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THE USE OF RECYCLED PLASTICS IN WARM MIX ASPHALT

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Abstract

The production of plastic in the world has increased exponentially over the last fifty years, and the amount of plastic waste has increased accordingly. Governments around the world are beginning to ban single-use plastics, while investing in the development of waste management facilities and promoting recycling practices. The use of recycled plastics in the production of asphalt mixtures has become widespread due to the economic and environmental benefits. To date, numerous studies have been conducted on the feasibility of blending various types of recycled plastic into hot mix asphalt (HMA). The results of these studies have shown that the addition of recycled plastic increases resistance to rutting, fatigue and moisture sensitivity while reducing susceptibility to cracking at low temperatures. The use of recycled plastic in asphalt mixtures should be further investigated, particularly with regard to compatibility with technologies for the production of warm mix asphalt (WMA). Technologies for the production of WMA are based on reducing the viscosity of bitumen using foaming techniques or additives. WMA is produced at a temperature that is about 20°C – 40 (60)°C lower than conventional HMA. Lower temperature of mixed and compacted WMA allowed reduce energy consumption and greenhouse gas emissions, bringing numerous benefits: ecological, economic and structural. This review paper aims to present the current state of the art, the benefits and the challenges related to the application of recycled plastics in WMA.

Keywords: recycled plastics, warm mix asphalt, reclaimed asphalt pavement, environmental benefits, greenhouse gas emissions, energy consumption

1 Introduction

The daily demand for plastic products is rising inexorably, with annual production increasing from 1.5 million to 430 million tonnes between 1950 and 2018 [1]. Accordingly, the amount of plastic waste has also risen dramatically, which is why single-use plastics are increasingly being banned in many countries. At the same time, considerable resources are being invested in the development of waste disposal facilities. With the aim of promoting sustainable development, the possibilities of reusing and recycling plastic waste are also being researched. The use of recycled plastic in asphalt mixtures has been explored for the last thirty years, and the Chinese government's decision to ban the import of plastic waste from January 2018 [2] made this a topic extensive scientific research. Up to that point, China imported around 45% of the world's plastic waste. The use of recycled plastic in asphalt mixtures was proposed as one of the possible solutions for its disposal [1]. To date, numerous studies have been conducted on the possibility of using different types of recycled plastic in hot mix asphalt (HMA) [3-5]. Previous research has shown that the use of recycled plastic in HMA leads to an improvement in resistance to rutting, fatigue and moisture sensitivity, but also to a reduction in resistance to cracking at low temperatures.

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The use of recycled plastic in asphalt mixtures needs to be further researched, also in terms of compatibility with the technologies for producing warm mix asphalt (WMA) with the addition of reclaimed asphalt pavement (RAP). WMA technologies are a range of methods (additives, processes) that can be used to produce asphalt mixtures at temperatures lower than those used to produce HMA, while maintaining the properties of conventional mixtures [6-9]. The use of WMA reduces the need for energy sources and the production of greenhouse gases generated during the heating of aggregates and bitumen. RAP is material that is removed and recycled (milled or crushed) from existing asphalt layers and contains aggregates and bitumen. By using RAP in asphalt mixtures, savings can be made on virgin bitumen and natural aggregate. This partially eliminates the pressing problem in the production of asphalt mixtures, which is reflected in the need for large quantities of natural stone.

2 Process of recycling and types of plastics

In order to achieve the appropriate properties of asphalt mixtures, it is recommended that recycled plastic rather than waste plastic is used in the production process. The process of obtaining recycled plastic is shown in Figure 1. In short, the process starts with the collection of waste material after use. The next step is sorting. There are different types of plastics that need to be separated during the recycling process. Plastics can also be sorted according to other properties such as colour, thickness and use. This is followed by washing, which is an important step as it removes some contaminants that can affect the operation of the plastic processing plant. Contaminants that are removed in this step include labels and adhesives, dirt and food debris. The plastic waste is then fed into shredding machines that grind it up. Unlike moulded plastic products, these smaller pieces can be processed in further steps for reuse. In addition, the shredded plastic parts can be used for other applications without further processing, e.g. as an asphalt additive, or simply sold as a raw material. The plastic parts are then tested and their class and quality determined. In the final step of the plastic recycling process, the shredded plastic parts are converted into a usable product for manufacturing. Shredded plastic is melted and processed into granulate to facilitate dispersion and dissolution in the asphalt binder. There are currently seven basic types of plastics (Table 1). They differ from each other in their physical and chemical properties. One of the main differences is certainly the melting point.

