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Effect of recycled plastic and compound additives on the properties of an injection-moulded polypropylene co-polymer

Part 4 *Pigments and an ultra-violet stabilizer*

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The falling-dart impact test and micromorphology studies have been used to investigate the effect of recycled material, pigments, ultra-violet stabilizer and co-polymer molecular weight on the properties of injection mouldings. Together with the results presented in Parts 1 to 3 the new results show that the spherulite morphology and impact properties are markedly dependent on compound formulation.

1. Introduction

The poor resistance of polypropylene to photodegradation is well documented and clearly shown by the results reported by the authors in the previous papers of this series [1–3]. These results support the widely held view that polypropylene co-polymers for outdoor applications have to be stabilized against ultra-violet degradation. Published work [4–9] indicates that various pigments can affect the efficiency of ultra-violet stabilizers. In view of these reports the study of the effect of using ultra-violet stabilizers in conjunction with pigments and recycled material upon the microstructure and mechanical properties of injection mouldings was undertaken. This enabled the effect of the total additive system on the microstructure and properties of injection mouldings to be investigated.

2. Experimental method

The set processing conditions used in the moulding of all test specimens prepared for the experiments reported in this paper were given in Table I of Part 3 [3]. The previously described moulding procedure [1, 2] ensured that contamination and the reproducibility of properties within batches of mouldings were kept to a minimum and a maximum, respectively. The results presented in this paper were all based on 3 mm thick 8 cm square plaques. The full range of feedstocks studied is given in Table I where the following notation applies. The type of pigmentation is represented by the letters V, A, B, C, which correspond to virgin unpigmented polymer, phthalocyanine blue, ultramarine blue and carbon black, respectively. The blues were used in powder form and the carbon black in the form of master-batch. The pigments were tumble-mixed with the virgin polymer prior to moulding. The letter S after the pigment type refers to the stabilized grade of polypropylene co-polymer, which was used as supplied by the manufacturer as the base polymer for the work. The second half of the notation represents the concentration and type of reground material used in the compound. For example 2.0BS–25G1 represents feedstock containing 2 wt% ultramarine blue pigment and containing 25 wt% reground material in granulate form which had been recycled once prior to the final injection-moulding cycle.

3. Impact test results

Falling-dart impact test results were obtained for the range of compounds identified in Table I before and after weathering, and these results are summarized in Figs 1 and 2, respectively. The first column in each figure shows the impact strength of plaques prepared from virgin feedstock containing no pigment and no ultra-violet stabilizer. The plaques were tested two weeks after moulding at test temperatures of 23° C and − 10° C. The remainder were naturally weathered near London for

TABLE I Tabulation of the compounds used for the main part of the work presented in this paper. In addition to pigment-free virgin polypropylene and compounds based on recycled virgin plastic, these compounds contained weathered plastic, ultra-violet light stabilized grade of polypropylene which also contained 2 wt% of phthalocyanine blue, ultramarine blue or carbon black pigment. The results relating to these compounds are presented in Figs 1 and 2, and Table IV. Results relating to ageing tests and a different molecular-weight polymer are given in Tables II and V, respectively

Unpigmented virgin material with increasing percentage of material recycled once	25 wt% of material weathered and recycled	Unpigmented ultra-violet stabilized virgin material with increasing percentage of material recycled once	2 wt% phthalocyanine blue pigmented ultra-violet stabilized virgin material with increasing percentage of material recycled once	2 wt% ultramarine blue pigmented ultra-violet stabilized virgin material with increasing percentage of material recycled once	2 wt% carbon black pigmented ultra-violet stabilized virgin material with increasing percentage of material recycled once
V	V	VS	2.0 AS–0G1	2.0 BS–0G1	2.0 CS–0G1
V–10G1	V–25 GW1	VS–10G1	2.0 AS–10G1	2.0 BS–10G1	2.0 CS–10G1
V–25G1		VS–25G1	2.0 AS–25G1	2.0 BS–25G1	2.0 CS–25G1
V–100G1		VS–100G1	2.0 AS–100G1	2.0 BS–100G1	2.0 CS–100G1

