	97 ± 16	20.97	13.39	3.97
MB blue (3001)	1.34 ± 0.04	20.05 ± 0.06	162 ± 64	21.07	12.81	3.83
MB blue (3002)	1.36 ± 0.03	20.10 ± 0.04	131 ± 37	21.05	13.49	3.84
MB blue (3010)	1.39 ± 0.06	20.70 ± 0.06	121 ± 30	21.10	13.92	3.93
MB blue (3011)	1.32 ± 0.03	20.18 ± 0.14	102 ± 11	21.47	13.82	3.95
MB blue (3102)	1.30 ± 0.04	20.10 ± 0.03	101 ± 4	21.33	12.48	3.84
MB blue (3110)	1.31 ± 0.02	20.29 ± 0.06	99 ± 11	21.14	13.5	3.93
MB blue (3202)	1.28 ± 0.02	20.26 ± 0.07	85 ± 12	21.59	12.95	3.85
MB blue (3211)	1.33 ± 0.03	20.37 ± 0.04	140 ± 71	21.44	13.30	3.93

Young's modulus, yield stress, failure strain and impact energies for the mouldings together with the mean thickness of each batch of plates. These data represent the averages and standard deviations of five tests (where no standard deviation is quoted the results are the average of three measurements).



(a)



(b)

Figure 1 – Design and dimensions of moulding cavity;
(a) in-plane and (b) thickness.

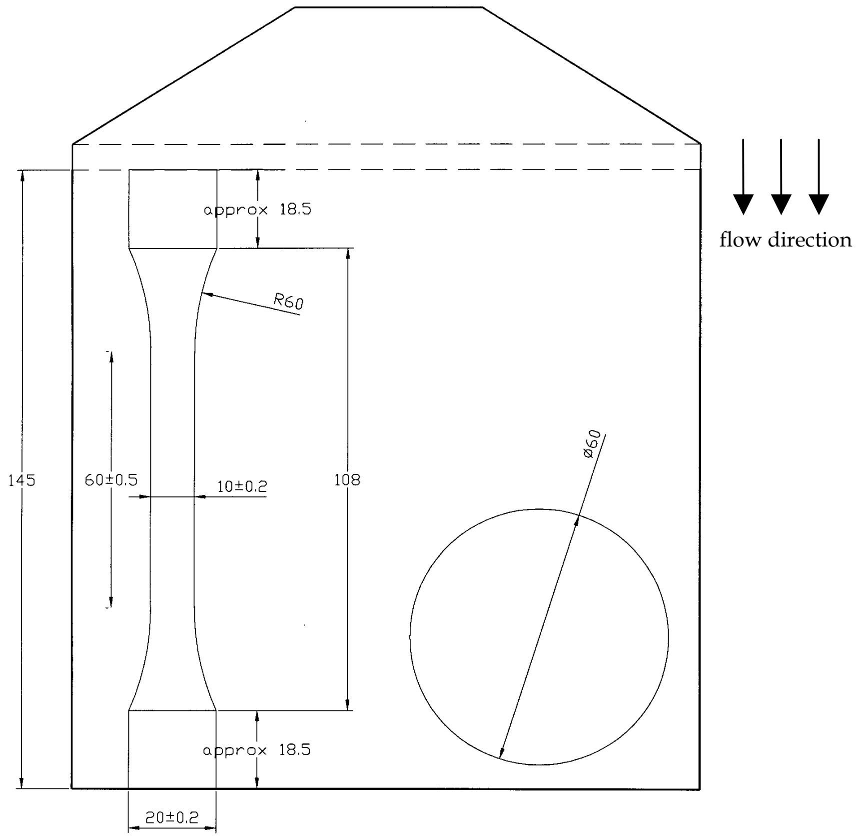


Figure 2 – Schematic diagram of the location and orientation of test-pieces machined from each moulded plate (dimensions marked in mm).

