Plast endurunnið í vegi: mat á hagkvæmni þess að nota úrgangsplast til vegagerð á Íslandi

Plastic recycled in roads: feasibility study on the use of plastic waste for road paving in Iceland

ReSource International

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Date of publication: 9th of April 2017
Amended: 24th of April 2017

Cover image: Malbikunarstöðin Höfði's gravel stockpiles in winter. (*ReSource)*

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Acknowledgements

This project received grant funding from Vegagerðin, the Icelandic Roads Authority. ReSource also thanks Malbikunarstöðin Höfði and Hlaðbær Colas for their help.

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Contents

1 Introduction

This report aims to study the feasibility of using mixed waste plastic as an additive in paving materials in Iceland. As there is no existent comprehensive review of the literature on the use of waste plastic, it mostly focuses compiling the evidence on the technical case, and then gives some attention to the potential economic, social and environmental costs and benefits of such usage.

2 Background

Roads have been paved with coal and oil-derived bitumen fractions since the late 1830s, and asphalt surfacing has spread to become ubiquitous on major and minor roads of most countries. Mass manufacturing of plastics began in the 1940s and by the 1970s there were a number of virgin plastic additives used to improve various qualities of the pure bitumen binders used in asphalt concrete. These notably include styrene-butadiene-styrene (SBS) and, from the 1990s, various polypropylene and polyester fibres [1], [2]; for a review, see [3].

In the early 2000s, rising environmental awareness and demand for cheap additives to bitumen in rapidly-developing countries (most notably India, Iran and China) led to tests on the properties of bitumen and aggregate modified with recycled waste plastic. Initially this work focused on high quality graded material of single polymers [4]–[9], but in the last ten years much has been published on the use of low-quality mixed waste polymers such as street litter as well as further study on graded recycled HDPE, LDPE, PET, PS and other plastics [10]–[27]. Thus, in twenty years we have seen a shift in focus from using a virgin resource, to using high-quality recycled material with other uses, to using currently non-recyclable material that otherwise poses a waste management problem.

India has taken actual practice the furthest, with officially-adopted standards for the use of waste plastic additives in bitumen. In 2015 the government mandated that all roads built within 50km of a city of 500.000 or more should use waste plastic additives. Over 30.000km of such road has been laid since 2003, and a further 5000km is currently laid per year. Crucial to its uptake has been engineers' and planners' experience of its technical capabilities, such as tendency for reduced potholing and rutting and increased lifespan.

3 Technical Feasibility

3.1 General improvements

The logic of adding plastic to asphalt is relatively simple. Bitumen, while abundantly available, is not the ideal glue for holding aggregate together. It becomes brittle and cracks at low temperatures which makes road surfaces weak and allows water penetration, and it may become too soft at high temperatures, at which point it deforms relatively inelastically. In some mixes such as stone-matrix asphalt, it may also drain down from the surface of the road, causing swift destruction of the wearing course. Polymer additives aim to solve this in several ways.

First, they may increase the stiffness of the bitumen, making the roads less likely to deform. They may also increase the viscosity and thus the elastic rebound of the road when it has been deformed, e.g. by a heavy truck [1], [28], [29]. Second, they improve temperature susceptibility at high temperatures, allowing softer bitumen to be used and thus improving resistance to fracturing at low temperatures and preventing drain-down in stone matrix asphalt. Third, if used to coat aggregate, plastics may increase the roughness of surfaces and provide a superior bond between binder and aggregate [1], forming a complex multiphase mixture within the binder and improving its adhesion and cohesion strength [30]. Bitumen modified with plastic displays some non-Newtonian fluid properties affecting the zero-shear viscosity, which seems to be one of the main sources of the binder‘s increased stiffness at medium service temperatures [29], [31].

On top of the benefits to road strength, the reuse of waste plastic is generally much cheaper than recycling, incineration or landfilling, and solves the issue of disposing of the most troublesome mixed fractions of plastic waste, such as street litter or even medical waste [21]. Remarkably, it has taken many decades for us to discover that recycled polymers generally give similar improvements compared to virgin polymers [32]–[34]. The reasons for this delay are unknown, but it is noteworthy that most innovation in the field has come from developing countries with large road networks, where cost-effectiveness is a high priority.

3.2 Methods of use

There are three principal methods of adding plastic to roads. The first two concern different methods of adding shredded (c.2mm) plastic to the bitumen binder in hot-mix asphalt. This can either be added to bitumen at c. 160°C and mixed for 30 minutes or more to make a homogeneous glue (“plastic-modified bitumen”), or used to first coat hot aggregate at 160°C for 30 seconds[35] before adding bitumen in order to produce a heterogeneous plastic-bitumen mixture (“plastic-coated aggregate”). As shall be described in more depth, the latter process appears to give superior results, and also is much less energy-intensive. In both cases, it is usual to replace 10% or less of the binder with plastic, itself 10% or less of hot-mix asphalt, giving a total plastic content of less than 1%.

The third method, which is thus far comparatively poorly researched and thus not covered at great length here, is to replace graded aggregate with graded plastic particles of similar size, usually 2-3mm. The chief advantage of this is the possibility of using much greater quantities of plastic, up to 12% of the mass of the road vs. 0,5-1%, whilst also improving quality parameters [36].

In all cases, the norm of use at scale appears to be to modify hot-mix asphalt in an asphalt plant which is then transported to location, although there has been extensive use of virgin polymer in sprayed top-dressing bitumen [37, p. 6].