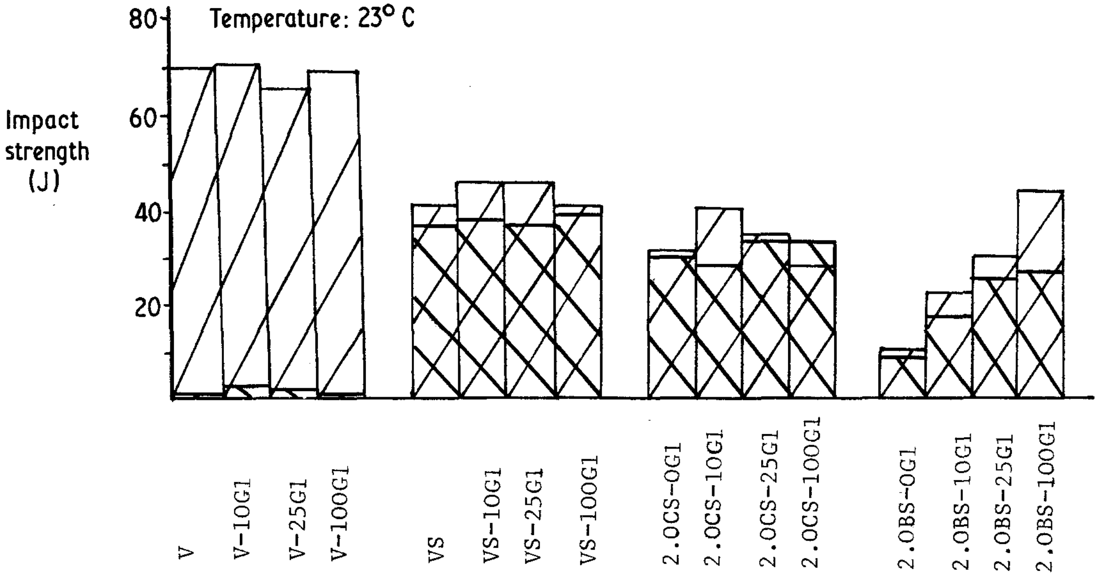

Figure 1 Impact test results obtained at a test temperature of 23° C, before and after natural weathering. The impact strength after natural weathering is shown in cross-hatching.

six months between the months of November and July prior to impact testing. In addition, some virgin plaques were aged for the same period, but in the absence of any damaging radiation. These were subsequently impact tested at 23° C and — 10° C.

The plaques prepared from natural co-polymer containing no additional stabilizer were impact tested at 23° C at intervals over a period of six months, in order to investigate the effect of ageing on impact properties.

A comparison of the results presented in this paper and those presented in [3] will show a substantial difference in impact strength for nominally similar mouldings. There are three main reasons for the reported differences. Firstly, a different injection-moulding machine was used to produce the test plaques. A great effort was made to match the processing conditions used for the two experiments. The same mould was used and the measured cavity pressures in both cases were