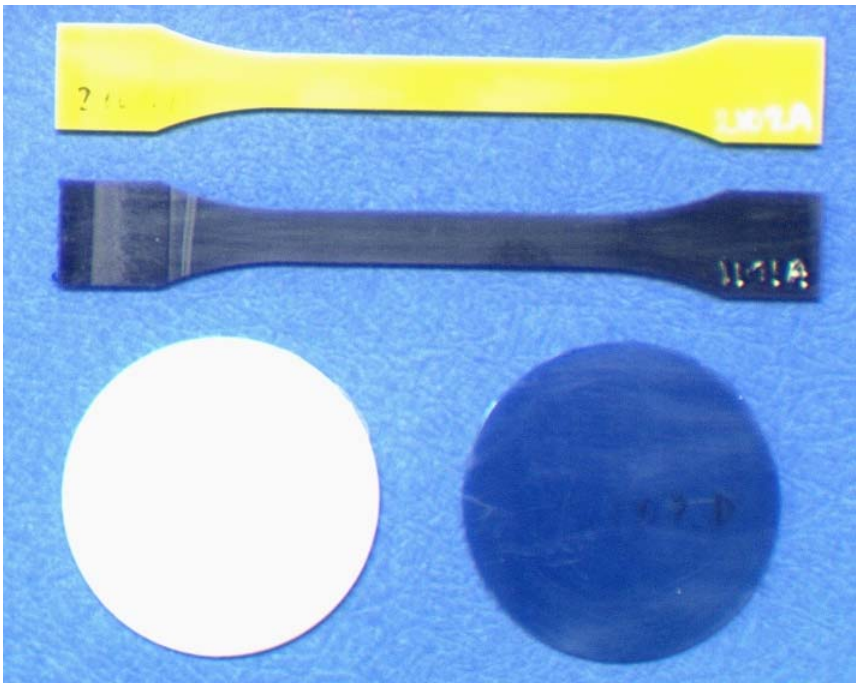


Figure 3 - Typical tensile and impact specimens; from the top: masterbatch yellow, direct blend blue, virgin and masterbatch blue.

