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# **Development of a Recycled Polymer Modified Binder for Use in Stone Mastic Asphalt**

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## **Abstract**

The number of commercial vehicles using Irish roads has increased considerably in recent years, leading to higher demands being placed on pavement materials and increased use of polymer modified bitumens. This has also coincided with significant changes in Governmental policy which has produced large increases in Irish recycling rates. Improved recycling levels are set to provide Ireland with a new challenge: to find potential uses for the large quantities of recycled polymer that are becoming available. Towards this end, the potential of developing a recycled polymer modified binder was investigated. The polymers most commonly recycled in Ireland were identified and sourced from industry. Fundamental bitumen tests were conducted to assess the effect of the recycled polymer and a mixing methodology developed. It was found that the

addition of 4% recycled HDPE into a pen grade binder produced the most promising results, and the mixing process was then optimised with respect to mixing parameters and binder additives. A developmental recycled binder was produced and compared in performance tests to binders currently used in road construction practice. Results obtained from wheel track and fatigue tests show that although the binder does not deliver equivalent performance levels to a proprietary polymer modified binder, it does out-perform traditional binders used in stone mastic asphalt. Recommendations are offered on the further development of the recycled polymer modified binder to achieve the standards currently required.

*Keywords:* Polymer modified binder, recycled plastic, road construction.

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## **1. Introduction**

Recent years have seen a significant increase in the number of heavy goods vehicles (HGVs) operating across Europe. In the 10 years to 2005, freight transport within the EU 15 member states rose from 1,124 to 1,478 billion tonne-kilometres, an increase of 31% (European Commission, 2007). This trend appears set to continue; Mantzos & Capros (2006) have predicted that in the current EU 27 member states, freight traffic will jump from 1,706 billion tonne-kilometres in 2005 to 2,824 billion tonne-kilometres in 2030,

representing a further increase of 66%. In Ireland alone, the National Roads Authority has forecast a similarly dramatic increase in the number of HGVs using Irish roads, with numbers expected to increase by 50% over the next 20 years (NRA, 2003). Such an increase in HGV numbers will inevitably place increasing demands on Irish roads, particularly with respect to issues such as deformation and fatigue cracking. A key component in providing roads with a long service life is the use of polymer modified bitumens (PMBs) in areas where the demands on the pavement material are considered to be of concern. PMBs are proprietary binders formed by introducing virgin polymers into a straight run bitumen, resulting in a binder with enhanced performance characteristics. The quantities of virgin polymer used can be significant (up to 5%) and results in a binder cost that is considerably more expensive than the straight run bitumen.

### *1.1. Current use of PMBs in Ireland*

PMBs are currently used for a wide range of applications. When originally introduced to asphalt practice their use was confined to areas where regular remedial works would lead to large scale traffic disruption, e.g. roundabouts, bends and bridge decks (Fordyce & O'Donnell, 1994). The use of PMBs has broadened considerably since that time. A feature of current asphalt practice is that PMBs are used where it is essential that roads are designed to resist deformation and fatigue cracking due to the presence of large volumes of fully loaded HGVs. Use is also common when it is necessary for the road surface to possess a longer design life than normal, or specialist applications whereby the use of

PMBs allow the specification of a much thinner road surface than would normally be required.

Current Irish specifications (National Roads Authority, 2005) also state that PMBs are required for all stone mastic asphalt (SMA). SMA is a gap-graded asphalt mixture that typically possesses a high binder content (5.5 – 7.5%) that can sometimes lead problems with binder drainage and stability. Traditionally this was solved through introducing cellulose fibres to the mix, but modern practice is to use proprietary PMBs to address this; it is this area of application at which the developed recycled binder will be targeted.

The majority of PMBs used in Ireland contain the polymers Ethylene Vinyl Acetate (EVA), Styrene Butadiene Styrene (SBS) or a blend of the two. Continuous commercial research and development over the past number of years has led to significant increases in the performance levels associated with PMBs.

### *1.2 International recycling of plastics*

The waste streams produced in Ireland are quantified annually by the Irish Environmental Protection Agency. The most recent figures available (EPA, 2005) for municipal waste collection show that while quantities of municipal waste collected continue to rise, so too is the quantity of this waste being recycled. This is illustrated below in Figure 1, where the most recent recycling rate was approaching 35%. A more detailed analysis of these figures show that plastics account for approximately 11% of this recycled municipal waste, but that the recycling rate for these plastics is only 15%. Similar trends can also be

seen internationally. For example, in Finland Sokka et al (2007) have found that the share of plastic in municipal waste is increasing and currently stands at 10%. Burnley et al (2007) have similarly reported that in Wales, plastic consistently comprises approximately 10% of the municipal solid waste stream.

Clearly there is a requirement that national plastic recycling rates be increased, and that new uses be found for these recovered materials. Huang et al (2007) have reported on the incorporation of a number of waste streams into asphalt, including glass, steel slag, tyres and plastics. In this particular study the use of plastic as an aggregate replacement was discussed.