3.3 Technical qualities of plastic-enhanced bitumen binder

Brûlé succinctly describes the properties of an ideal binder as follows:

An ideal binder should have enhanced cohesion and very low temperature susceptibility throughout the range of temperatures to which it will be subject in service, but low viscosity at the usual temperatures at which it is placed. Its susceptibility to loading time should be low, whereas its permanent deformation resistance, breaking strength, and fatigue characteristics should be high. At the same time, it should have at least the same adhesion qualities (active and passive) as traditional binders. Lastly, its aging characteristics should be good, both for laying and in service.[38]

3.3.1 Basic Stiffness and Flow

This describes how resistant asphalt is to deformation under load, and is broadly a component of two factors: the stability before deformation and the permanent flow under load. The first can be described using a test for Marshall stability, and the second by testing Marshall flow, and a composite index of stiffness can be made by dividing stability by flow, making the Marshall quotient (MQ).

In general, plastic additives increase the Marshall stability and may increase or decrease flow, thereby giving improvements to MQ, such as 55% (HDPE at 5%[39]); 50% (HDPE at 4%[5]); 60% (PET at 6%[1]); and other significant improvements with PE foam, PP and LDPE at 5 and 10%[18] and even similar improvements to styrene-butadiene-styrene virgin additive when using 8% mixed shredded waste plastic coating (albeit in stone-matrix asphalt). Interestingly, it seems that generally flow values increase compared to controls when adding plastic to bitumen directly (Figure 2), but when using it to coat aggregate, flow is affected much less, presumably because of the heterogeneity of the mixture. Thus, this method seems to be highly preferable, particularly for larger volumes of additive.

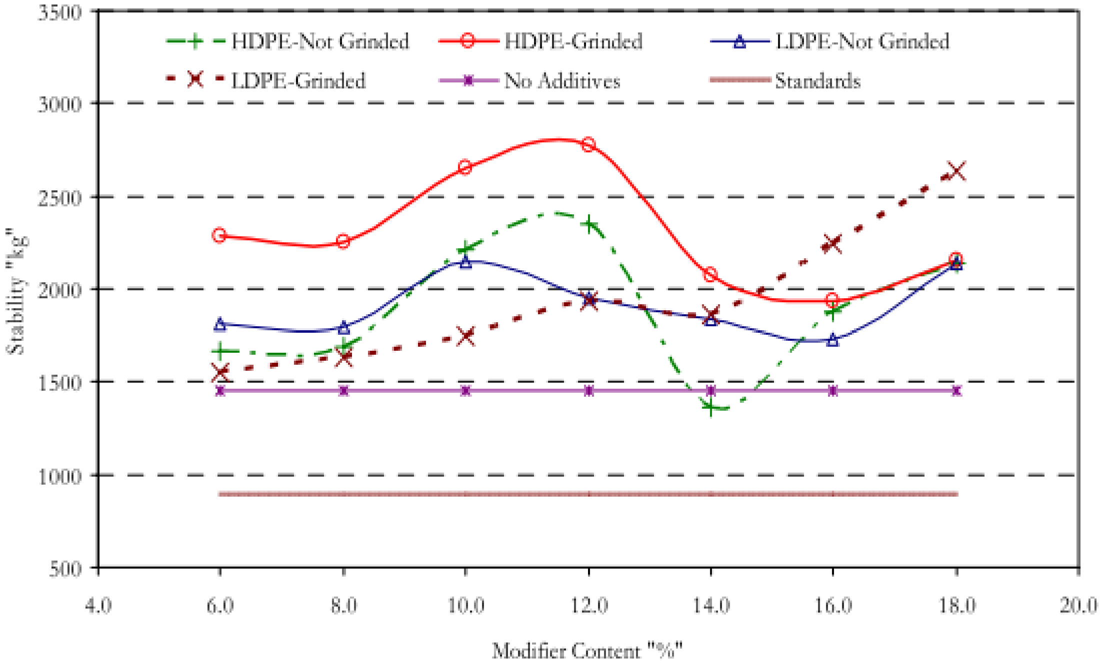

Figure 1 - Almost all additives at up to 18% give improved Marshall stability over control. Standards are Jordanian. [28]

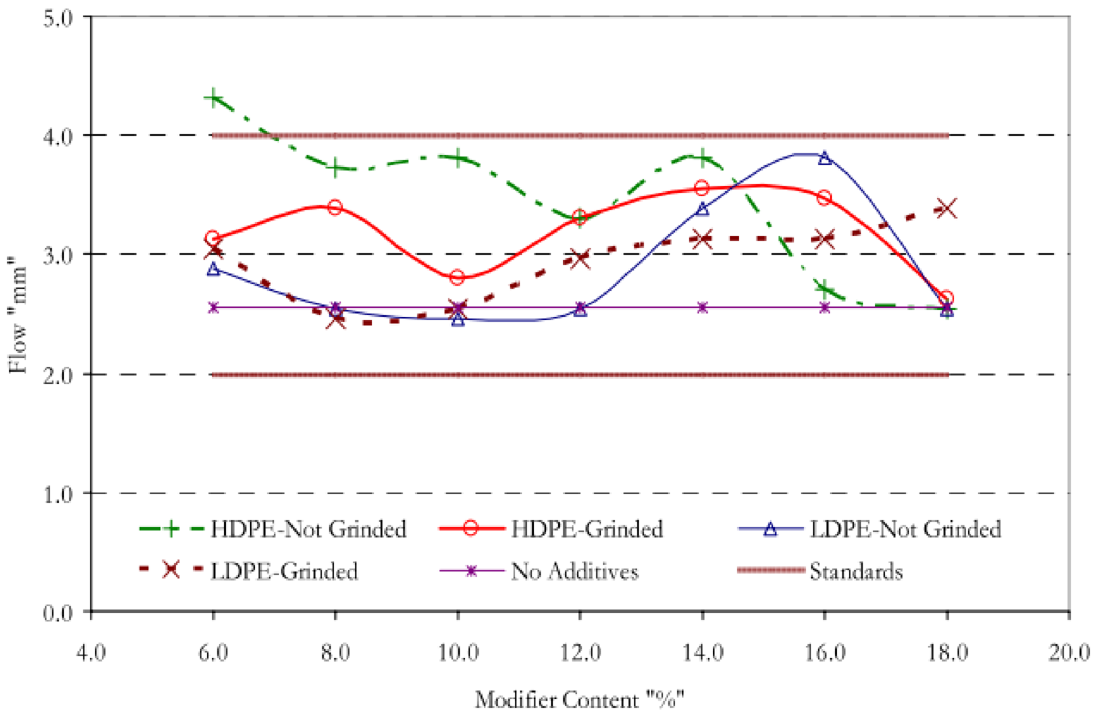

Figure 2 – Flow is somewhat increased in this experiment under all conditions, but not to an unsatisfactory degree. Note that plastic is added directly to bitumen, not as aggregate coating. Standards are Jordanian. [28]