Figure 1 Process of recycle plastic production [10]

Provided that the bitumen is modified with the recycled plastic, the plastic must be able to melt and bond with the bitumen. Due to the melting point temperatures, some types of plastic are not suitable for use in asphalt mixtures. PET and PVC, for example, has a melting point of 250°C [11]. LDPE, on the other hand, generally has a melting temperature range which is below the processing temperature of asphalt mixtures (around 145°C to 180°C). Typical values for the melting point of HDPE are around 130°C. ABS is an amorphous polymer and has no actual melting point, but changes from a glassy to a rubbery state at approx. 100°C (glass transition temperature). HDPE requires higher temperatures to soften. Therefore, a higher viscosity of the bitumen-plastic mixture can occur at 6% and 8% plastic content [12]. More viscous binders result in a thicker binder film around the aggregate particles, which ultimately leads to an enlargement of the voids between the particles. The properties of the plastic waste such as type, chemical composition and structure as well as the molecular weight influence the time required for blending, as plastics with a higher molecular weight require more time to mix homogeneously with the asphalt binder [13].

Table 1 Types of plastic and melting point [2]

Types of plastic	**Melting point** [°C]
Polyethylene Terephthalate (PET)	< 250
High Density Polyethylene (HDPE)	130 but can vary in grade
Polyvinyl Chloride (PVC)	100 - 260
Low Density Polyethylene (LDPE)	110 - 120
Polypropylene (PP)	160 - 165
Polystyrene (PS)	glass transition at 100
Other (Polycarbonate (PC), Polylactide (PLCA), Acrylonitrile Butadiene Styrene (ABS), Nylon, Fiberglass, Acrylic)	based on grade and plastic type

3 The technologies of WMA produced

The technologies used to produce WMA are based on reducing the viscosity of the bitumen, i.e. reducing the interfacial friction between thin layers of asphalt binder and coated aggregates by foaming bitumen or using various additives. This enables the production and paving of WMA at temperatures between 100°C and 150°C, which is about 20°C – 40 (60)°C lower than conventional HMA, while maintaining the physical and mechanical properties of the mixture.

Bitumen application technologies can be divided into direct (water-based) and indirect (water-bearing). In direct technology, the bitumen is foamed in the expansion chamber by injecting 1% - 5% cold water from the bitumen mass into the hot bitumen with a nozzle (Figure 2), which leads to the formation of water vapour [6, 7]. The water vapour released in this way creates a large number of bubbles and leads to a temporary but significant increase in the effective bitumen volume (≥ 10-fold), which facilitates the coating of the aggregate by bitumen at lower temperatures. In the indirect technique, minerals are used as the water source for foaming. Most commonly used are hydrophilic minerals from the zeolite family, which contain around 20% crystallised water [7]. The crystallised water is released at a temperature of over 100°C, creating a controlled foaming effect. This facilitates installation and compaction over a period of 6 to 7 hours or until the temperature drops below 100°C [8]. Some authors [8] mention the possibility of adding wet aggregate or RAP directly into the asphalt mixer.

This method should be avoided as it leads to expansion under uncontrolled conditions and the expansion coefficient cannot be controlled. In general, additives of chemical and organic origin are used. Organic additives are special types of paraffins produced from natural gas and fatty acid amides [6, 9]. Organic additives usually enable a temperature reduction of around 20 - 30°C and improve the deformation resistance of WMA [9]. Chemical additives do not change the viscosity of bitumen. As surfactants, they reduce the interfacial friction between the thin layers of asphalt binder and the coated aggregates, improving the workability and enable mixing and compaction at lower temperatures. The additives may contain built-in anti-stripping agents that promote adhesion between the asphalt binder and aggregate and reduce the potential for moisture-induced damage [9]. The package of chemical additives is either used in the form of an emulsion or added to the asphalt binder at the terminal and then mixed with the hot aggregates. It is therefore possible to mix bitumen and aggregates and compact the mixture at lower temperatures. Chemical additives can reduce the temperature during mixing and compaction by around 20°C - 40°C.