In this light there is a clear need to find not only new areas of application for recycled plastics, but also means of adding value to these materials. This approach will enhance the commercial viability of the recycling process as a whole and promote a more sustainable approach towards waste management. This study will support this approach by investigating the use of recycled polymers as bitumen modifiers – the development of a potential high added value use for this waste stream.

### *1.3 Polymer modification of bitumens*

There exists a wide variety of polymers that have the potential to be mixed with bitumen. Of these polymers, styrene–butadiene–styrene (SBS) and ethylene vinyl acetate (EVA) are the most frequently used polymer in binder modification. The main advantage of SBS

is that it has a two-phase morphology consisting of glassy micro-domains made of polystyrene connected to rubber polybutadiene segments, exhibiting cross-linked elastomer behaviour. This allows the polystyrene domains to maintain a morphological structure and this partial solubility is a key factor in making SBS a good asphalt modifier (Chen et al., 2006). This thermoplastic elastomeric behaviour allows SBS to become usable for extensive applications in asphalt modification.

Fuentes-Audén et al (2007) have reported on the challenges associated with using recycled polymers as binder modifiers, as the recycling process will inevitably lead to a loss in mechanical properties of the polymer. They investigated the rheology of binders incorporating large amounts (up to 40%) of recycled plastic and found these blends to be thermodynamically incompatible. Ho et al (2006) investigated the use of recycled low density polyethylene with polyethylene wax and found that polymers with lower molecular weights tended to disperse more evenly within the asphalt binder but again focussed on rheological behaviour of the modified binder. Hınıslıoglu & Agar (2004) investigated the use of recycled high density polyethylene (HDPE) as a binder modifier for asphalt samples, using the Marshall Stability test as an indicator. They found that 4% recycled HDPE resulted in improved Marshall Quotient values, but that this dropped significantly with higher quantities of recycled HDPE.

## **2. Development of initial blends**

### *2.1. Selection of appropriate polymers*

Through contact with several Irish plastic recycling companies it was established that there are seven main polymers recycled in Ireland. These include low, medium and high density polyethylene (LDPE, MDPE, HDPE), widely used in packaging and plastic bottles; polypropylene (PP) often used in straws and sweet wrappings; polyvinyl chloride (PVC), used in plumbing pipes and fittings; polyethylene terephthalate (PET), widely used in water and soft-drink bottles and acrylonitrile butadiene styrene (ABS), used in electronic devices such as laptops and mobile phones. It was suspected that some of these materials would be unsuitable for use in manufacturing recycled polymer modified bitumen. Nonetheless samples were taken from each stream with a view to incorporating them into the bitumen. Although the above recycled polymers are available in sufficient quantities so as to be commercially feasible, not all are suitable for the proposed use. Factors influencing suitability for use with bitumen include melting point and density.

### *2.2. Initial evaluation process*

The initial evaluation process involved attempting to incorporate the recycled polymers into a straight run bitumen. The selected bitumen was a 200 pen grade Middle Eastern bitumen with a softening point of 39.8°C and a penetration value of 160 dmm.

Of the seven common recycled polymers available in Ireland, it was determined that samples could be sourced from two commercial plastic recycling firms. Representative samples were selected for testing, including:

- PVC mulch
- ABS chips
- Isotactic PP mulch
- Isotactic PP powder
- LDPE mulch
- MDPE mulch
- HDPE mulch
- PET chips

All samples were first mixed at low polymer concentrations, beginning with 2% of the bitumen by weight. If a blend was successfully made under these conditions the polymer was set aside for further study. However if a blend was not successful, a change in the mixing conditions was introduced and the blending process was repeated. Various mixing conditions were changed incrementally, until either a homogenous product was achieved or it became evident that it was not possible to produce a desirable binder efficiently. The main conditions altered to improve blending were increasing the mixing time, increasing the temperature, or decreasing the polymer addition rate.

It was clear from an early stage that PET, PVC, ABS and MDPE would not be suitable for blending of any type. This lack of compatibility was due to a combination of several factors. In the case of PET and PVC, their high melting points hindered the mixing, making it impractical to make any further attempts to incorporate them into the bitumen. The recycled ABS had a relatively low melting point but the hardness of the material led to it being processed into relatively large particles. This in turn resulted in the material

taking a considerable amount of time to melt sufficiently so as to allow blending. The long time delays associated with this made the polymer unsuitable for this type of application. Finally, it was found that the MDPE did not perform as anticipated; the polymer did not melt at the expected temperature and all attempts to incorporate this into the bitumen failed. It is speculated that the original application for the MDPE involved some sort of treatment, rendering it unsuitable for blending with bitumen.

The remaining four polymers were successfully blended into the bitumen. To determine the effect of the recycled polymer a series of blends with varying concentrations of polymer were developed. Binders incorporating LDPE, HDPE, PP powder and PP mulch at concentrations ranging from 2% to 5% by mass of bitumen were produced and tested. Blends containing 6% polymer by mass were found to have a less desirable consistency as they appeared to be fully saturated at this level. The surface of these blends would lose the glossy appearance associated with bitumen, eventually leading to a rough skin forming on the binder. The successfully blended binders were subjected to a series of standard bitumen tests.