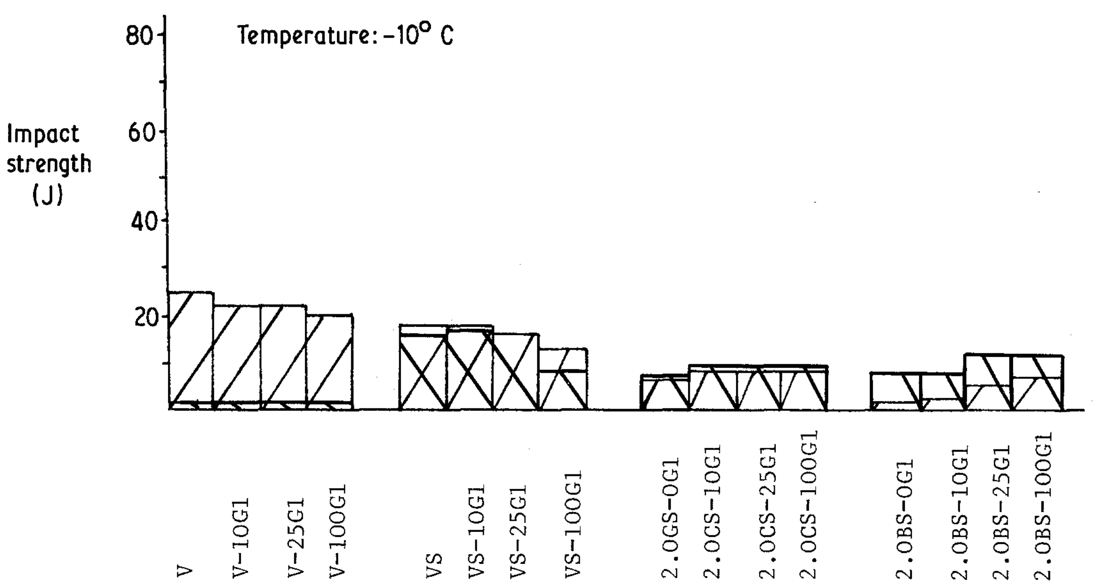

Figure 2 Impact test results obtained at a test temperature of — 10° C, before and after natural weathering. The impact strength after natural weathering is shown in cross-hatching.

very similar. It is well known [10], however, that reproducibility of properties of mouldings produced in different machines is difficult to realize in practice. Secondly, a different batch of the same grade of polymer was used for the experiments reported in this paper, and this too could result in a significant difference in the measured values of impact strength. Thirdly, the previously reported impact results [2] were carried out six months after injection moulding, which could account for a significant decrease in impact strength, as indicated by the experiments reported in Section 6 of this paper. The batches of material used for the stabilized and unstabilized grades were also different and too much emphasis should not be placed on small differences in the results quoted for these two materials.

4. Results of impact tests at 23° C

Fig. 1 shows the effect of incorporating recycled material, pigment and an ultra-violet stabilizer upon the impact strength of 3 mm thick plaque mouldings tested at 23° C two weeks after moulding and after six months natural weathering. The impact test results obtained at − 10° C are presented in Section 5.

4.1. Results, two weeks after moulding

4.1.1. Unstabilized, 0% pigment

At an impact test temperature of 23° C and two weeks after moulding the impact strength of plaques prepared from unstabilized, natural co-polymer was $\simeq 80$ J. The effect of increasing the percentage of recycled material up to the 100% level was negligible, and confirms the results presented in Parts 2 and 3 of the work [2, 3].

4.1.2. Stabilized, 0% pigment

At a test temperature of 23° C the impact strength of plaques prepared from the stabilized grade of the same co-polymer was $\simeq 30$ J lower than that of the corresponding plaques prepared from the unstabilized grade. The effect of incorporating recycled material up to the 100% level was again negligible.

4.1.3. Stabilized, 2 wt% carbon black

A smaller decrease of $\simeq 10$ J in the impact strength resulted from the incorporation of 2 wt% carbon black pigment. An improvement in the impact strength, compared to the virgin plaques, was observed at the 10 wt% and 25 wt% level of recycled material. At the 100% level of recycled material the impact strength fell to a value of $\simeq 28$ J, which was slightly below the impact strength of the virgin plaques.

4.1.4. Stabilized, 2 wt% ultramarine blue

Introducing 2 wt% ultramarine blue pigment markedly reduced the impact strength of the mouldings. The value falling from $\simeq 40$ J for the natural stabilized grade to $\simeq 10$ J for the same grade of co-polymer containing 2 wt% ultramarine blue.

A gradual improvement in the impact strength of the mouldings was observed as the percentage of recycled material was increased. The improvement at the 100% level of recycled material was such that the value of the impact strength was the same as that for plaques prepared from the natural stabilized co-polymer. This improvement in properties with increasing percentage of recycled material was attributed to better dispersion of pigment and a reduction in the proportion of Type III spherulites [3].

4.1.5. Stabilized, 2 wt% phthalocyanine blue

The effect of incorporating 2 wt% of phthalocyanine blue and ultra-violet stabilizer was to cause a drastic reduction in the impact strength of all the plaques, to approximately 1.5 J, compared with $\simeq 40$ J for the corresponding unpigmented plaques at a test temperature of 23° C.