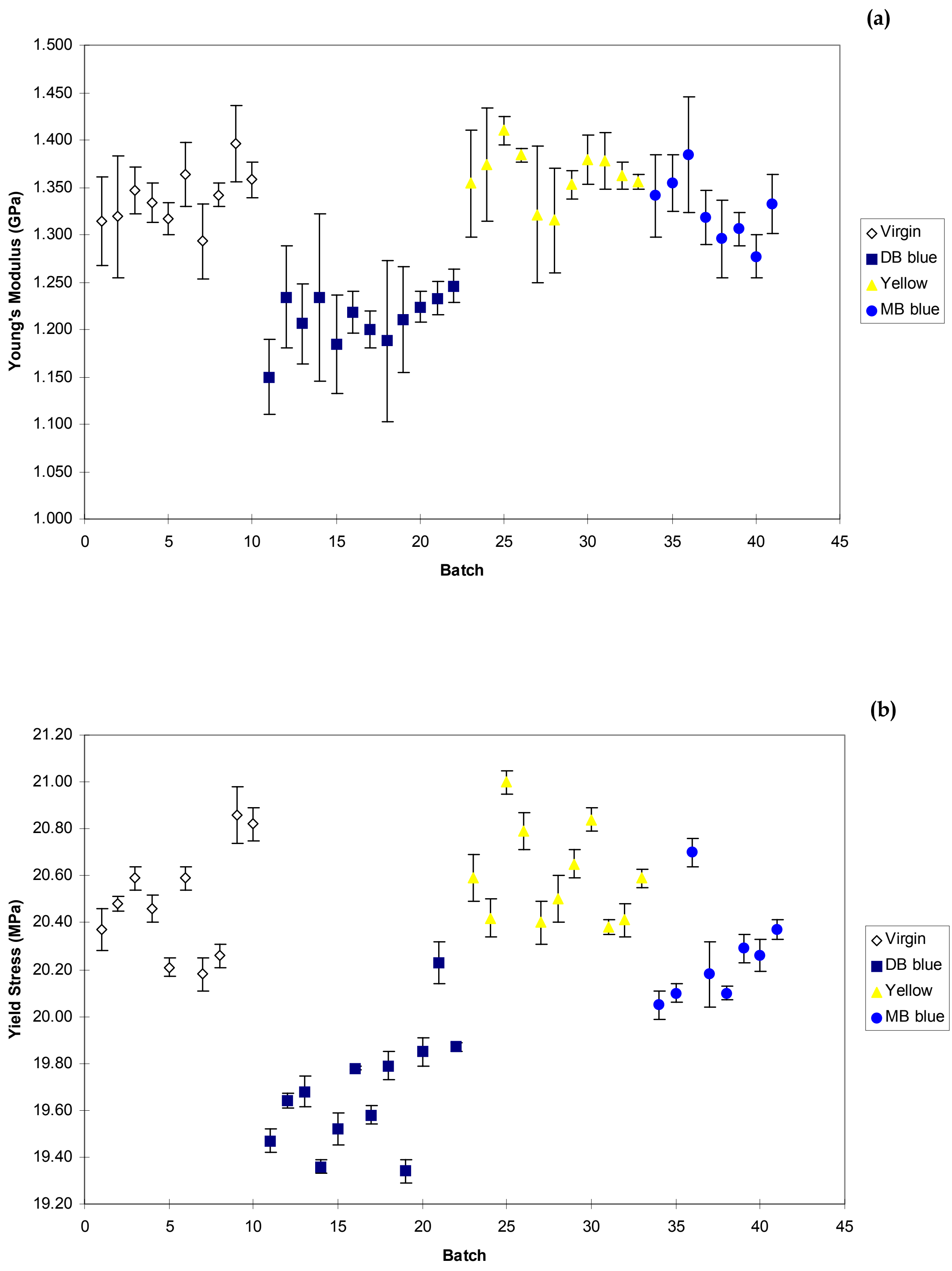
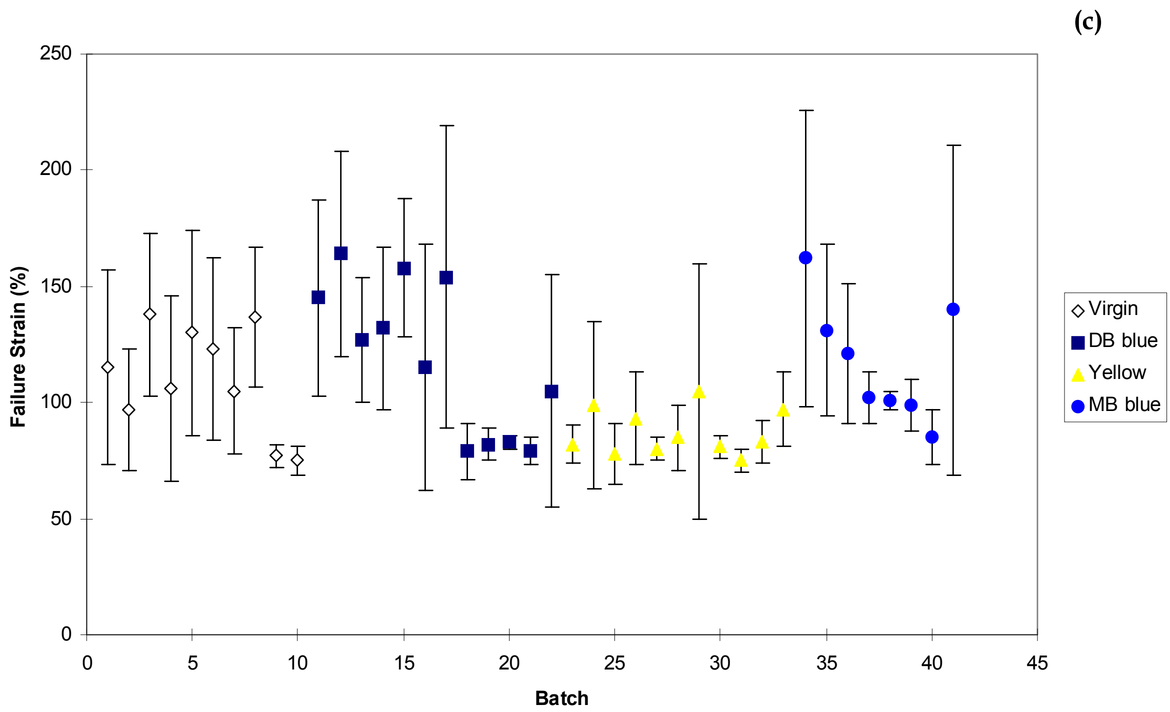


Figure 4 – Average batch results and standard errors for (a) Young's modulus and (b) maximum yield stress (direct blend and masterbatch blue labelled DB and MB blue respectively).