### *2.3. Standard bitumen tests*

The successfully developed binders were subjected to a series of standard bitumen tests for viscosity, softening point and penetration value.

### *2.3.1. Viscosity*

The viscosity-temperature relationship of a binder is key to identifying the temperature range for successful mixing and compaction of bituminous mixtures. If the viscosity of a bitumen is too high, the binder may not completely coat the particles in the bituminous mixture; if the viscosity is too low, binder drainage is likely to occur during the storage and transportation of the mix. Identifying the most suitable temperature range for mixing allows decisions on the suitability of the binder to be made.

Viscosity is measured in the laboratory using a cone and plate viscometer to the procedure described in EN 13702 Part 1 (CEN, 2003). Using this instrument a small sample of the bitumen specimen is placed on a hot plate; a cone is then brought into contact with the plate and rotated. The amount of resistance provided by the bitumen to the rotation of the cone is determined and used to calculate the viscosity of the bitumen at that particular temperature. The viscosity of each bitumen is measured at 135°C, 150°C, 180°C and 195°C. This viscosity is usually reported in Poise, where 1 Poise = 0.1 Pa.s.

### *2.3.2. Penetration value*

Penetration is a measure of the consistency or hardness of a bitumen and is the most common control test for penetration grade bitumens. The penetration value is measured in the laboratory using a penetrometer, and is carried out to the procedure described in EN 1426. The test uses a standard stainless steel needle under a load of 100 g. The needle is allowed to penetrate into a sample of bitumen for 5 seconds at a fixed temperature of 25°C. The distance the needle penetrates is measured and reported in units of

decimillimetres (dmm). This test is carried out 3 times and the average is taken as the penetration value of the bitumen.

### *2.3.3. Softening point*

The softening point is a measure of the temperature at which a bitumen begins to show fluidity. It has a direct influence on the required mixing temperature when incorporating the binder into a bituminous mixture. The softening point of a modified bitumen can give an indication of the improvement in temperature susceptibility of the binder achieved through the addition of the polymer. The Irish authorities specify a minimum softening point of 60°C for PMBs with pen values of less than 100 to be used in road surfaces (NRA, 2007).

The softening point of a bitumen is measured in the laboratory using the procedure outlined in EN 1427. Using this procedure, bitumen samples are poured into two tapering brass rings. The bitumen is allowed to cool and immersed in water or glycerol. A 3.5 g steel ball is placed on each bitumen sample and the fluid heated at a rate of 5°C/ minute until the bitumen is soft enough to fall through the ring and drop 25 mm to a base plate. The temperature of the fluid at the time the ball touches the base plate is deemed to be the softening point of the bitumen.

## *2.4. Results of standard bitumen tests*

The successfully developed binders were subjected to a series of standard bitumen tests for viscosity, softening point and penetration value. The results of these tests are shown below in Table 1.

### *2.4.1. Effect on viscosity*

Table 1 shows the typical viscosity response observed due to the addition of recycled polymers in concentrations ranging from 2% to 5%. The test is carried out at a number of temperatures between 135°C and 195°C, and it can be seen that at high temperatures and low polymer contents, the viscosity levels are quite low. However as the temperature is reduced and more polymer is incorporated into the bitumen, the binder becomes more and more viscous. This trend is observed for all polymers, with similar values recorded at equivalent polymer contents.

Lancaster (2000) describes the best viscosity for mixing as being approximately 2 Pa.s. Virgin polymer modified binders are typically mixed at temperatures between 170°C and 195°C; using the data presented above, an appropriate balance between temperature and polymer content may be achieved.

### *2.4.2. Effect on penetration*

Table 1 also shows the effect of the recycled polymer on the penetration value of the binder, and it can be seen that in all cases that increasing quantities of polymer leads to a

reduction in the measured penetration value. It is notable that the polymer most effective in reducing penetration is the HDPE, with an addition of 2% reducing the recorded penetration from 160 dmm to 105 dmm. It is also interesting to note that the introduction of further quantities of HDPE has a reduced effect on the penetration value. At a polymer content of 4% it can be seen that the HDPE outperforms the other three blends, returning a penetration value of 100 dmm; this is at least 10 dmm better than other values at this polymer content. The difference in performance of the PP powder and the PP mulch is also of interest, with the mulch having a greater effect on the measured penetration value.

#### *2.4.3. Effect on softening point*

Using both the PP mulch and PP powder it can be seen that the softening point fluctuates across all polymer concentrations. This is particularly the case with the mulch where there is no visible correlation between softening point and polymer concentration. Much more consistency was observed with the LDPE and HDPE, with the highest recorded values associated with 5% HDPE – a softening point of 52°C. It is of note however that the Irish authorities require a minimum softening point of 60°C for polymer modified binders having Pen grades of 65-105 (NRA, 2007).