3.3.2 Viscoelasticity

Bitumen is a glassy solid at low temperatures (and thus able to crack or creep[1]) but shows significant viscoelastic properties at medium and high service temperatures and transitions to a more-or-less Newtonian fluid at higher temperatures, thus allowing it to flow freely and thus be poured, sprayed or pumped (Figure 3). This all means it deforms in a rather complicated way compared to other compounds. For one, it may recover from deformation through elastic rebound; some elastomeric polymers (e.g. styrene-butadiene-styrene, or SBS) are specifically designed to enhance this property. It also has viscous properties; under constant stress, strain in bitumen will increase, and also its effective stiffness depends on the rate of application of a load. Continuous application of even a small load will result in bitumen permanently deforming, at least below the temperature where it freely flows.

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[1] Solids will creep (i.e. deform slowly when held under constant force), but do not flow of their own accord. Viscoelastic materials may do both.

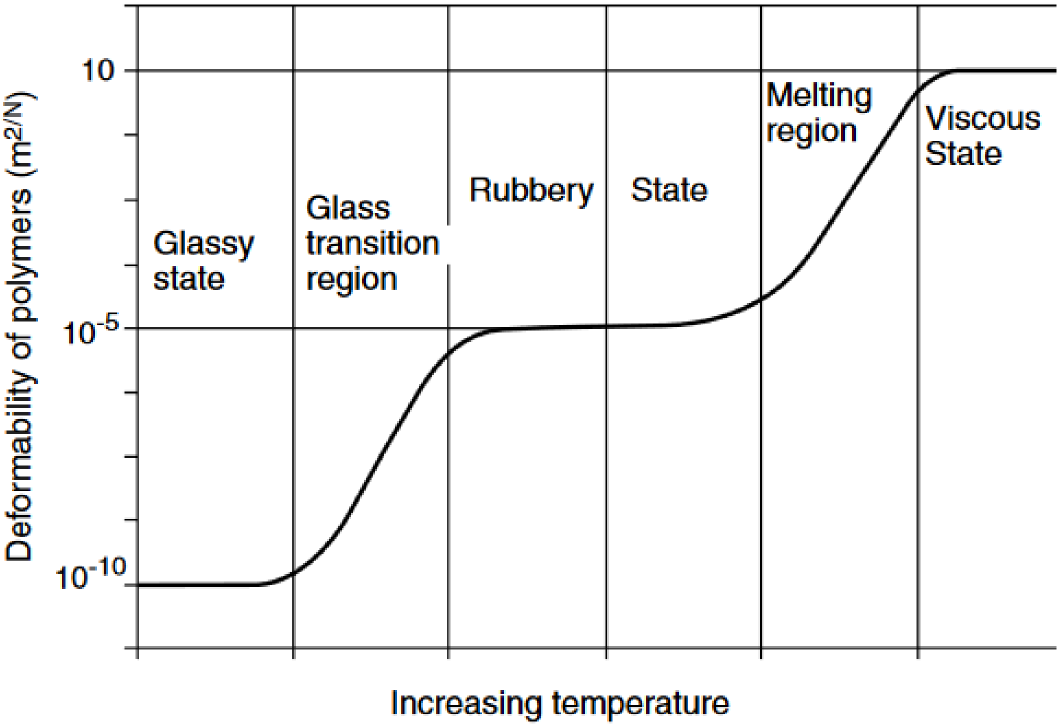

Figure 3 – Idealised graph of transitions in thermoplastic polymers and other viscoelastic compounds [40]

Adding plastic to the binder may improve elasticity. This is particularly so for or affect the viscosity directly but if added as a coating to the aggregate it may also produce shear thickening, where apparent viscosity shows a non-Newtonian increase in response to greater stress, in much the same well-known way as cornstarch mixtures [31].

3.4 Wheel track and direct methods

For a number of technical reasons, the Marshall test does not correspond entirely with real-life conditions. In an attempt to measure more accurately the kind of wear that roads receive, wheel-track tests are sometimes used, although they require more expensive machinery.

Various studies have tested different kinds and quantities of waste plastic in wheel-test analyses, and the results are universally positive. For example, in one Korean study, 12% waste PE film (i.e. plastic bags) added to bitumen gave over 80% reduction in rutting, comparable or better than commercial LDPE and SBS additives [41]. In an Irish study, HDPE-modified binder at 4% gave results that comfortably exceeded the standards for high-traffic areas, although it was not as effective as SBS[42]. In an Argentinian study, waste PE flakes and pellets and PP all gave a 50-90% reduction in rutting compared to control at 4-6% loading[22]. Interestingly, one of the few studies on plastic as an aggregate replacement (5 to 25% PET by weight of the mixture) showed good results, with up to 25% reduction at 20% addition. This would allow for the use of two orders of magnitude more plastic waste than the more usual plastic-modified bitumen or plastic-coated aggregate methods.

Wheel-tracking on plastic-coated aggregate (1,6% nitrile rubber and 6,4% waste PE w/w bitumen) showed around a 50% improvement in rutting depth in one study [17] and others provide empirical observations of reduced rutting on roads laid using this method in many different places in India [10], [43]. When using this method with mixed plastic waste in stone-matrix asphalt (primarily as a stabiliser to prevent asphalt drain-down), the benefits are almost as good as expensive custom polymer binders (Figure 4).