4.2. Results, after six months natural weathering

4.2.1. Unstabilized, 0% pigment

At 23° C the impact strength of the mouldings fell from a value of $\simeq 70$ J before weathering to $\simeq 2$ J after six months natural weathering. The effect of incorporating recycled material up to the 100% level upon the weathering characteristics of the mouldings was negligible.

4.2.2. Stabilized, 0% pigment

At 23° C the value of incorporating an ultra-violet stabilizer was clearly demonstrated. The impact strength of stabilized plaques falling by only $\simeq 7$ J after six months natural weathering. The deleterious effect on the weathering characteristics of the mouldings was observed with the incorporation of recycled material at the 100% level, and was attributed to the introduction of chromophores.

4.2.3. Stabilized, 2 wt% carbon black

The protection afforded by a combination of 2 wt% carbon black and an ultra-violet stabilizer was in general better than that for the stabilizer alone. The fall-off in performance was limited to $\simeq 2$ J with the exception of the plaques containing 10 wt% recycled material, in which case the impact strength fell from 41.4 J before weathering to 28.7 J after six months exposure. This compares with a fall-off of $\simeq 7$ J for the unpigmented plaques.

4.2.4. Stabilized, 2 wt% ultramarine blue

The incorporation of ultramarine blue pigment afforded no more protection than the ultra-violet stabilizer alone. The weathering characteristics of the mouldings deteriorated with increasing percentage of recycled material. The fall-off in performance of plaques containing 100% of recycled material being $\simeq 20$ J compared to a small improvement upon weathering the virgin plaques of $\simeq 3$ J. The impact strength of the weathered plaques containing recycled material did not, however, fall below that recorded for the weathered or unweathered virgin plaques.

5. Results of impact tests at -10° C

Fig. 2 shows the effect of incorporating recycled natural pigment and ultra-violet stabilizer upon the impact strength of 3 mm thick plaque mouldings at a test temperature of -10° C two weeks after moulding and after six months natural weathering.

5.1. Results, two weeks after moulding

5.1.1. Unstabilized, 0% pigment

The effect of lowering the test temperature from 23° C to -10° C is to decrease the impact strength of the plaques by 50%. The impact strength of the plaques prepared in two different injection-moulding machines were very similar when tested at -10° C, and the results were not influenced by ageing the plaques in the absence of damaging radiation.

Increasing the percentage of recycled material up to the 100% level generally had a negligible effect upon the impact strength of the plaques tested at -10° C.

5.1.2. Stabilized, 0% pigment

At -10° C the incorporation of an ultra-violet stabilizer reduced the impact strength of the mouldings by $\simeq 6$ J compared to the corresponding plaques containing on stabilizer. The incorporation of recycled material up to the 100% level had very little effect upon the performance of the mouldings.

5.1.3. Stabilized, 2 wt% carbon black

The presence of 2 wt% carbon black and ultra-violet stabilizer reduced quite markedly the impact strength of the mouldings when tested at -10° C. The value falling from 18.8 J for the unpigmented stabilized virgin plaques to 5.9 J for the corresponding plaques containing 2 wt% carbon black. The incorporation of recycled material slightly improved the performance of the plaques.

5.1.4. Stabilized, 2 wt% ultramarine blue

At -10° C the combination of ultra-violet stabilizer and 2 wt% ultramarine blue pigment drastically reduced the impact performance of the plaques. The impact strength of the virgin plaques falling to $\simeq 3$ J compared with a value of $\simeq 19$ J for the corresponding unpigmented plaques. An increase in the percentage of recycled material improved the performance of the plaques, although the improvement was not as marked as at 23° C.

5.1.5. Stabilized, 2 wt% phthalocyanine blue

The performance of plaques prepared from feedstock containing 2 wt% phthalocyanine blue and an ultra-violet stabilizer was so poor that none of the plaques passed the impact test at -10° C; that is, all specimens failed under the impact of the lightest tup when dropped from the minimum set height of the apparatus.