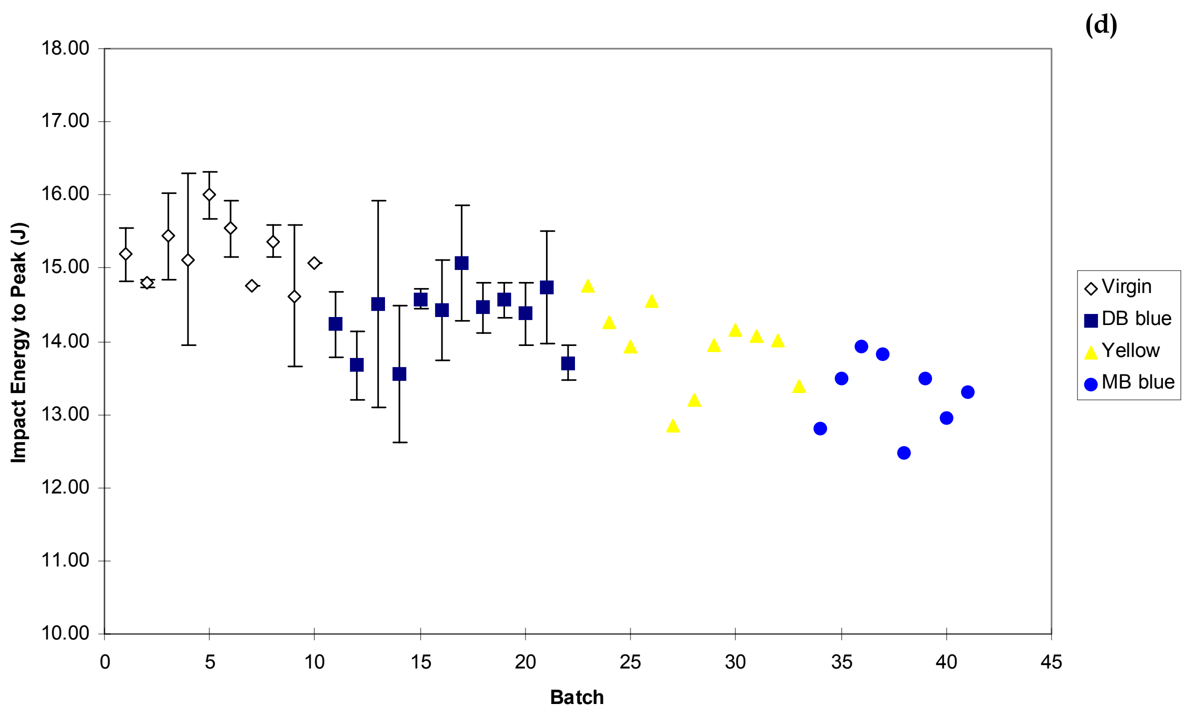
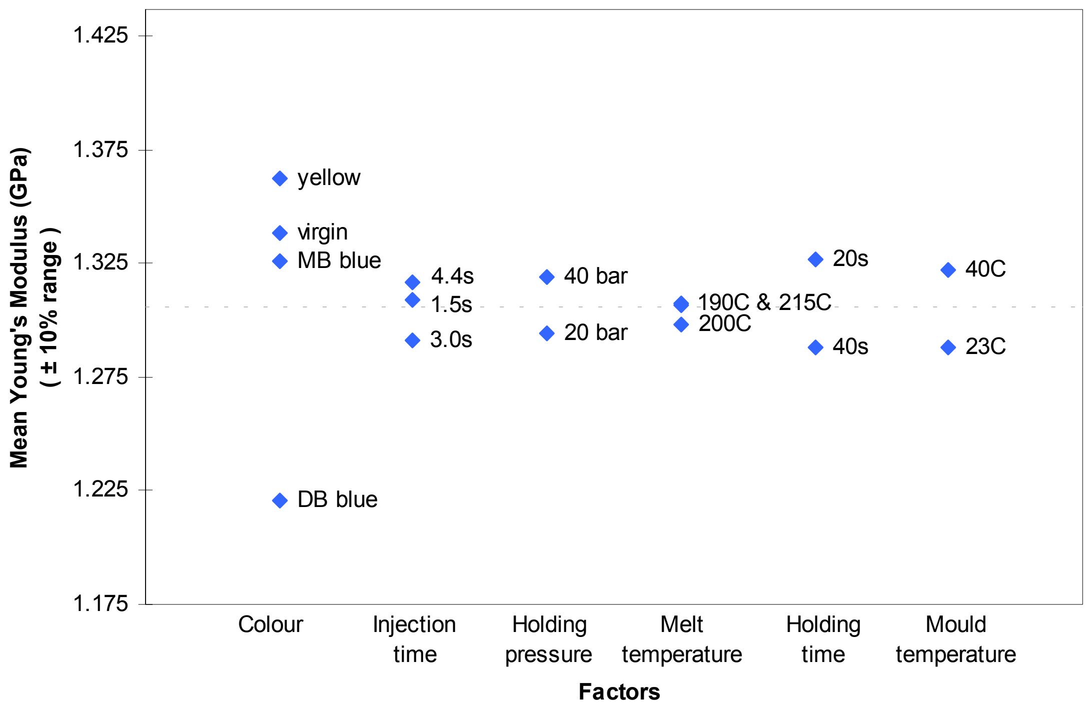