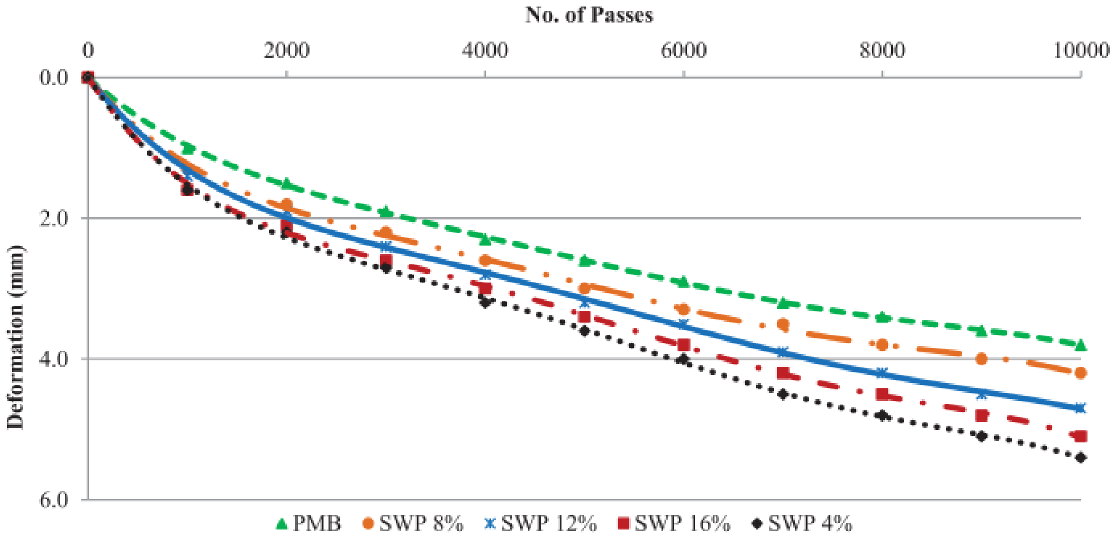

Figure 4 - Results of wheel-track test on standard polymer-modified bitumen (PMB) and shredded waste plastic aggregate coating (SWP) additives in stone-matrix asphalt [34].

Wheel track experiments are not the only way to predict the susceptibility of hot mix asphalt to rutting. For example, a Saudi Arabian team used AASHTO ME-PDG software and direct measurements of the viscoelastic properties of asphalt to produce an estimate of the rutting of the mixture for standardised traffic, temperature and other variables (Figure 5). This result clearly has implications for the life of the road, although rutting is not always cause of replacement.

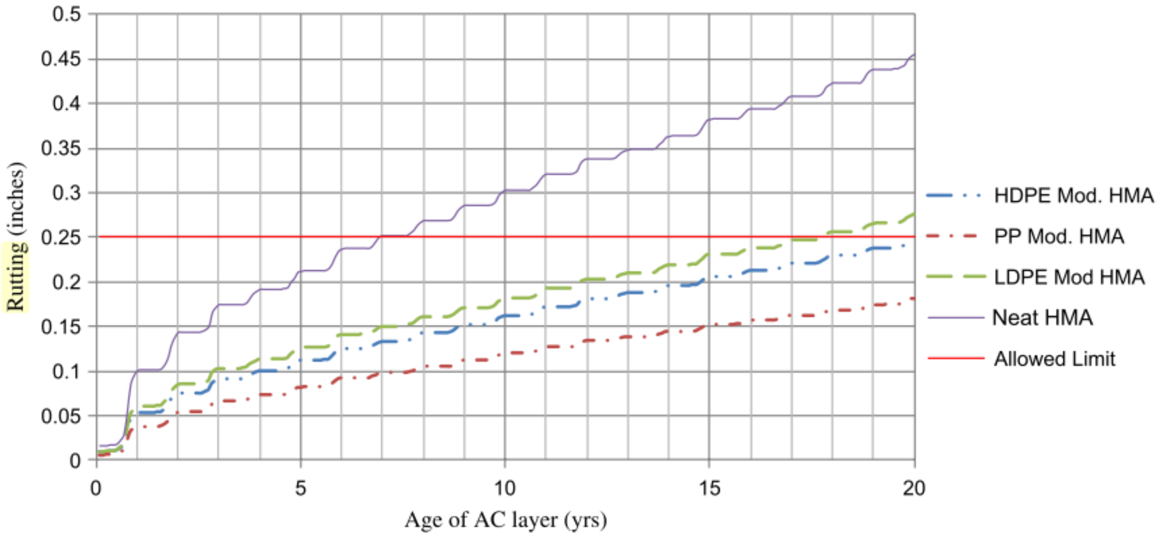

Figure 5 – Predicted rutting depth. All additives at 4% (w/w) of bitumen. Standards Saudi Arabian [44].

3.5 Abrasion

Almost all of the research on waste-plastic modified asphalt has taken place in hot countries with no studded tyre use. Thus, there is a research gap on abrasion parameters, measured by either the Prall test or by the Swedish circular road simulator [45]. There is actually little measurement of even virgin polymer-modified bitumen in these tests, although it is commonly-used in the North, particularly in Canada.

One Norwegian study looked at empirical evidence from road sections and compared it to laboratory analysis. They found that results from the Prall abrasion test had a good correlation with rutting depth, and also that rutting was reduced by around 40% on roads with plastic modifiers, and so conclude that it gives significant protection from abrasion [46]. Another Swedish study looked at rubber and polymer additives and found a 50% and 25% decrease in wear respectively [47], though the rubber mix did not perform better under wheel-track tests, and a second Norwegian study found 32% less abrasion damage in Prall testing with polymer-modified bitumen[48].