5.2. Results, after six months natural weathering

5.2.1. Unstabilized, 0% pigment

The impact strength of all the mouldings fell to $\simeq 1$ J when tested at -10° C after exposure to six months natural weathering.

5.2.2. Stabilized, 0% pigment

At -10° C the impact strength of plaques prepared from natural stabilized co-polymer containing up to 50 wt% of recycled material remained unaffected after exposure to six months natural weathering. This was not the case, however, for 100% recycled material where the impact strength dropped to 50% of its original value after weathering.

TABLE IIA Impact test results measured at 23° C for ultra-violet stabilized polypropylene containing 2 wt% of a range of pigments after ageing and natural weathering.

Type of feedstock	Impact strength (J)		
	2 weeks after moulding	After 6 months storage in the dark	After 6 months natural weathering
Virgin material, 0% pigment unstabilized	70.0	49.0	1.6
Virgin material, 0% pigment stabilized	40.6	50.3	36.4
Virgin material, 2 wt% carbon black stabilized	31.2	35.0	30.3
Virgin material, 2 wt% ultramine blue stabilized	10.2	15.6	13.2

5.2.3. Stabilized, 2 wt% carbon black

The presence of 2 wt% carbon black and ultra-violet stabilizer gave total protection to the plaques, all of which retained their impact strength at − 10° C after exposure.

5.2.4. Stabilized, 2 wt% ultramarine blue

The impact strength at − 10° C of mouldings containing 2 wt% ultramarine blue pigment and ultra-violet stabilizer all showed a small improvement after exposure to six months natural weathering.

6. Ageing in the absence of any damaging radiation

For completeness, some injection mouldings from the same batch as those used in the tests reported above were aged in the absence of damaging radiation, and the impact properties of the 3 mm thick injection mouldings were measured at 23° C and − 10° C. The results at 23° C and − 10° C are presented in Table II, together with the impact strengths of virgin plaques prepared under the same injection-moulding conditions and tested two weeks after moulding and six months after exposure to sunlight.

The results show that only those plaques prepared from natural co-polymer containing no ultra-violet stabilizer exhibit a marked deterioration in impact strength after six months ageing in the absence of ultra-violet light. In contrast all of the plaques prepared from the stabilized grade, whether pigmented or unpigmented, exhibited a small improvement in impact strength.

The effect of ageing was much more apparent when the plaques were tested at 23° C rather than − 10° C, indeed, at − 10° C very little change was observed in the impact performance with ageing time. The changes that were observed were similar to those occurring at 23° C test temperature, although to a much smaller degree.

Impact tests at 23° C on plaques prepared from natural unstabilized co-polymer during a six months period showed a gradual fall-off in impact strength for the first four months, after which the values remained constant at approximately 49 J, see Table III.

Virgin feed stock was used to prepare 3 mm thick plaque mouldings containing no additional ultra-violet stabilizer. These plaques were then weathered for one year, granulated and then mixed with virgin granules to give feedstock containing 25 wt% of weathered material. This simulated to a certain extent the situation which occurs in practice when artefacts such as beer crates are recycled after normal application in use. The melt-flow index of the weathered material was 40 g

TABLE IIB Impact test results measured at − 10° C for ultra-violet stabilized polypropylene containint 2 wt% of a range of pigments after ageing and natural weathering

Type of feedstock	Impact strength (J)		
	2 weeks after moulding	After 6 months storage in the dark	After 6 months natural weathering
Virgin material, 0% pigment unstabilized	26.4	22.8	1
Virgin material, 0% pigment stabilized	18.8	19.4	17.2
Virgin material, 2 wt% carbon black stabilized	5.9	7.8	6.1
Virgin material, 2 wt% ultramarine blue stabilized	2.6	4.4	6.1

TABLE III Variation in impact strength with time after moulding for natural unstabilized co-polymer

Time after moulding (weeks)	Impact strength (J)
2	70.0
6	54.8
23	49.0
29	49.0

per 10 min, as opposed to 4.5 g per 10 min for the virgin granules, and reflected the high degree of photodegradation that the plaques were subjected to during the test. Table IV shows the impact strengths of the plaques prepared from virgin material and feedstocks consisting of 25 wt% weathered material.

