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Article

Plastic waste in dense asphalt mixes for road pavements

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Abstract: Recycling plastic waste in asphalt pavements records increasing statistic figures of application during the last decade worldwide. Due to environmental constraints, but also, to some beneficial properties of plastic waste, recycling in asphalt tends to become current practice, in several countries. In the Aristotle University of Thessaloniki (AUTH), the first attempt to produce asphalt mix using plastic waste consisted of mixing recycled plastic flakes with non-modified binder. Following an asphalt mix design in the laboratory, the whole mass of conventional aggregates was replaced by PET flakes. Recycled PET flakes were chosen to be introduced in the asphalt mix since they are hard, resilient and water repellent. Bitumen emulsion was first preferred as a binder to produce a cold asphalt mix. At a second stage of experimental research, plastic flakes replaced a part of the limestone sand while conventional asphalt 50/70 was used as a binder. At this stage, the experimental research provided more encouraging outcomes. Stability of asphalt mixes decreases as the plastics content in the mix increases, but all recorded values were still within limits of acceptance. At a third stage of research, LDPE recycled material of fine gradation was used to replace a part of the asphalt binder in dense mixes. The objective was to produce a modified binder and a more durable asphalt structure. Test results showed a significant improvement of the performance of asphalt mixes, in terms of strength and deformability of the asphalt mix structure. The research is completed by comparing the conventional techniques with the outcomes of the recycling process and by delineating potential fields of application of the recycled plastics in asphalt pavements.

Keywords: recycling; plastic; waste; asphalt; pavement; road

1. Introduction

The amount of plastic, produced worldwide has increased significantly, over the last 50 years; from 40 million tons in 1972 to 400 million tons in 2022 [1]. Furthermore, the tendency is still positive with an expected annual rate of production increase of 2.5%, despite the continuous warning from environmentalists about the risks of waste disposal [2]. It seems that, despite persistent campaigns against production of new plastic, statistic figures will keep on growing, thus generating serious disposal issues.

The open debate and the consistent concern about the potential negative effects of recycling plastic waste on human health [3] seem to refer mostly to food packaging. All plastic types are synthetic polymers which do not maintain their structural integrity, while recycled, but they break up into smaller and smaller particles until they turn into microplastics or even nanoplastics, able to penetrate the vital human organs. By contrast, recycling plastic waste in road and pavement construction is a less questionable process; in many countries it tends to become regular practice.

There are multiple benefits from recycling plastic waste into asphalt mixes and pavements

(a) reduction of landfill needs for waste disposal

(b) production of equally or more resistant asphalt layers, with respect to the conventional practice.

(c)needs for fresh raw materials, either asphalt binder or mineral aggregates, may be reduced.

Research on reutilization of plastic waste in asphalt pavements started in the 90's and keeps on recording increasing statistic figures in several countries (India, China, USA, UK, Italy, Ghana). Research aims at providing stable and resistant asphalt mixes, while effectively addressing the issues of leaching and contamination of aquifers and of reducing the cost of recycling plastic waste.

2. Plastic waste recycling techniques

Recycling plastic waste in road construction is a new challenge and a tempting prospect. During the last 20 years, research on potential use of plastic waste in pavements has been intensified in many countries, especially, in those, experiencing acute problems of plastic disposal. However, despite some inspiring labels and signs introducing "Plastic Roads", no roads have been constructed entirely, or even, principally, from plastics to date.

A review study on the topic [4] suggested that recycled plastics can either replace aggregates or serve as a binder modifier. Specifically, LDPE waste has potential for use in bituminous layers as its addition in small doses (about 5%–10% by weight of bitumen) helps in substantially improving the stability, strength, fatigue life and other desirable properties of bituminous mixes, leading to improved longevity and pavement performance [5–7]. It seems that the use of LDPE waste in asphalt mixes is well established to date. The problem, in this case, is that prospective quantities of plastic waste to be recycled in asphalt are limited: since the rate of bitumen replacement by LDPE is up to 10%, only 1% of the total weight of asphalt mix may be recycled material [8].