Figure 4 – Average batch results and standard errors for (c) failure strain and (d) peak impact energy (direct blend and masterbatch blue labelled DB and MB blue respectively).

(a)



(b)

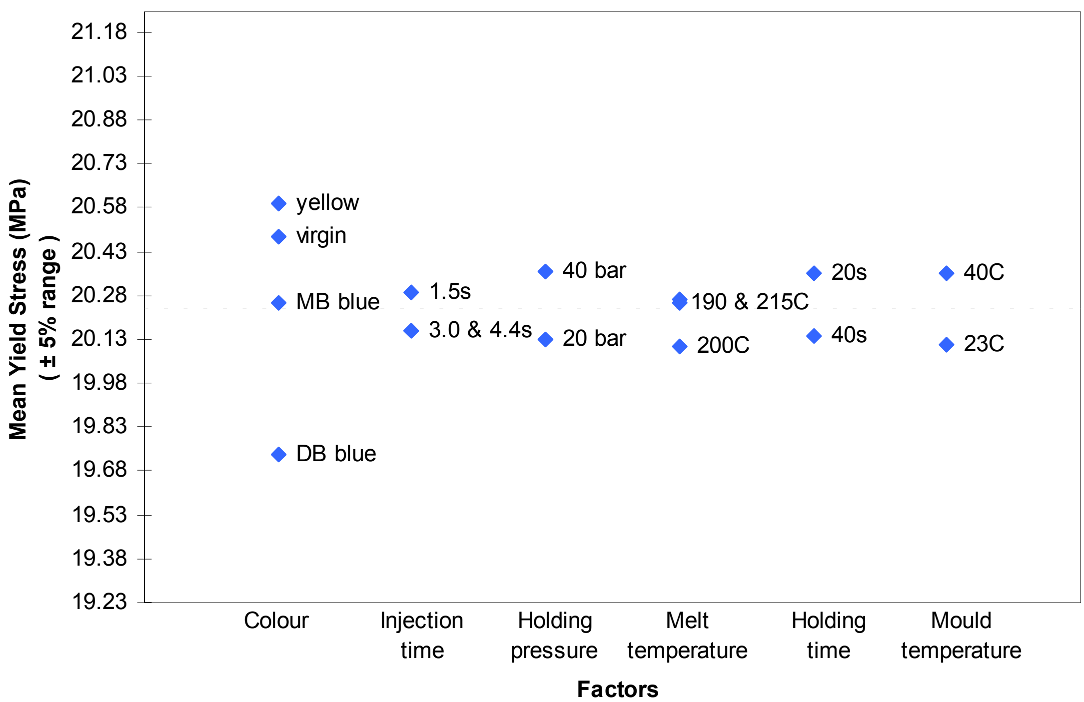
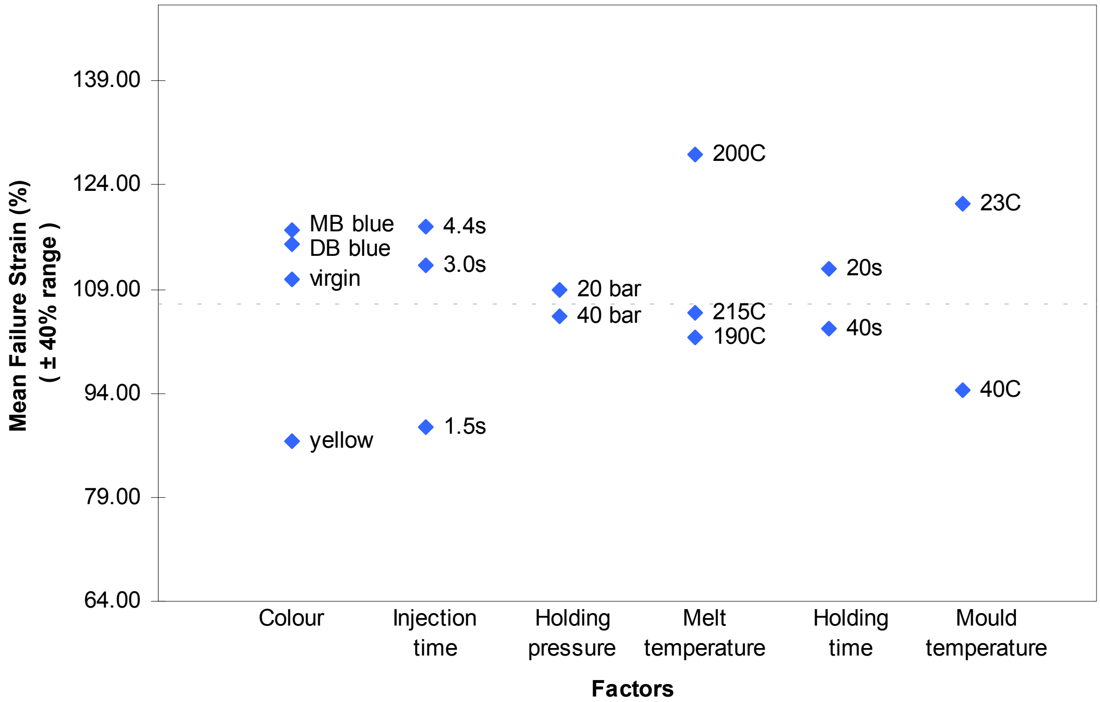