### **3. Optimisation of selected blends**

Alongside the properties described above, it is also necessary that the binder display satisfactory storage stability. This however was not achievable with either of the selected polypropylene blends, which began to separate a number of hours after blending. It was

found that after the binders were allowed to cool, they developed a skin on the surface up to 10 mm thick. When tested, this skin was found to consist almost entirely of polypropylene. This skin could not be reintroduced into the bitumen, leaving behind a binder with characteristics almost identical to the original base binder. As such, it was decided that the optimisation process should focus on the LDPE and HDPE blends which exhibited no such separation problems.

### *3.1. Polymer characteristics*

To assist understanding the behaviour of the recycled polymers some fundamental characterisation tests were required. As such, a melt-flow analysis was carried out on the LDPE and HDPE samples. The melt-flow rate test measures the rate of extrusion of thermoplastics through an orifice at a prescribed temperature and load, and is often used as a tool to detect degradation of the plastic as a result of the moulding process. The results of the tests are shown below in Table 2.

The average melt-flow rate of the HDPE of 6.12 g/10 minutes is typical of what may be expected for such a material. This is not seen for the LDPE which returned a melt-flow rate of 0.76 g/10 minutes. This value is very much in the lower range of that expected for a sample of LDPE, and considerably lower than that observed for the HDPE. This would suggest that the HDPE is less resistant to flow than the LDPE and may indicate a better ability to mix with the bitumen binder.

### *3.2. Polymer stability*

To avoid the need for expensive bitumen mixing equipment, it is desirable that the bitumen be satisfactorily storage stable. To test for stability, a 500 ml can was filled with the polymer modified bitumen and placed in an oven at 4 days at 160°C. It was then removed from the oven, the bitumen allowed to cool and the can divided into three. The middle third of the can was discarded; the top and bottom sections were subjected to standard tests for viscosity, penetration value and softening point. The results of these tests are shown in Table 3.

From these results it can be seen there is a low level of separation associated with a 3% polymer content, whereas at 5% moderate levels of disassociation were evident. It was felt that the levels of disassociation observed are too significant to rectify through alterations to the blending method or chemical additives. It was considered, however, that at a polymer concentration of 4% it would be possible to minimise disassociation while maintaining the improved performance levels associated with high polymer content.

### *3.3. Chemical additives*

Based on the tests outlined above, it was determined that LDPE and HDPE were the most suitable recycled polymers. Furthermore, to achieve an appropriate balance between stability and performance a polymer content of 4% was considered optimal. However to meet performance requirements set down by the national authorities (NRA, 2007) it is

also necessary to achieve a softening point of 60°C and a 65/105 penetration grade. To achieve these goals it was deemed necessary to introduce some chemical additives into the blends. Two commercially available additives were tested, namely diethylenetriamine (DETA) and polyphosphoric acid (PPA).

### *3.3.1. Effect of DETA addition*

DETA was added to binders containing 0% recycled polymer, 4% LDPE and 4% HDPE. DETA was introduced in concentrations up to 2% and was found to have both positive and negative influences on binder performance. The DETA was found to have a positive effect on the penetration value of the binder incorporating LDPE, but a negative effect on that containing HDPE. No significant effect was observed on the softening point of bitumens incorporating either recycled polymer. Of particular note is the effect of the DETA on the storage stability, as illustrated in Table 4.

### *3.3.2. Effect of PPA addition*

The introduction of PPA at concentrations up to 0.8% had a pronounced effect on the properties of the binder blend. Its effect on viscosity was to make all binders considerably more viscous at lower temperatures. The effect on penetration was notable, leading to significant reductions in recorded penetration value, as shown in Figure 2.

Similar behaviour was observed when assessing the effect of the PPA on softening point. In all cases the addition of increasing amounts of PPA up to a concentration of 0.8% has led to an increase in softening point, as illustrated in Figure 3. For the case of LDPE the

effect has been to increase the softening point from 44°C to 52°C. The case for HDPE is more noteworthy, where the softening point has increased from 50.6°C to 61.7°C. This is especially significant as this blend now satisfies the national requirement that all polymer modified binders should have a softening point in excess of 60°C.

### *3.3.3. Storage stability of PPA blends*

As before, a similar series of tests were carried out to assess the storage stability of the blend incorporating 4% recycled polymer and 0.8% PPA. The results for the stability tests are shown below in Table 5 and suggest that minimal disassociation occurs within the binder, with similar values obtained for softening point, penetration value and viscosity in samples taken from the top and bottom halves of the can.

### *3.4. Binder optimisation*

From analysis of the test results above, it was determined that the optimal blend was one incorporating 4% HDPE and 0.8% PPA. This blend possessed a softening point above 60°C, a penetration value of 71 dmm and satisfactory viscosity results. This blend was selected therefore as the candidate binder to be subjected to an optimisation programme.

Potential variables in the optimisation step include the grade of the base binder, the polymer blend time, the PPA blend time and the time at which the PPA is introduced. In an effort to further reduce the pen grade of the binder, the base binder of choice was changed to a 150 pen binder. The optimum blending procedure was found to be:

- Heat the base binder to a temperature of 160°C
- Add 0.8% PPA by mass and mix for a period of 60 minutes
- Add 4% HDPE and mix for a further 90 minutes.