The results show a fall-off in impact strength of $\simeq 10$ J folowing the incorporation of 25 wt% recycled weathered material at a test temperature of 23° C. A similar but smaller fall-off in performance of $\simeq 6$ J was observed at a test temperature of − 10° C. These reductions are much more marked than those recorded for the mouldings which contained 25 wt% of unweathered recycled material, and was attributed to the deleterious effect of the low molecular-weight polymer on impact properties. The resultant mouldings would, however, be suitable for some application not exposed to ultra-violet radiation. An extension of these tests to take account of natural weathering showed that the incorporation of weathered recycled material, and hence chromophores, lead to a marked fall-off in impact performance. A detailed treatment of this situation, which includes the assessment of additional ultra-violet stabilizers and combinations of stabilizers has been carried out with encouraging results, which will be presented elsewhere [11].

7. Summary of results for ultra-violet stabilized compounds

The incorporation of an ultra-violet stabilizer initially embrittles the polypropylene co-polymer injection mouldings selected for investigation. The impact strength of 70 J for the unstabilized mouldings falls to approximately 40 J for the stabilized mouldings when tested at 23° C, two weeks after moulding. However, after storage for six months in the absence of any damaging radiation the impact strength of the unstabilized plaques fell to the same value as that measured for the stabilized plaques. This effect, together with the marked improvement in the weathering resistance of the ultra-violet stabilized grade, justifies the use of the stabilizer for the protection of artefacts intended for outdoor applications.

The efficiency of the stabilizer was not deleteriously affected by the presence of 2 wt% carbon black or 2 wt% ultramarine blue pigments. Indeed, some improvement was observed in the weathering impact resistance of the stabilized grades with the addition of carbon black. The incorporation of a phthalocyanine blue pigment resulted in very poor impact performance for all formulations of the polypropylene co-polymer selected for investigation.

The incorporation of recycled material at the 50 wt% level had no effect on the efficiency of the stabilizer. However, at the 100% level of recycled material this was not the case, and at a test temperature of − 10° C and after exposure to six months natural weathering, the impact strength fell by 6 J compared with 1.5 J for the corresponding virgin plaques. This difference was attributed to the introduction of free radicals during recycling or to the decomposition of the stabilizer. This result was not observed at the 23° C test temperature when the performance of weathered virgin and 100% recycled plaques were similar for the natural co-polymer.

A combination of 2 wt% carbon black and ultra-violet stabilized co-polymers afforded the best protection against ultra-violet degradation.

8. Overall conclusions

The main conclusions resulting from the work reported in Parts 1 to 4 of this work may be conveniently divided into three parts which are presented in Sections 8.1 to 8.3, respectively.

8.1. Effect of compounding on the physical properties of a polypropylene co-polymer

8.1.1. Recycling

A comprehensive study of the effect of the incorporation of recycled material on the reproducibility of injection mouldings was carried out [2]. This revealed that shot-weight and peak cavity pressure increased in steps with increasing percentage of recycled material. These steps were attributed to an increase in effective hold-on time during injection under set conditions and to an increase in the efficiency of the melt to transmit pressure, which resulted from the fall-off in molecular weight and accompanying changes in melt rheology of recycled plastic.

TABLE IV Impact test results for polypropylene co-polymer containing up to 25 wt% weathered reground material

Type of feedstock	Impact strength at 23° C (J)	Impact strength at – 10° C (J)
Virgin material (V)	70.0	26.4
25 wt% weathered reground material (BGW)	60.4	20.3
25 wt% reground material (BG)	65.8	24.6

The incorporation of recycled material up to 100% of material recycled once was shown to have no effect upon the impact properties of the injection mouldings. It was only when 100% of material which had been recycled twice was incorporated into feedstock that any deleterious effect upon the impact properties of the mouldings was observed. This change has been related to a marked change in skin thickness and accompanying changes in melt rheology which occur with the reducing molecular weight of recycled plastic. The adverse effect of incorporating recycled material was far less than that associated with the incorporation of one of the pigments recommended by the polymer manufacturer for use with the co-polymer, namely the phthalocyanine blue pigment.