Waste plastic generally changes asphalt parameters in the same direction as virgin polymers (although often to a different extent) so it is expected that waste plastic additives should improve resistance to studded tyre wear. It is also worth noting that, when used as an aggregate replacement instead of a binder additive, waste plastic improves results from the LA-test of aggregate abrasion [10].

3.6 Fracturing and temperature susceptibility

Fracturing of road surfaces can result in water infiltration, frost heaving, increased erosion of the road surface and other problems. The binder may fail in cohesion or lose adhesion to the aggregate, with the latter more typical and low temperatures [9], [49]. The strong consensus amongst studies is that both waste and virgin plastic additives improve adhesion and reduce cracking at low temperatures, both by lowering the glass-transition temperature and by improving the cohesion and adhesion of the bitumen [17], [24], [31]–[33], [50]–[52].

On the other hand, road temperatures in Iceland can reach 45-50°C, and in fact deformation at high temperatures is said to be a significant source of ruts on Iceland’s roads [53]. Better adhesion at lower temperatures could allow use of bitumen with a higher softening temperature, reducing the impact of this. More directly, waste plastic additives reduce penetration [54], [55], increase the softening point [56], One study found that 5% and above waste LDPE film additive (i.e. shredded plastic bags) effectively eliminated rutting at 40°C and reduced it to very low levels at 50°C with 7,5% and 10% additive [55], and another found that 5% granulated HDPE thoroughly mixed with bitumen could increase the softening point of asphalt to 71,1°C from 52,2°C, with the effect of LDPE-modified bitumen less pronounced, softening at 59,5°C [51]. Both of these are above the service temperatures for Icelandic roads. Notably, using granular rather than powder additives doubled the improvements in both cases.

There is also evidence that higher elasticity mentioned previously is maintained at high temperatures, while using several kinds of different waste plastic additives [31], [33], [57]. Thus it can be said that waste plastic additives should improve both the high- and low-temperature service qualities of roads.

3.7 Volumetrics and voids

Asphalt concrete typically has three measured void parameters: air voids, voids in aggregate and voids filled with asphalt. Achieving the correct void density for these parameters is critical. Too much air in the mix will lead to ravelling, rutting, cracking or premature binder aging, while too little will lead to rutting by plastic deformation. Typically a high void content can somewhat be avoided by better compaction on laying the road, but low void content always requires changes to the mix.

It seems that different additives have differential effects on void content in plastic-modified bitumen and plastic-coated aggregate, but generally they lead to higher air void contents, some unacceptably so, but others around the “sweet spot" of 2-4% [11], [14], [52], [58], [59]. It is certainly possible to find levels of additives that satisfy requirements (e.g. Figure 6), and some additives produce a much lower void content, probably through the use of less viscous bitumen grades (Figure 7). Little research has been done on field cores to determine whether compaction can reduce voids in the case of waste plastic additives. Although the contribution of plastic additives to void content deserves close attention and optimisation, it does not seem to have a critical effect on the functionality of the end product.

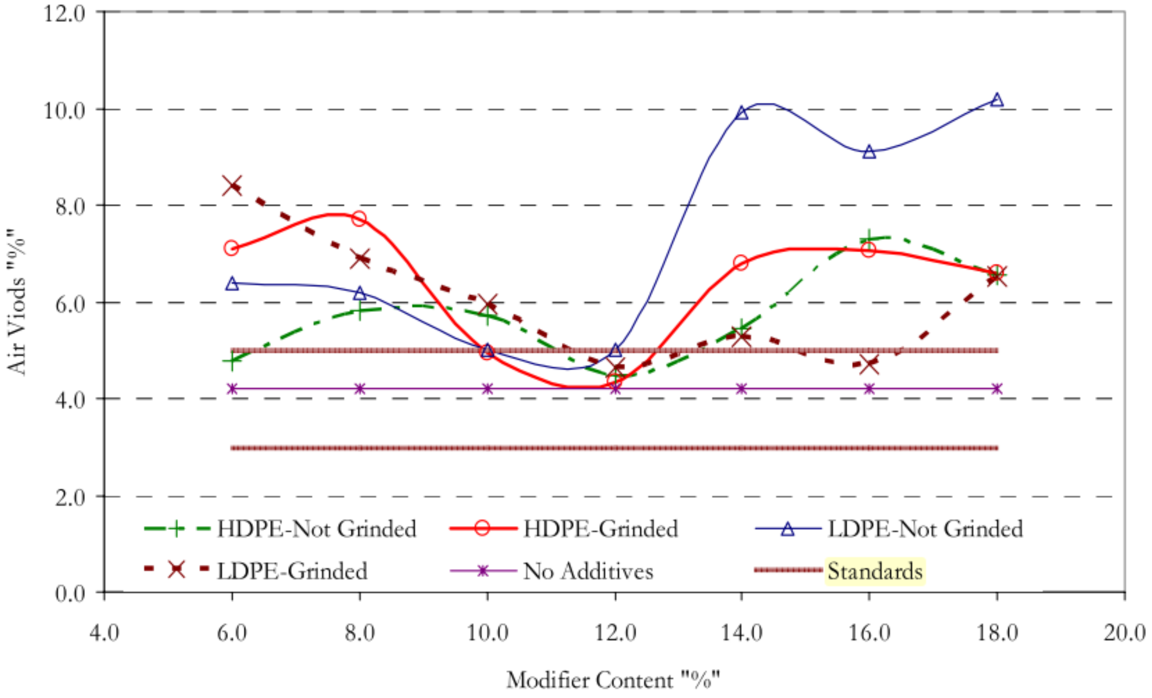

Figure 6 – void content of asphalt concrete with various plastic modifiers. Bitumen was 60/70 grade. Standards are Jordanian [28].