Using this procedure it was possible to produce a binder with a softening point of 63°C, a penetration value of 43 dmm and a viscosity requiring a mixing temperature of 180°C. A number of batches of this binder were manufactured and subjected to a series of performance tests for use in road construction.

#### **4. Performance testing**

To gain a real understanding of the performance of the recycled polymer binder, a series of bituminous mixtures were manufactured for assessment under selected performance tests. The tests chosen were on the basis of demonstrating the potential improvement in performance that may be achieved using PMBs. Of particular interest was the resistance to permanent deformation and fatigue resistance (Owende et al, 2001; Hartman & Gilchrist, 2004) and as such the wheel track test and the indirect tensile fatigue test (ITFT) were chosen. The selected bituminous mixture was a 14 mm stone mastic asphalt (SMA). SMA is a dense wearing course material, developed in Germany and Scandinavian countries to overcome the problem of rutting brought about by the action of studded tyres on road surfaces. The binder content of SMA usually varies between 5.5 and 7.5 per cent depending on the coarse aggregate size. This binder content can create

difficulties with binder drainage during manufacture and laying, leading to the traditional addition of fibres to SMA mixes.

#### *4.1 Mix design*

A series of SMA mixes were designed to meet the current Irish specifications (NRA, 2005) for a 14 mm SMA. Previous research by Butler (2005) found that the use of industrially sourced asphalt sand led to issues with binder drainage and consistency. As such, sand was omitted from the mix, with rock fines being the only fine aggregate included. The aggregate skeleton consisted therefore of 62% 14 mm aggregate, 35% crushed rock fines (CRF) and 3% filler. As the focus of the research was on binder performance, three distinct binders were selected for use, namely:

- a traditional pen and fibres binder (PF)
- a proprietary PMB used in practice (PMB)
- the developed recycled HDPE modified binder (RP)

The optimal binder content had to be high enough so as to provide stability and durability, yet low enough so as to avoid any binder drainage. In consultation with industry partners, a binder content of 5.7% was selected. For the PF mix a 40/60 pen bitumen was used in association with 0.4% fibres by mass of aggregate. The mix design was then slightly altered for the PMB and RP binders to ensure that the grading curve

stayed within the required envelope. Specimens were then manufactured for wheel track and ITFT testing.

## *4.2 Test methods*

### *4.2.1 Wheel track test*

The Institute of Asphalt Technology (2002) require that wheel track tests are carried out on all SMA mixes. It is a simulative performance test used to describe how susceptible a particular mix is to deformation under the action of a moving wheel load. Specimens are manufactured with dimensions 305 x 305 x 50 mm using a roller compactor and are typically allowed to rest at 20°C for about 24 hours. The test procedure involves subjecting the roller compacted slab to a rolling wheel which traverses the specimen at constant speed producing 21 load cycles per minute at a standard temperature. In this particular case all of the testing was carried out at 60°C in order to simulate a heavy loading and to promote rutting. The wheel load used was a standard load of 520N. The rutting due to the wheel load is measured throughout the 45 minute test. The National Roads Authority specify (NRA, 2005) that for heavily trafficked areas the SMA mix must achieve a maximum rut rate of 5mm/hr and a rut result not in excess of 7mm at a temperature of 60°C.

### *4.2.2 Indirect tensile fatigue test*

The ITFT test was carried out according to the procedure described by the British Standard, BS DD AFB. The Coopers Research Technology NU-10 testing apparatus was

used to determine the resistance of the mixtures to failure under repeated loading. A series of specimens were manufactured from each mix, each specimen being 100 mm in diameter and 70 mm in height. These were prepared using a gyratory compactor in accordance with the method described in EN 12697 Part 31. The specimens were subjected to a repeated constant load with  $124\text{ms} \pm 4\text{ms}$  loading time and pulse repetition time of  $1.5 \pm 0.1$  sec. at a temperature of  $20^{\circ}\text{C}$ . Prior to the ITFT test, the indirect tensile stiffness modulus parameter was obtained for specimens, at the fatigue test stress level. Readings were taken for two diameters at  $90^{\circ}$  to each other and the average value was calculated.

The pulse repetition in the ITFT test simulates traffic passing over the pavement, which results in the repeated applications of tensile stress and strain within the test sample. The test is a simple, practical, inexpensive and easily repeatable method for evaluating the life to crack initiation of bituminous pavement mixtures. It has been shown to have the ability to distinguish between mixtures containing different binders based upon stiffness and cycles to failure and so can be used to rank similar mixes containing different binders (Read et al., 1997). The fatigue life was defined as the total number of load pulses that caused the total structural failure of the test specimen. The strain was calculated from the direct computation of maximum tensile stress at the centre of the specimen using the indirect tensile stiffness at the maximum tensile stress.