The result of recycling the co-polymer containing 2 wt% ultramarine blue was to improve the impact properties of the injection-moulded plaques. This surprising result was related to distinct changes in the proportion of Type III [3] spherulites which were present in the mouldings.

Recycling was shown to greatly improve the dispersion of the pigment, especially in the case of carbon black. This effect is important when good dispersion is an essential requirement for long-term weathering resistance.

8.1.2. Pigments
The effect of incorporating phthalocyanine blue pigment was to markedly reduce the impact strength of the injection mouldings. This effect has been related to the nucleating characteristics of the pigment [12].

The carbon black pigment had the least effect, of the three pigments studied, upon the physical properties of the mouldings, although at 2 wt% pigment concentration some embrittlement was recorded at low impact test temperatures. Ultramarine blue showed a gradual embrittlement of the mouldings as the percentage of pigment was increased from 0.1 to 0.5 to 2 wt%. This was related to a corresponding increase in the proportion of Type III spherulites [3], which were present in a narrow band in the shear zone of the mouldings as the percentage of pigment was increased.

8.1.3. Stabilizer
In comparison with the unstabilized grade of polypropylene co-polymer, the incorporation of an ultra-violet stabilizer had an initial embrittling effect upon the plaques which were tested two weeks after moulding. However, after ageing for six months the impact strength of the plaques made from the unstabilized grade of co-polymer fell to that of the corresponding stabilized grade.

8.2. Effect of compounding on the natural weathering and ageing characteristics
8.2.1. Recycling
The weathering resistance of the natural grade of unstabilized polypropylene co-polymer was poor. After exposure for six months to sunlight, the impact resistance of the plaques was negligible at test temperatures of – 10° C and 23° C and it was not possible to ascertain whether recycled material accelerated photodegradation of the plaques.

For the stabilized grade, recycling up to the 50 wt% level of recycled material had very little effect upon the weathering characteristics of the plaques. At the 100% level, however, some acceleration of photodegradation was observed.

8.2.2. Pigments
In the case of the co-polymer having no additional ultra-violet stabilizer, the results of impact testing showed that carbon black at the 2 wt% level imparted almost total protection against photodegradation. The phthalocyanine blue pigment afforded 50% protection but the ultramarine blue gave very little protection.

In the stabilized grade no deterioration in the efficiency of the stabilizer by any of the pigments studied was identified. This was the case for impact tests carried out both before and after weathering.

8.2.3. Stabilizer
The use of an ultra-violet stabilizer resulted in a considerable improvement in the weathering resistance of the plaques made from the natural compound.

8.3. Effect of compounding on the microstructure of injection mouldings

8.3.1. Recycling

It has been shown [1, 2] that repeated injection moulding or pelletizing of the same plastic results in a marked increase in melt-flow index, which reflects a reduction in the molecular weight of the co-polymer. It was also shown that this change in properties of the melt results in a corresponding change in the microstructure of the solid mouldings, and was represented by different thicknesses of the outer skins of the moulded plaques and the dimensions of the shear-nucleated zones of Type III spherulites. The latter were reduced by increasing the proportion of recycled material in the feedstock.

8.3.2. Pigments

The effect of carbon black, ultramarine blue and phthalocyanine blue pigments on the microstructure of a polypropylene co-polymer were also investigated. The carbon black in master-batch form gave rise to poor dispersion which was markedly improved in recycling. The formation of rows of Type III spherulites nucleating from the streaks of pigments was also noted. A typical example is shown in Fig. 3. A similar effect was observed with phthalocyanine blue pigment. The streaks of pigment follow the lines of greater shear in the melt providing sites for row nucleation.

The nucleating abilities of phthalic acid and its derivatives have been well reported [12]. The pigment was no exception and even at low concentrations it acted as a powerful nucleating agent, and gave rise to mouldings which exhibited poor impact strength. The incorporation of ultramarine blue pigment at low loadings (0.1 wt%) had little effect upon the microstructure of the mouldings. Increasing the percentage pigment, however, gave rise to an increase in the proportion of Type III spherulites with an accompanying decrease in the impact strength of the mouldings.