Replacement of mineral aggregates by plastic waste is a more complicated and difficult issue. The form of the commercial supply, as well as, quantities available in due time, may be significant impediments. Moreover, technical issues, such as poor binding between the plastic particles and bitumen may lead to poor construction quality. In most countries the price of recycled plastic is far higher than the price of aggregates. In this case, it is mostly the environmental benefit that dictates the recycling practice.

In this regard, the most successful application is a variation of the Plastiphalt technique [9], in which PET wasteis used in asphalt concrete mixes for aggregate replacement [10]. The PET waste used in this application was in the form of granules of about 3 mm diameter, which replace anequal portion (by volume) of the mineral coarse aggregates of the same size (2.36 mm–4.75 mm). The optimum bitumen content of the asphalt mix was estimated at 6.6% and the rate of replacement of aggregates was 20% by volume. Undoubtedly, this is a successful technique of significant cost. In fact, the cost of PET granules is much higher than the cost of aggregates used in conventional applications.

3. Research on asphalt mixes with plastic waste

The literature review pointed out that, although research in several countries is far ahead, the rate of recycling plastic waste in road pavements, worldwide, remains very low. This may be attributed to several reasons, including technical, practical and economic impediments. It seems that a major concern of any experimental research in the field of plastics recycling is the elaboration of a technique that would lead to applicable and affordable site works.

In line with this concern, the research on recycling plastic waste in asphalt mixes, conducted in the Aristotle University, had three specific driving considerations:

- Explore relatively simple and realistic methods of recycling which may provide promising and applicable outcomes.
- Investigate domains of significant environmental impact, which means, prospects of high rate of recyclable material.
- Respect barriers defining a moderate budget.

a) Why in asphalt mixes

Bitumen is a product of crude oil produced through a refining process. Soft and liquid at high temperatures, viscous and resistant at moderate and deformable/hard to break at low temperatures. On account of its adherence to mineral aggregates, bitumen is used as a binder to produce asphalt mixes. These are the main features, in fact, the advantages, of bitumen and the reasons for using it in the production of asphalt mixes and layers. Likewise, plastics are also products of crude oil. Resistant at ordinary temperatures, they melt at higher ones. It seems that following some melting at high temperature, plastic wastes can stick to mineral aggregates. In fact, incorporation of plastic waste, especially LDPE, in asphalt mixes is more than a mixing process: at high temperatures, chemical reactions between the bitumen and the plastic produce a binder consisting of polymers and exhibiting an improved performance, that is, a modified binder: more resistant at high temperatures, more deformable at low temperatures [11]. Consequently, a strategy for recycling plastic waste in asphalt mixes is expected to produce, besides the obvious environmental benefits, strong and durable asphalt layers and high-performance road pavements.

The beneficial impact on the environment can be even more important, if hard plastic waste (PET, PVC) proves to be suitable to replace a part of mineral aggregates. This is an option which remains, practically, unexplored.

b) Why in road pavements

Road pavements are engineered structures of significant length and volume, which absorb big quantities of raw materials, principally, mineral aggregates and bitumen. If a recycling technique proves to be effective, the environmental effect will be important; the recycling practice will decrease the need for extraction of raw materials and diminish the need for waste disposal landfills.

c) Field of application

Asphalt pavements in the urban network provide the most suitable field of application for recycling plastic waste in road construction. Plastic waste is produced in urban environment and processing plants are mostly located in the peri-urban area.

Since transport cost is never negligible, it is preferable to use plastic waste in urban road pavements.

Moreover, the leaching issue is less serious in the urban environment where runoff water is directed to processing plants before final disposal.

4. Asphalt mixes with plastic flakes instead of aggregates

4.1. Plastic flakes replacing mineral aggregates

Hard plastic waste seems suitable to be introduced in asphalt mixes as an aggregate, replacing a part of mineral aggregates. This can be achieved mainly through a shredding, or, eventually, a granulation process of the waste material, thus creating flakes or granules respectively. This preliminary processing of the waste material is absolutely necessary for any experimental research.

The basic concept is based on the potential tensile strength of plastic particles intended for replacement of mineral aggregates in asphalt mixes. Especially, in countries where the cost of conventional aggregates is high, this prospect seems sustainable and promising.