### 4.3 Test results

#### 4.3.1 Wheel track test

The results of the wheel track tests are shown below in Figure 4, with key parameters listed in Table 6. When the parameters of rut depth and rut rate are analysed, it can be seen that the recycled polymer binder performs well, comfortably meeting the specified requirements with respect to deformation. There is, however, a notable difference in performance between the recycled polymer binder and the proprietary polymer modified binder. Nonetheless, the performance of the recycled polymer binder may be considered as encouraging as it is well within the requirements for heavily stressed sites requiring high rut resistance.

#### 4.3.2 Indirect tensile fatigue test

The results of the ITFT test are shown below in the log-log plot of Figure 5, where the applied strain level is plotted against the number of load cycles to failure. From the data shown in Figure 5, an empirical growth relationship was used to perform a regression analysis:

$$Nf = k_1(\epsilon_T)^{k_2}$$

where  $Nf$  is the number of strain applications to failure;  $\epsilon_T$  is the initial tensile strain (expressed in micro-strain); and  $k_1, k_2$  are the fatigue growth rate coefficients listed below in Table 7. From the regression analysis, it can be seen that the proprietary PMB

performs better than the R P and PF binders, requiring  $2.1 \times 10^7$  cycles to reach 100 micro-strain. It is speculated that the reason for this is due to a slight lack of elasticity on the part of the RP binder. It is notable however that the RP binder outperforms the traditional PF binder, which had previously been used extensively in national practice. Once again, this suggests that the development RP binder has the potential to be used in future pavement construction.

## **5. Conclusions and Recommendations**

Seven widely available thermoplastic polymers were examined for their suitability in PMBs, namely LDPE, MDPE, HDPE, PVC PP, PET and ABS. Initial screening was conducted to assess compatibility with the base binder, resulting in the elimination of MDPE, PVC, PET and ABS. The PP was successfully blended but was subsequently found to offer excessive variation in basic binder characterisation tests. LDPE and HDPE were considered to offer the most promise and a blend based on 4% HDPE was optimised. This was subjected to standard performance tests such as wheel-tracking and fatigue, and although the recycled polymer modified binder did not perform to the same high levels as the proprietary commercially available binder, it did however demonstrate enhanced performance when compared with unmodified binders and binders incorporating cellulose fibres. These results suggest that the recycled polymer modified binder has great promise.

For future work, it is speculated that to match the proprietary PMB, further elasticity is required when the asphalt is subjected to loading during testing. It is possible that this required elasticity could be provided through the incorporation of a small percentage of virgin polymers, which could be used in conjunction with the recycled polymer in order to boost the binders' elasticity.

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<b>Binder Description</b>	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 135°C (Pa.S)</b>	<b>Viscosity at 150°C (Pa.S)</b>	<b>Viscosity at 180°C (Pa.S)</b>	<b>Viscosity at 195°C (Pa.S)</b>
Base Binder	39.8	160	3.1	1.7	0.7	0.5
2% PP mulch	42.8	124	3.7	2.0	0.8	0.5
3% PP mulch	42.0	122	4.3	2.4	0.9	0.6
4% PP mulch	48.9	113	5.2	2.7	1.0	0.6
5% PP mulch	48.4	82	6.4	4.0	1.6	1.0
2% PP powder	41.8	148	3.6	1.9	0.8	0.5
3% PP powder	43.9	131	4.6	2.3	0.9	0.6
4% PP powder	43.7	110	5.1	2.6	1.0	0.6
5% PP powder	46.5	99	5.4	3.0	1.1	0.7
2% LDPE	43.0	141	4.8	2.6	1.0	0.8
3% LDPE	44.1	132	4.8	2.7	1.1	0.8
4% LDPE	44.1	117	5.1	2.9	1.2	0.8
5% LDPE	48.1	103	6.4	3.6	1.4	1.0
2% HDPE	46.6	104	4.1	2.3	0.9	0.6
3% HDPE	48.8	103	4.5	2.6	1.0	0.7
4% HDPE	50.7	100	5.4	3.2	1.3	1.0
5% HDPE	51.2	94	6.3	3.8	1.4	1.0

Table 1. Results from standard binder tests

<b>Parameter</b>	<b>Polymer Sample</b>	
	<b>LDPE</b>	<b>HDPE</b>
Melting Point (°C)	110	131
Melt-flow Rate (g/10 minutes)	0.76	6.12
Typical Melt-flow Range (g/10 minutes)	0.14 - 58	0.02 - 9.0

Table 2. Results of melt-flow test

<b>Binder Description</b>	<b>Top</b>			<b>Bottom</b>		
	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>
3% LDPE	47.2	84	2.3	47.2	88	2.4
5% LDPE	52.2	87	4.1	43.0	114	2.4
3% HDPE	50.5	98	2.8	49.9	106	2.5
5% HDPE	58.0	83	4.2	43.8	107	3.1

Table 3. Results from storage stability tests

<b>Binder Description</b>	<b>Top</b>			<b>Bottom</b>		
	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>
1% DETA, 4% LDPE	81.5	116	5.4	47.5	72	2.4
2% DETA, 4% LDPE	58.4	91	5.8	53.6	57	3.1
2% DETA, 4% HDPE	61.4	144	5.7	46.0	104	2.9