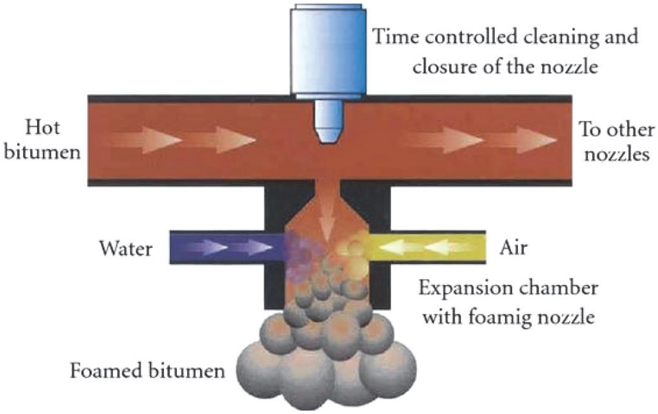

Figure 2 Foam bitumen process [14]

The ability to lower the production temperature of WMA is the main advantage which directly leads to a reduction in fumes, greenhouse gas emissions, air pollution and energy savings. However, this result is highly dependent on the production temperature and the type of fuel used [15]. Lower fumes have a positive impact on the health of workers, but also on the communities surrounding production plants and construction sites, which is particularly important in densely populated urban areas. Additionally, lower production temperatures reduce the ageing of the bitumen, which improves the structural flexibility and durability of the pavement and reduces susceptibility to fatigue and temperature cracking in the initial phase of pavement exploitation [15]. The higher workability of WMA reduces the compaction effort, which is particularly advantageous in cold weather due to the low temperature difference between the mix and ambient conditions compared to HMA. Consequently, WMA increases the time window for construction and allows for an extended paving season or overnight paving, offering contractors significant economic benefits. The ability of WMA to compact at lower temperatures also extends transport distances. Another indirect benefit is less wear and tear on the asphalt plant due to the lower mixing temperature. Additional environmental benefits can be achieved by adding RAP to WMA. The use of RAP leads to savings on virgin crushed stone aggregate and bitumen. This helps to preserve landfill space and reduce the energy required for excavation. Research [16] conducted in the USA in 2020 shows that the average proportion of RAP in new bituminous mixtures is only 21.1 %, although this could be increased to almost 100% through the development and use of suitable rejuvenators [17].

Apart from the above-aforementioned advantages of WMA, their main disadvantage is their greater sensitivity to rutting and the effects of moisture. A detailed description of the shortcomings of WMA is given in [15]. In short, the problem of rutting with WMA arises from the fact that a lower mixing temperature of WMA can lead to incomplete drying of the aggregate, insufficient coating with bitumen and reduced oxidative curing of the bitumen. This could be mitigated by the addition of bonding agents or by initially selecting a harder type of binder grade. Moisture damage causes a failure of adhesion between the bitumen and aggregate and/or the cohesive bond within the asphalt binder. Loss of adhesion is caused by the breakdown of the interfacial bond between the surface of the aggregate and the bitumen, mainly due to the action of water and water vapour. The loss of cohesion is primarily caused by the effect of moisture within the bitumen, which leads to softening and thus to a loss of stability of the mixture. Moisture susceptibility of WMA pavements is of greater concern than that of HMA, as WMA technologies rely on the use of water (i.e., water-bearing additives or water-based foaming processes) as a workability aid. The presence of water after foaming and even incomplete drying of aggregates due to lower production temperatures can affect the bond between binder and aggregates and lead to increased susceptibility to moisture damage.

4 Recycling plastics in WMA

Empirical studies indicate that plastic waste in asphalt pavements can be recycled in two ways: in a dry process and in a wet process. The dry process is less complicated than the wet process as it does not require specialized equipment such as bitumen mixers to mix bitumen and plastic waste [18]. The dry process may be unsuitable for some stiffer plastic waste due to the high melting point of some types of plastic. However, instead of replacing part of the mineral aggregate with plastic, as is common in the dry process, plastic waste can be added as a bitumen extender. In this case, the aim is to improve the performance of the asphalt mixture, even if the plastic is only added during the mixing process after all the ingredients have been mixed. In the wet process, the plastic waste is added to the bitumen as an additive before it is mixed with the aggregate. In addition, some plastic waste, such as LDPE, has difficulty diffusing into the bitumen in the wet process and tends to separate during storage even after high shear mixing [19]. Techniques such as chemical stabilization, chemical functionalization of the polymer or bitumen blending in the plant are recommended to reduce these problems.

To date, numerous studies have been conducted on the influence of recycled plastic on the properties of HMA [18- 21]. The most common types of plastic were used in the studies (Table 1). The results indicate that the use of recycled plastics improves performance parameters such as stiffness, rutting and fatigue strength. In addition, the performance of polymer-modified asphalt mixes tends to be temperature-dependent. This means that they perform better at high temperatures (rutting resistance) and worse at low temperatures (resistance to fatigue cracking). However, there are still relatively few studies on recycled plastics in WMA.