Figure 5 – ANOM results for (a) Young's modulus and
(b) maximum yield stress (dashed lines represent the global average).

(c)



(d)

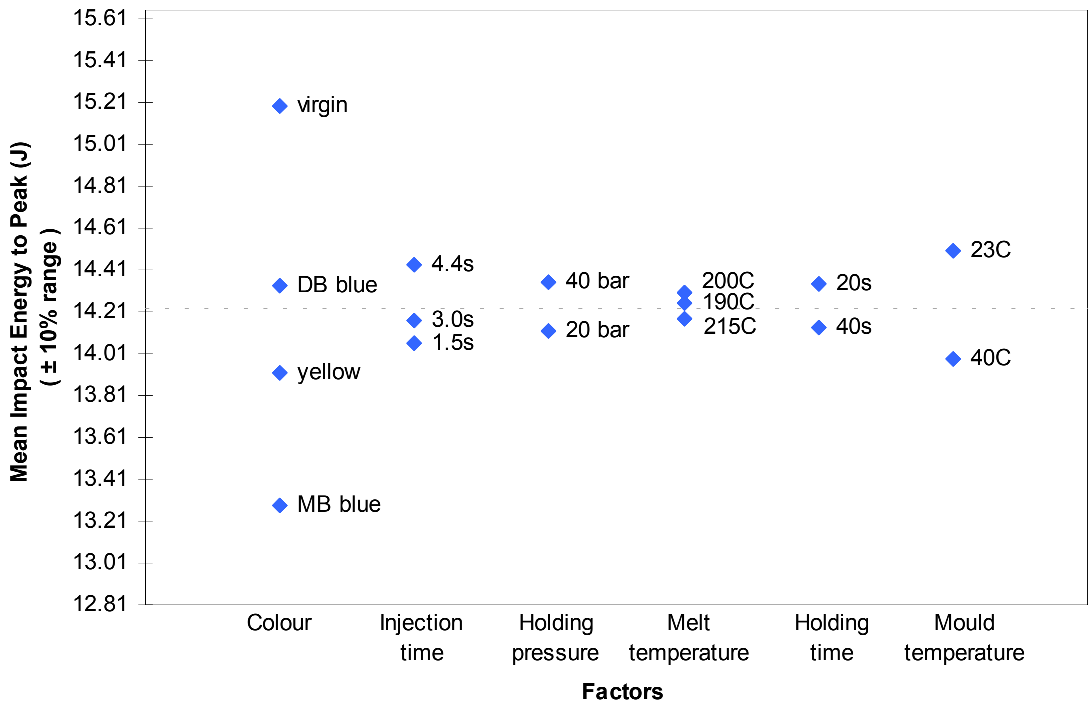


Figure 5 – ANOM result for (c) failure strain and
(d) peak impact energy (dashed lines represent the global average).