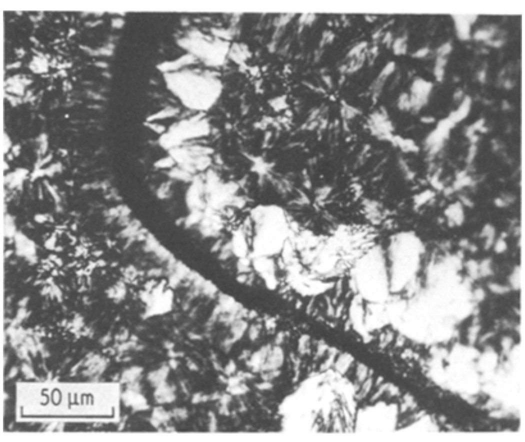

Figure 3 Light micrograph taken parallel to the injection-moulding directions showing Type III spherulites along a streak of carbon black pigment. A similar effect was observed in micrographs containing phthalocyanine blue pigment.

8.3.3. Stabilizer

The incorporation of an ultra-violet stabilizer had little effect upon the spherulite microstructure of the co-polymer. A slight reduction in the injection-moulding skin thickness being the only observable change.

9. Concluding remarks

The thermoplastic compounds used for the experiments referred to above were all based on a single injection-moulding grade of a general-purpose polypropylene co-polymer. The addition of pigments, ultra-violet stabilizer and recycled material were shown to cause marked changes in microstructure and impact properties, and indicate the inherent dangers of placing too much reliance for practical applications on results solely gained from natural grades, which mainly form the basis of work reported in the literature.

This is well demonstrated by recording the results of falling-dart impact tests which were carried out on a series of injection mouldings containing three different pigments. The compounding procedures were the same as those described previously [2]. In this case the molecular weight of the co-polymer was substantially greater than that of the grade used for the generation of the results presented above. The results are presented in Table V. In contrast to the results presented in [3] for the lower molecular-weight grade, the performance of the ultramarine blue pigmented plaques for the higher molecular-weight grade were acceptable. This improvement was partly due to the increase in strength associated with an increase in molecular weight and partly due to very low proportion of Type III spherulites present in all of the high molecular-weight mouldings, irrespective of the concentration and type of pigment. It is therefore clear that the microstructure of practical compounds in terms of spherulite morphology is compound formulation specific, in terms of molec-

TABLE V Impact test results at 23° C for a higher molecular-weight co-polymer containing 2 wt% of a range of pigments

Virgin polypropylene co-polymer plus additive	Impact strength (J)		
	After 2 months storage in the dark	After 6 months storage in the dark	After 6 months natural weathering
Virgin material, 0% pigment	73.0	42.2	27.6
Virgin material, 2 wt% ultramaring blue pigment	77.0	26.0	13.0
Virgin material, 2 wt% yellow pigment	70.0	37.4	19.5
Virgin material, 2 wt% orange pigment	70.0	38.5	26.0

ular weight as well as in terms of compound additives.

The following recommendations for moulding can be made in the case of the lower molecular-weight co-polymer, which was used as the basis of the work described in Parts 1 to 4 of this work.

(a) The use of recycled material up to 50 wt% has no significant effect on the ageing, weathering impact strengths.

(b) The use of phthalocyanine blue pigment should be avoided for use in lower molecular-weight co-polymer.

(c) The presence of a band of Type III spherulites in the shear zone within the mouldings should be avoided.

(d) The use of carbon black pigment at 2 wt% concentration provides excellent protection against ultra-violet degradation.

The recommendation relating to the use of recycled material requires qualification. Recycled material used in the context of Parts 1 to 4 of this report, with the exception of the small number of results presented in Table IV, has always related to clean unweathered plastics which are representative of factort-generated scrap, such as rejected parts, off-cuts, sprues or runners. A more detailed treatment of the effects of using used polypropylene artefacts as feedstock material for injection molding will be described elsewhere [11].

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