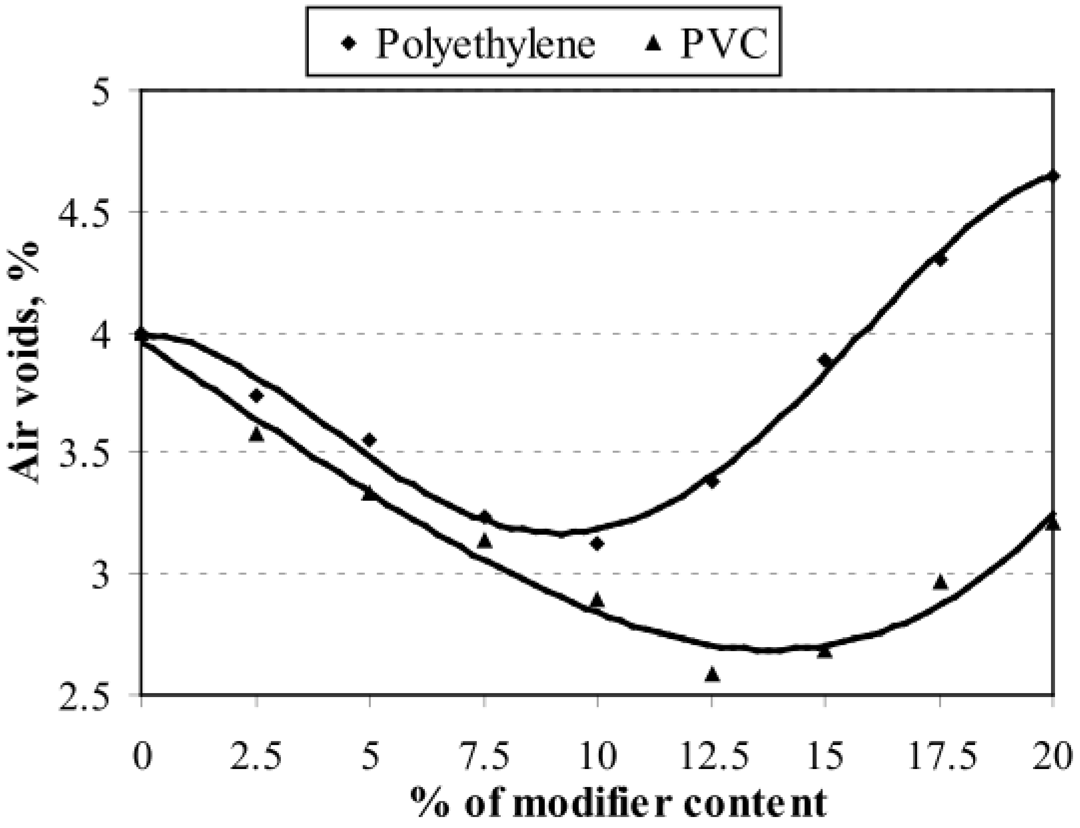

Figure 7 - void content of asphalt concrete modified with PE and PVC (latter not recommended due to health concerns). Bitumen was 80/100 grade. [19]

3.8 Usability

There is no well-described method of full-scale replacement of aggregate by plastic, so it is not assessed here. The mixing of plastic-coated aggregate is simple – aggregate is heated to 160°C and the dry shredded plastic (c. 2mm) is added manually or through a blower and mixed for around 30 seconds. The mixing of plastic into bitumen takes at least 30 minutes at high temperatures and tends to separate over a period of days [15], [33], [60], and require separate storage.

In laying, plastic-modified bitumen may separate [19], but plastic-coated aggregate has no reported problems in this regard. Vasudevan et al. report from lab tests and their experience of road-laying in India that polymer-modified bitumen has poor penetration, ductility and viscoelastic properties [10] and recommend that the aggregate coating technique is used. Normal laying temperature is 110-120°C according to Indian regulations [61]

3.9 Other considerations

3.9.1 Density

All forms of plastic have a lower specific gravity than bitumen. Depending on the amount of bitumen in the mix, and especially with mixes where plastic replaces aggregate, density of hot-mix asphalt can be reduced and therefore also potentially reduce haulage costs [36], [58].

3.9.2 Chemical Stripping

Kamada et al. note that PP, PE and PET-modified asphalt mixtures show improved resistance to oil and water binder-stripping [62].

3.9.3 Stone-Matrix Asphalt

For sections that see harder wear, it is possible to make a mixture of hot-mix asphalt where stones are selected to form a lattice structure that is very resistant to abrasion and rutting, known as “stone-matrix asphalt” or “stone-mastic asphalt” (SMA). This suffers from the problem of drain-down of neat bitumen, so it is routine to add stabilisers such as cellulose fibres to such mixes. An area of the waste-plastic asphalt literature focuses on the effect in stone-matrix asphalt, and universally concludes that waste plastic is a suitable replacement for stabilisers, as well as imparting some or all of the strength improvements previous described, often to a comparable or greater extent as that given by stabilisers [1], [11], [14], [29], [34], [42], [46], [48], [56], [63]–[65]. Of particular note for Icelandic conditions is an empirical Norwegian study that compared the effect of virgin plastic additives to normal asphalt and unmodified SMA where the plastic-modified asphalt actually performed slightly better than SMA in terms of rutting after 8 years, as well as 40% better than unmodified normal asphalt.

3.9.4 Lifespan and thickness

The use of waste-plastic asphalt has only been extensively done in India thus far, although there are many pilot projects. Due to its resistance against wear, it is generally reported and predicted that plastic-modified asphalt should have a longer lifespan than unmodified [2], [29], [56], [66]. One Indian review shows an increase in lifespan by up to 50% using their normal method, which is plastic-coated aggregate at 8-10% w/w bitumen [67]. Another study, modelling an SMA surface over asphalt concrete predicts a 36% improvement in lifespan with SBS at 5% addition [29]. Alternatively, the authors calculate that with a constant subbase and asphalt concrete, the thickness of base and SMA can be decreased by 25% and 34% respectively to give a consistent service life. Either of these would obviously infer significant cost and environmental benefits.