Table 4. Storage stability – effect of DETA addition

<b>Binder Description</b>	<b>Top</b>			<b>Bottom</b>		
	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>	<b>Softening Point (°C)</b>	<b>Penetration Value (dmm)</b>	<b>Viscosity at 150°C (Pa.S)</b>
0.8% PPA, 4% LDPE	52.0	81	4.3	50.2	89	4.1
0.8% PPA, 4% HDPE	62.1	72	4.1	59.8	81	3.8

Table 5. Storage stability – effect of PPA addition

Parameter	Binder Description		
	PM Binder	RP Binder	Upper Limit
Mean Rut Depth (mm)	1.3	3.4	7
Mean Rut Rate (mm/hr)	0.5	2.2	5

Table 6. Effect of binder type on rutting resistance of SMA

Binder	Fatigue Coefficient		R <sup>2</sup>	Cycles at 100 micro-strain
	k <sub>1</sub>	k <sub>2</sub>		
Pen & Fibre	2.E+11	-3.26	0.983	5.9E+04
PM Binder	3.E+16	-4.58	0.997	2.1E+07
RP Binder	6.E+11	-3.37	0.960	1.1E+05

Table 7. Effect of binder type on ITFT performance

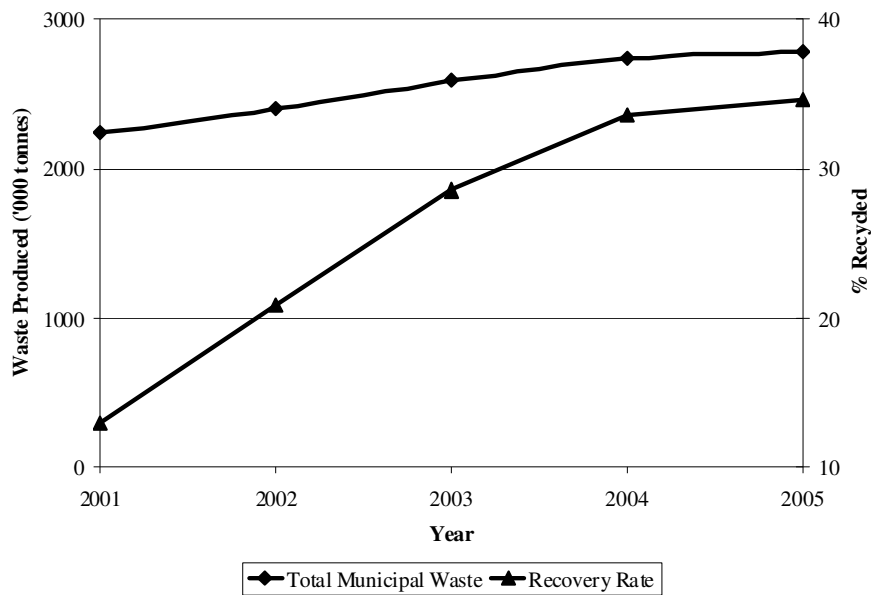


Figure 1. Municipal waste recycling rates in Ireland

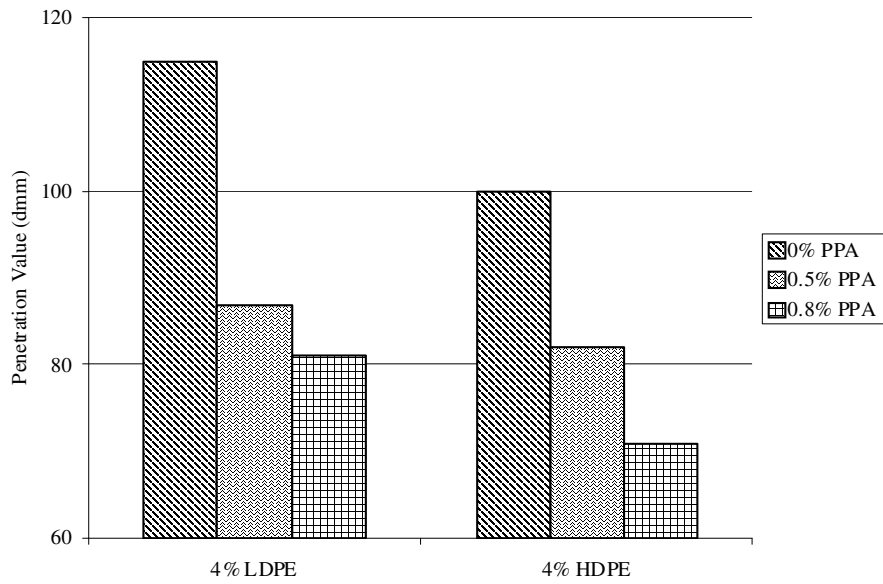


Figure 2. Effect of PPA addition on measured penetration values

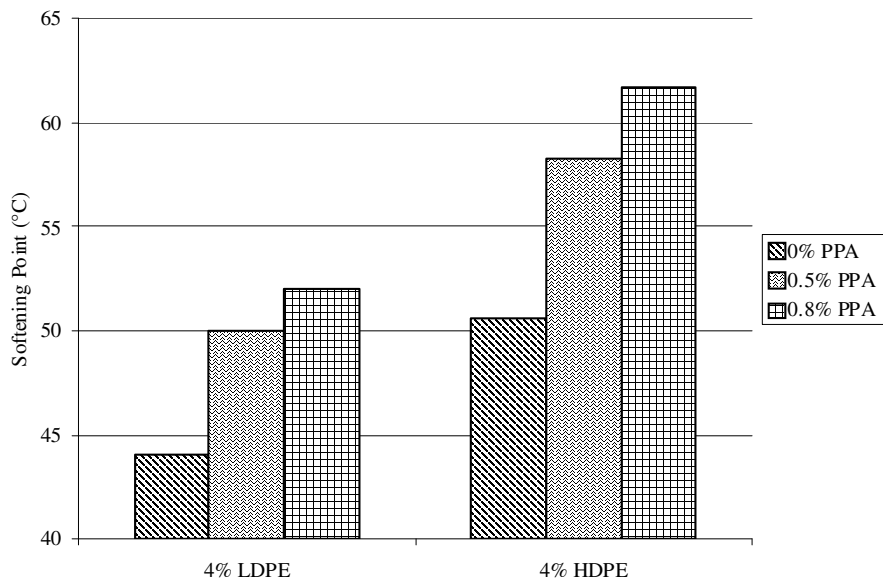


Figure 3 Effect of PPA addition on measured softening point

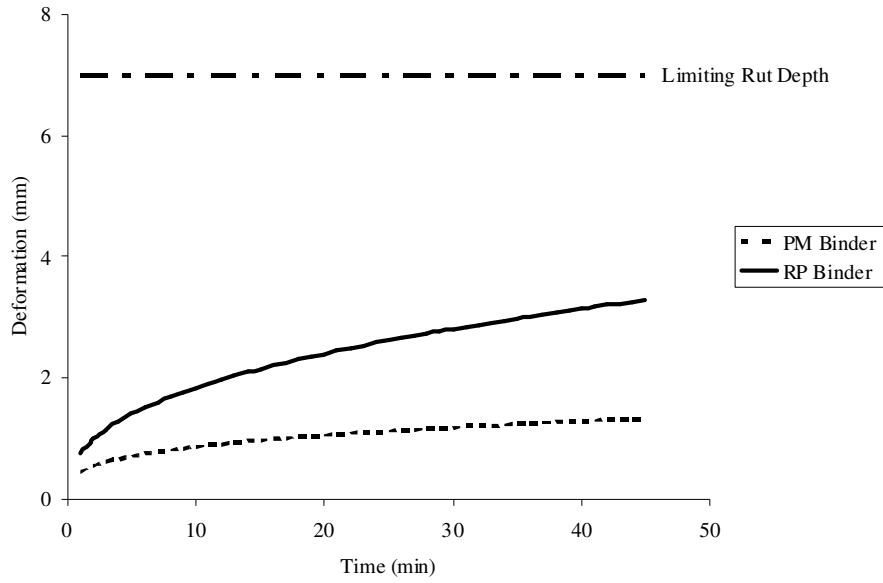


Figure 4. Results of wheel track test

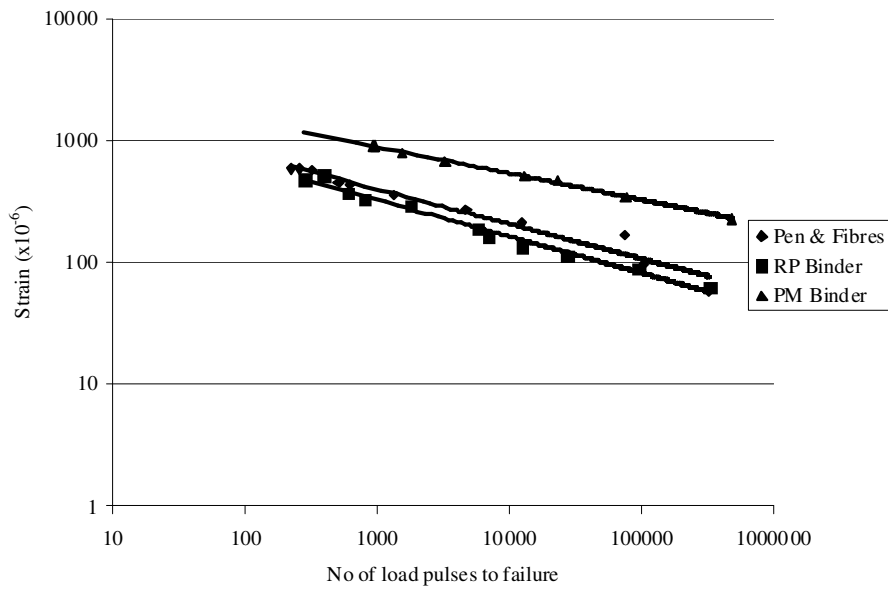


Figure 5 Results of ITFT tests