4.2. Asphalt mixes with plastic flakes and bitumen emulsion

The first experimental attempt to produce asphalt mix using plastic waste consisted of mixing recycled plastic flakes with non-modified binder. Flakes were a relatively low-cost option, their cost ranging about twice the cost of mineral aggregates (by weight). Following an asphalt mix design, the whole mass of conventional aggregates was replaced by PET flakes. Moreover, PET waste was chosen to be introduced in the asphalt mix (**Figure 1**), since it is hard and able to provide resistant asphalt mixes. Flakes were preferred to granules because of their substantially lower cost.

Figure 1. Asphalt mix.

Bitumen emulsion was used as a binder to produce a cold asphalt mix. The idea was to maintain the structure and the form of plastic flakes and prevent the softening risk. The mixing temperature should not reach 70 °C since the glass transition temperature of PET varies from 69 °C to 85 °C. Cationic rapid setting emulsion KE-1 was introduced in the mix, due to its presumed high adhesion to plastics. This method seemed ideal for implementation in the urban environment.

Traditional tests on the PET flakes were conducted in the laboratory. The specific gravity of the plastic material was estimated at 1.38 g/cm^3 while the bulk density of the flakes structure was found 0.35g/cm^3 [12]. The binder content was defined at 5.5%, equal to the lower limit for emulsion mixes because due to its origin, the material could not absorb any bitumen.

At the first set of specimens, the emulsion content was set at 10%, corresponding to approximately 5%–6% of asphalt binder. Mixing was performed in a testing bowl and compaction was achieved by 50 blows. However, the stripping phenomenon was observed during extrusion of specimens. In some specimens, insufficient bonding led to failure (**Figure 1**).

Subsequently, the emulsion content was raised up to 15% and 20% to provide adhesion and consistency. The specimens produced were more consistent but highly deformable, making evidence of poor mixing process and bonding failure.

The tensile strength of the specimens varied from 20 to 35 kPa (**Figure 2**), while the Marshall flow was found equal to 4.5 mm–5.8 mm (acceptable < 4.0 mm [13,14]) and the Marshall stability 2.1 kN–2.8 kN (acceptable > 8.0 kN [13,14]). Test results are shown in **Table 1**.

Table 1. Laboratory tests on asphalt mix specimens with emulsion and recycled plastic flakes.

Characteristics	**Plastic flakes and emulsion**	**Mineral aggregates (MA), plastic flakes (PF) and bitumen 50/70**			
		MA/PF = 100/0	**MA/PF = 75/25**	**MA/PF = 50/50**	**Permissible values**
Binder content (%)	5.5-8.0	4.7	4.7	4.7	>4.0%
Tensile strength (kPa)	20.8-35.0	-	-	-	>500
Stability (kN)	2.1-2.8	13.4-14.3	10.0-11.7	9.0-9.8	>8.0
Voids (%)	>10	3.5-4.6	7.8-8.8	11.0-12.3	3-5
Flow (mm)	4.5-5.8	3.3-5.7	5.1-5.2	6.1-7.2	2.0-3.5
Consistency	Low	High	Fair	Fair	
Mixing temperature (°C)	40	150	155	150	<180

Figure 2. Indirect tensile test.

The testing process of this 1st stage of research, practically, failed and led to the following important conclusions:

- Regardless of the binder content, the consistency and the shear strength of the specimens remain very low, mainly due to insufficient adhesion.
- The shape of flakes had a negative effect on the strength of the mixes.
- Bitumen emulsion is probably inadequate as a binder since the low mixing temperature prohibits softening and reshaping of flakes, which would produce suitable consistency of the mix.

4.3. Asphalt mixes with mineral aggregates, plastic flakes and hot bitumen

The failure of the first stage of experimental research led to a more conservative second stage of experimental research introducing:

- Hot bitumen instead of emulsion as a binder, to soften and reshape plastic flakes and provide better adhesion
- Partial replacement of aggregates. Only the sand fraction was replaced by flakes in volume percentages of 25%, 50%

The initial composition of the aggregate mixture for specimen group M0 (100% mineral aggregates) contained 40% crushed stone, 32% gravel, and 28% sand [12]. The conventional Marshall procedure was followed to produce specimens of 3 different asphalt mixes (0%, 25%, 50% PET waste).