3.9.5 Skid resistance

One parameter that has had little reliable study is skid resistance. New lab research from Spain has indicated that the effect of waste plastics on skid resistance (as measured by the British Pendulum Test, ASTM E303-93) may be negative – in that study, 5% PE, PP and PS reduced skid resistance (Figure 8). This appears to be an effect of the state of the material; PE and PP are solids at service temperature, PS is in its glass transition phrase and rubber is above the transition temperature.

The general initial requirements of skid-resistance are 65 for difficult sites such as tight bends, gradients, traffic lights etc.; 55 for trunk roads and motorways; and 45 for general usage [68]. This might indicate that selecting some polymers (e.g. polystyrene) would be a good strategy for more difficult sites. None of the initial values falls below 45 in the aforementioned study, although polyethylene falls below this value after wear. However, clearly more study and testing is needed in this area.

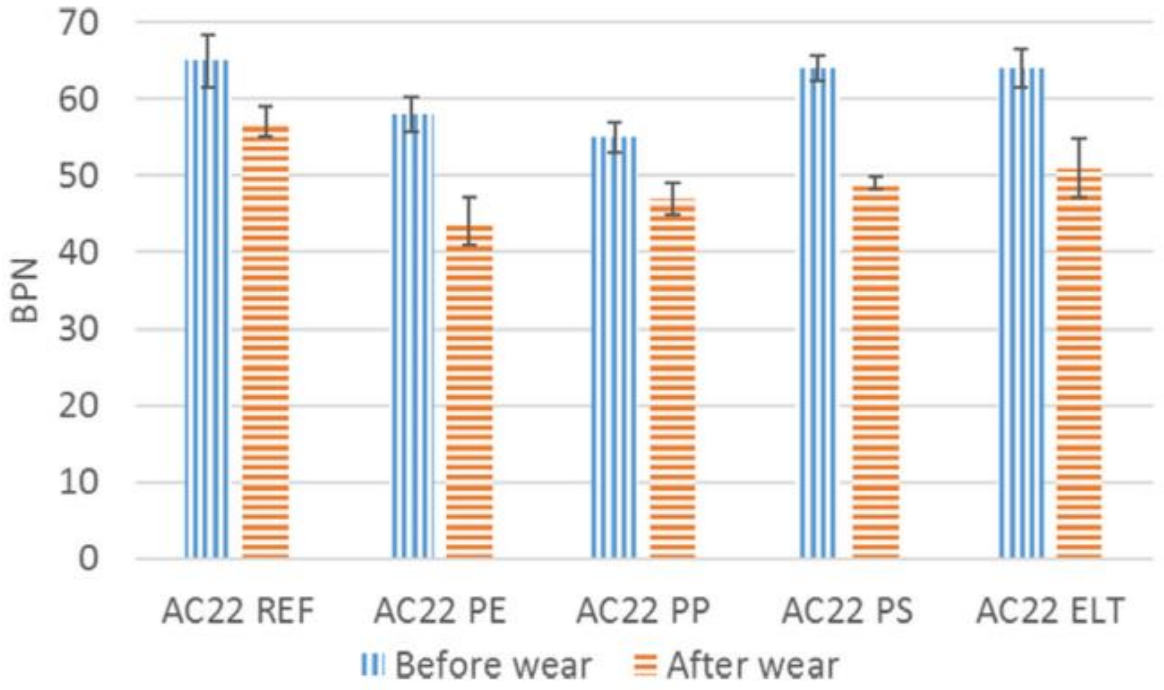

Figure 8 - Skid resistance tested using the British Pendulum. BPN = British Pendulum Number; REF = control; ELT = End of Life Tyres.[69]

3.9.6 Safety

Aside from PVC, all common types of waste plastic (PP[18], PE[17], [18], PET[70], PS[18], PC[71], PU[72], ABS [40] etc.) are thermally stable (although molten, except for PS) at 180°C, the maximum temperature where they might be mixed (more usually 160 [35]), and generally remain stable until at least 200-250°C. The risk of overheating to the point of combustion is negligible in asphalt plants.

PVC, found mostly in plastic pipes but also in shower curtains, wire coatings and some clear plastic wraps, should be minimised in any additive streams to prevent danger to road workers as is common practice in the Indian industry [50], [61]. As PVC decomposes, it may produce toxic hydrogen chloride gas, with emissions beginning around 200°C [73] although emissions may be significantly reduced if mixed with other plastic [74]. At 180°C the risks are not extreme, and it has been proposed as an additive in roads [19], but there is a consensus that the risk does not make it worthwhile.

One field study found some genotoxic effects to pavers from stone-matrix asphalt with waste plastic and tall oil additives, but found the same effects without the additives [75]. Another found small but measurable amounts of resin acids – a sensitizer – in the air at a Finnish road construction site with a similar mix and noted that road workers found the mix more irritating to work with than regular mixes. Aside from these, there is no peer-reviewed data indicating extra effects from laying of roads with waste plastic modifiers, and many hundreds of thousands of kilometres of road have already been laid worldwide with virgin plastic polymers.

3.9.7 Direct environmental impacts

The environmental impacts of using polymers in roads are likely to be, in total, positive, as can be seen in the next section. There is a possibility of negative environmental impact from plastic dust from wear of the roads, but it is unclear how much ecological difference there is between plastic dust and bitumen dust. Particles are also likely to be small, and as previously discussed, additives in asphalt should reduce abrasion of roads and therefore reduce the amount of pollution from road wear. The vast majority of particulate emissions from roads comes from tyres, which have a high proportion of plastic in them. Additionally, SBS and other polymers have been used for many decades without any research linking plastic road dust to extra environmental effects. However, as with safety, this is an area for monitoring and study.