In a study [22] conducted on standard HMA and WMA with the addition of zeolite at 0.2% of the bitumen mass and LDPE at 8% of the bitumen mass, the stability and flow behavior were analyzed according to Marshall. The test results showed that lower stability and Marshall test values and a lower void ratio were achieved for WMA with the addition of recycled plastic. In the study [23], asphalt mixtures were analyzed in which part of the aggregate was replaced by waste PET in proportions between 0.1% and 1.1% (with step 0.2%) of the mass of the aggregate. The WMA was produced with the addition of zeolite in a proportion of 0.3% of the total mass of the mixture. The waste PET was mechanically ground to a maximum particle size of 2.36 mm. Viscosity tests were carried out on the mixtures produced in order to determine the optimum mixing and compaction temperature.

For each mixture, three samples were prepared using the Marshall method and the following properties were determined: density, stability and flowability according to Marshall, void ratio, void ratio in aggregate, stiffness and rutting. The research results show that the addition of PET to WMA increases Marshall stability, stiffness and indirect tensile strength and reduces susceptibility to rutting. The proportion of PET of 0.5 % can be regarded as optimal, as the highest value for Marshall stability was achieved at this proportion and the mixture was least susceptible to rutting. Chowdhury et al. [24] investigated WMA with plastic waste (a mixture of various plastics, polyethylene, polyester, etc. in unknown proportions) and a chemical additive. The plastic waste was added in the dry phase in proportions between 2%, and 12% (with step 2%) of the bitumen mass and the chemical additive with the trade name ZycoTherm was added in the wet phase in proportions of 0.15% and 0.20% of the bitumen mass. The research results show that the use of plastics in bituminous mixtures improves the Marshall stability and leads to a reduction in the optimum bitumen content. With the addition 8% of plastic waste, the Marshall stability increases; it then decreases with a further increase in the plastic content. 8% was selected as the optimum plastic content. The addition of the chemical additive ZycoTherm reduces the Marshall stability and the optimum bitumen content. The optimum proportion of the chemical additive in the study was 0.15%. Ultimately, the study led to an increase in stability, indirect tensile strength and a reduction in moisture sensitivity. Almeida et al. [25] investigated HMA and WMA without and with the addition of LDPE in a proportion of 6 % of the bitumen mass. The WMA was produced by adding an organic additive in the amount of 1.5% of the bitumen mass. The additive was added to the bitumen mixture in the wet process, while the LDPE was added in the dry process at a mixing temperature of 100°C. The mixtures produced were tested for their stability and flow behavior according to Marshall, the proportion of voids and the proportion of voids in the aggregate, stiffness and resistance to cracking due to fatigue and rutting. The results of the investigation showed that WMA with the addition of LDPE exhibit higher stability and lower flow behavior according to Marshall as well as a higher proportion of voids and voids in the aggregate. The addition of LDPE to WMA led to an increase in stiffness, a slight reduction in resistance to the occurrence of cracks due to fatigue and an increase in resistance to the formation of rutting.

5 Conclusion

The vast majority of plastics produced are used only once, and most of them are used for the most common of all single-use applications - packaging. Mass production combined with single use results in unimaginable amounts of waste. Certain types of plastic take hundreds or even thousands of years to decompose, and even then, they do not disappear but turn into microplastics. For this reason, plastic waste must be continuously collected, separated and recycled. One of the ways of recycling is the use of plastic in WMA. The technologies used to produce WMA are based on reducing the viscosity of the bitumen, i.e. reducing the interfacial friction between thin layers of asphalt binder and coated aggregates by foaming bitumen or using various additives. This enables the production and paving of WMA at temperatures between 100°C and 150°C, which is about 20°C – 40 (60) °C lower than conventional HMA. Lowering the temperature has numerous advantages, e.g. environmental (lower emissions of greenhouse gases and exhaust fumes from the plant), economic (lower energy consumption and lower financial costs), production-related (increase in RAP content possible) and paving-related advantages (better workability and compaction efficiency, longer transport distances and shorter cooling time). The main disadvantages of WMA are its greater sensitivity to rutting and moisture, which depends on the technologies used for production. Currently, there are only a few studies dealing with the influence of recycled plastic on the physical-mechanical properties of WMA.

Compared to WMA without added plastic, mixtures with recycled plastic have higher Marshall stability, stiffness and rutting resistance and are less sensitive to the effects of moisture, regardless of the production technology. It should also be noted that all technologies for the production of WMA (foaming, chemical and organic additives) have been considered in the research work to date. Based on previous experience with the use of recycled plastic in HMA, it can be expected that the addition of recycled plastic will lead to an improvement in the properties of WMA, in particular rutting and moisture sensitivity. It can be assumed that new innovative methods are required for further research into their feasibility and adaptability to the various requirements of flexible pavement structures. Future research must also show that the use of recycled plastic in large quantities in WMA allows similar or better performance compared to standard HMA.

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