By visual examination, it seemed that specimens containing plastic flakes present a high void ratio and a rougher macro-texture with respect to specimens with mineral aggregates. Moreover, quite reasonably, plastic flake specimens had a low bulk density. These characteristics may lead to the implementation of this type of mixes in porous asphalt layers and in bridge deck surfacings [12]. Results of laboratory testing are shown in **Table 1**.

The experimental procedure of this second stage of research provided more encouraging outcomes. Stability of asphalt mixes decreases as the plastics content increases, but all values recorded are within limits of acceptance.

In sum, findings of the second stage of research, compared to literature data, point at three factors, seriously affecting the performance of the mixes:

a) hot mixes with PET waste perform better than cold ones, due to softening and reshaping of plastic

b) the shape (flakiness) and the micro-texture (sleek) of plastic waste flakes create more voids than granules and produce fewer resistant mixes

c) the percentage of aggregates to be replaced should be limited, probably, defined at 25%.

It seems that the micro-texture of the plastic waste and the lack of adhesiveness is probably the most serious impediment to provide resistant asphalt mixes using PET waste. Use of granules instead of flakes would probably lead to better results, although the issue of texture would remain.

5. Asphalt mixes with an asphalt—ldpe binder

In a frame of a different perspective about recycling plastic waste in asphalt mixes, experimental research introducing LDPE granules in asphalt mix as a bitumen modifier has been carried out. Two different LDPE materials were used in the experiments: white granules (3 mm), product of first cycle of recycling and grey granules (3 mm), product of second cycle of recycling (**Figure 3**). The cost issue remained a priority throughout the overall research on plastic waste. The cost of white granules was estimated at 70% the cost of bitumen and the cost of grey granules was estimated at 50% the cost of pure bitumen. Therefore, replacement of bituminous binder at any percentage would have a positive economic effect on the cost of the final product.

Figure 3. Asphalt mix specimens with LDPE waste.

After a conventional design study, 3 types of asphalt mix specimens with mineral (limestone) aggregates were produced: the ordinary type with 4.4% hot bitumen 50/70, the modified type with white granules replacing 10% of bitumen and the modified type with grey granules replacing also 10% of bitumen. The results of the Marshall and other tests are shown in **Table 2**.

Table 2. Laboratory tests on asphalt mixes with conventional and LDPE modified binder.

Characteristics	**Asphalt mix with mineral aggregates and bitumen 50/70**			
	No plastic waste	**Plastic granules from 1st recycling**	**Plastic granules from 2nd recycling**	**Acceptability limits**
Binder content (%)	4.4	4.5	4.5	>4.0%
Bitumen replacement (%)	0	10	10	-
Mixing temperature (°C)	170	170	170	140-180
Stability (kN)	15.4	18.2	19.4	>8.0
Flow (mm)	3.1	3.1	3.2	2.0-3.5
Water sensitivity (%)	80.7	87.8	90.2	>70

The results of all tests on specimens containing recycled LDPE granules illustrate an excellent performance. It seems that a successful polymerization of the bitumen takes place at mixing temperatures. All characteristics of asphalt mixes improve at the presence of recycled plastic granules. The experimental research on this recycling option should be completed by more tests, especially crack propagation tests, but the first approach is more than encouraging.

6. Conclusion and perspectives

The experimental research on the use of plastic waste in dense asphalt mixes was conducted in line with the affordability and the environment-friendliness of the final product.

The PET waste, a relatively hard material, used in form of flakes, performed better in hot mixes due to the softening and reshaping of the flakes under high temperature. Conversely, in cold mixes with emulsion, asphalt mix specimens containing plastic flakes exhibited a very loose interconnection of particles and low strength.

Hot asphalt mixes with LDPE waste, replacing 10% of bitumen, performed exceptionally well. Marshall tests on stability and flow provided very satisfactory values and highlighted perspectives of further research.

Hot mixes with LDPE waste need further investigation in the direction of long-term performance. Long-term aging tests but also resilient behavior of the mixes containing LDPE waste must be explored.

Undoubtedly, this is a very promising field of research, since, in highway construction projects large quantities of plastic waste can be absorbed. Nevertheless, it is mandatory, with view to prospective application of the waste material in construction projects, to respect economic limitations and to suggest end-products that combine strength and resilience with affordability.

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