3.9.8 Recycling

One major factor that may be overlooked when optimising quality of road asphalt is the possibility of recycling. As waste plastic-enhanced roads are relatively new at any scale (10-15 years for India) there is not much evidence to answer this question. However, Zoorob and Suparma simulated the passing of a 15-year aging cycle in their study on aggregate-replacement “plastiphalt”, which has a much higher plastic content than most of the studies mentioned here, around 12% by weight compared to c. 0,5-1% by weight[36]. Their findings were that the recycled “plastiphalt” had significantly *improved* test results over original “plastiphalt” (particularly improved stiffness with 50% improved elastic recovery), which itself was better than the control in almost all measures. This is a surprising result, as bitumen tends to age-harden and thus increase stiffness at the expense of rebound.

There is also evidence from research on recycling SBS-modified asphalt that adding polymers may slow the age-hardening of asphalt, and that asphalt may slow the degradation of the polymers[76].

4 Social and Environmental Costs and Benefits

Many fractions of waste plastic are difficult to recycle, and many sources are remote from recycling centres. For example, there is little or no domestic plastic recycling in Iceland and so waste plastic must be exported at some environmental cost. Disposal of these waste fractions means either incineration or burial. As plastic is essentially a fossil fuel, incineration produces high carbon emissions (Table 1) along with ash and in some cases undesirable pollutants such as dioxins. In total, it is possible to save between 1,76 and 2,62 tonnes of CO2 for every tonne of bitumen replaced by plastic in asphalt production. Low-grade and mixed plastic waste streams in Iceland are currently in the order of several thousand tonnes annually and are increasing as greater separation is enforced.

Table 1: Estimated CO2-equivalent emissions from various components of plastic disposal. Sea shipping at 12g/tonne/km with 0,02t extra emissions for processing and transport in Sweden. 0,01t for transport from receiving facilities to hot-mix asphalt plant. Bitumen production from LCA.[77] *All other figures from U.S. E.P.A.*[78]. *Every tonne of bitumen replaced by plastic saves between 1,76 and 2,62 tonnes of CO2 emissions.*

Plastic	CO2e/tonne Incineration (raw)	CO2e/tonne Incineration (including fossil fuel offsets)	CO2e/tonne recycling	CO2e/tonne export Reykjavík to Gothenburg	CO2e/tonne landfilling	CO2e/tonne Plastic-coated aggregate	CO2e/tonne bitumen production and transport
HDPE	1,62	1,40	-0,97	0,05	0,04	0,01	0,33-0,45
LDPE	1,98	1,40	#N/A	0,05	0,04	0,01	0,33-0,45
PET	2,44	1,37	-1,25	0,05	0,04	0,01	0,33-0,45
LLDPE	1,74	1,40	#N/A	0,05	0,04	0,01	0,33-0,45
PP	1,71	1,40	#N/A	0,05	0,04	0,01	0,33-0,45
PS	2,76	1,81	#N/A	0,05	0,04	0,01	0,33-0,45
PVC	2,16	0,74	#N/A	0,05	0,04	0,01	0,33-0,45
Mixed	2,12	1,38	-1,14	0,05	0,04	0,01	0,33-0,45

5 Economic Costs and Benefits

The economic costs are difficult to calculate in the Icelandic context, as improved road longevity is a difficult variable to estimate. However, some facts are well-known. The export cost for mixed waste plastic is circa 30.190 kr. per tonne (SORPA, pers. comm.) and the price for one tonne of bitumen is circa 138.818kr as of April 2017 (Hlaðbær Colas, pers. comm.). The infrastructure for mixing exists already as part of the additive process in making stone matrix asphalt. Leaving aside some small capital investments in shredding and ignoring processing time and delivery (which are likely to be a small factor), and assuming a binder content of 6% with a plastic content of 10%, we can estimate that the immediate savings are around 1000kr per tonne of hot mix asphalt.

There is enough mixed waste plastic recycling to cover the entire annual demand of hot mix asphalt for Iceland, with circa 37.100 tonnes laid on behalf of Vegagerðin in 2015 and 14.100 laid on behalf of Reykjavík in 2016 [79], [80] and an estimated 2015 total of c. 193.000 tonnes according to the European Asphalt Paving Association [81]. If this were to be achieved, it would be possible under the above assumptions to sequester perhaps 1100-1200 tonnes of plastic per year in the roads of Iceland. This would save up to 3000 tonnes of CO2 every year, and save in the order of 196M kr. In avoided purchase of bitumen and plastic export.

So-called ‘known-unknown’ cost savings may also include the increased potential for recycling plastic-coated asphalt, reduced haulage costs due to reduced densities, reduced materials use due to thinner road layers and reduced use of other additives, such as cellulose fibres in stone-matrix asphalt.

Less directly, it should be possible to reduce cost significantly through reducing resurfacing intervals due to improved wearing properties. If, as studies claim, road lifespan can be increased by 36-50%, then cost savings in Reykjavík alone could be 172-216M kr. per year based on the cost of renewing old asphalt [29], [67], [80]. This is could generate much higher savings than the reduction materials usage itself, on the order of a billion kroner or more annually across the whole of Iceland. Although this is a best-case figure, it certainly seems worth investing in further research into the behaviour of plastic-modified asphalt. Real savings of two orders of magnitude less would still give a considerable benefit to Icelandic society.

6 General Conclusion

This literature review finds considerable support for further practical testing of plastic additives in asphalt in Iceland, specifically using the plastic-coated aggregate method. In almost all tests of desirable properties of asphalt road surfacing, plastic-modified roads outperform unmodified roads, and in general mixed waste plastic seems to give almost or equal improvement as virgin additives. The case study and official endorsement of the Indian government, which lays more than 5000km of waste plastic-enhanced roads every year, gives real-world testament to this. The infrastructure for making use of such additives exists currently, and if tests are successful then there seems to be little barrier to making waste plastic a standard component in hot mix asphalt, as it currently is in India. The potential economic savings from this switch could be from hundreds of millions of kroner to over a billion kroner annually. In addition there is potential to prevent over a thousand tonnes of waste plastic being landfilled or incinerated annually, along with avoiding up to three thousand tonnes of CO2 emissions.

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