Use of Steel Slag and Plastic Wastes in Asphalt Concrete: A Review

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ABSTRACT

The global concern over plastic wastes arises from its detrimental impact on agriculture, marine life and human health. Conversely, discarding steel slag in open environments threatens biodiversity and undermines land fertility. Prior researches indicate the potential use of these materials for pavement. This study reviews the use of steel slag and plastic wastes on asphalt concrete based on previous studies. Based on the reviews, it is advisable to limit slag content to no more than 30% of the total aggregate weight and plastic content to no more than 20% of the bitumen weight. In conclusion, for promising research, it is recommended to substitute stone aggregate with PET (Polyethylene Terephthalate) coated steel slag (using the dry mixing process) combined with bitumen as a binder in AC mixtures.

1. INTRODUCTION

Due to their low cost and durability, plastics exhibit remarkable versatility, leading manufacturers to prefer them over alternative materials for various applications [1]. Yet, the majority of plastics possess a chemical structure that hinders their breakdown through natural processes, causing them to degrade at a slow pace [2]. The impact of deteriorated plastic waste on humans can occur through direct or indirect ingestion, and interference with diverse hormonal mechanisms [3]ubiquitous in nature and therefore affect both wildlife and humans. They have been detected in many marine species, but also in drinking water and in numerous foods, such as salt, honey and marine organisms. Exposure to microplastics can also occur through inhaled air. Data from animal studies have shown that once absorbed, plastic micro- and nanoparticles can distribute to the liver, spleen, heart, lungs, thymus, reproductive organs, kidneys and even the brain (crosses the blood–brain barrier. The proliferation of plastic materials, initially celebrated for their versatility and convenience, has reached a critical juncture where the consequences of their indiscriminate use are glaringly apparent. UNEP (2023) claims that plastic waste was in tamable volume from 1950 to 1970 and increased exponentially in next two decades. Almost 400 million tons per year of waste plastic is being resulted [4]. If historical growth patterns persist, by 2050, the production of plastic is projected to attain 1,100 million tons. Plastic consumption in urban areas of Bangladesh has increased to 9 kg/capita in 2020 from 3 kg/capita in 2005 [5]. Plastic and polythene waste constitute a primary cause of waterlogging in Chittagong, with the city generating 249 tons of such garbage on a daily basis [6].

Improperly disposed waste, accounting for only 2% of the total waste, lacks formal management and involves disposal in landfills and open areas, posing a significant risk of polluting rivers and oceans [7]. Plastic pollution has diverse impacts on various aspects including its effects on the environment, climate change, land, flooding, terrestrial ecosystems, freshwater ecosystems, human health [8]. As plastic waste continues to accumulate at an alarming rate, it has triggered a cascading series of environmental and social repercussions, demanding urgent attention and innovative solutions.

Contrariwise, steel slag (a byproduct of steelmaking) threatens biodiversity and hampers land fertility when dumped in the environment [9]. Almost 7.5 million tons of steel and 40-70 kg slag per ton is being produced per year in Bangladesh [9]. Slags have been used in construction since the 1800s, initially for road and railroad ballast, and later as aggregate and in cement as a geopolymer. [10]. Slags and slag tailings are stored in “slag dumps” where weathering can lead to toxic leaching and hyperalkaline runoff, posing ecological risks, with non-ferrous, ferrous, and ferroalloy slags all potentially contributing to these issues [11], [12].

The dissolution of slags has the potential to generate groundwater with elevated alkalinity, characterized by pH values exceeding 12 [13]. The authors noted that calcium

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silicates in slags react with water, increasing groundwater alkalinity and causing calcite formation from dissolved CO2, potentially creating layers up to 20 cm thick.

Despite their drawbacks, both materials offer promising reuse potential. Researchers from east to west are studying and finding promising results. Waste plastic is being reused in various ways and so steel slag. Angularity, rough texture and hardness of slag assert its rutting resistance and soften plastic assert its binding property at 130°C - 180°C [14]instead of primary (virgin. The author mentioned the potentiality of waste plastic and steel slag as pavement materials. Several studies show better stability, water and thermal susceptibility, less OBC and cost when plastic (PET/HDPE/LDPE/Mixed) coated stone aggregate is used on AC mix [15]–[20]. Plastic coating filles the pores of demolished concrete and lower OBC and permanent deformation [21]. Researches have also been carried out by replacing stone aggregate with steel slag. Optimum slag content have found to be 25% [22] and 30 % [23]. Slag with PET (Polyethylene Terephthalate) and PP (Polypropylene) have been studied and some beneficial properties are found in AC mix [24], [25]. Despite of having many advantages, steel slag has a major disadvantage of consuming more bitumen. This can be improved by coating steel slag by a suitable agent [25], [26]. Despite numerous individual studies, there is a lack of consolidated analysis comparing performance outcomes between steel slag and plastic-modified asphalt mixes. Existing research typically focuses on case-specific experimental conditions, different waste processing methods, and varied proportions of additive materials, making it challenging to draw comprehensive conclusions about their relative effectiveness. This fragmented approach has resulted in a limited understanding of how steel slag and plastic waste respectively influence key performance indicators such as rutting resistance, moisture susceptibility, and overall durability under similar testing conditions. A systematic, comparative evaluation is therefore essential to identify the advantages, limitations, and potential synergies of each modification strategy.

This study aims to explore past studies involving polyethylene as pavement material, whether as a coating agent or a modified agent. The review extends to slag as pavement material, informed by earlier research. In conclusion, PET-coated steel slag is recommended as a potential pavement material.

1.1 Types of Plastic Debris

Plastic waste can be found from different sources with different sizes. Plastic waste can be classified based on their size, form and source. A several types of waste plastics are found based on their sources. They are shown on the Table I below:

Table I: Types of Waste Plastic and their Sources [27]

Type of waste plastic	Source
PET or Polyethylene Terephthalate	Bottles for drinks, water, beverages, and perishable food packaging.
HDPE or High-Density Polyethylene	Bottles for shower gel, shampoo, cleaning products, and children’s toys.
PVC or Polyvinyl Chloride	Piping, windows, different types of medical equipment, plastic wrap and cables.
LDPE or Low-Density Polyethylene	Plastic shopping bags, frozen food bags, and squeezable bottles.
PP or Polypropylene	Plastic containers, hot food containers, plastic straws, and medicine bottles.
PS or Polystyrene	Packaging protection, insulation, and use in cups and egg cartons.
Other Plastics	Sunglasses, baby bottles, and even CDs.

1.2 Technical Specification of Slag Chips

Slag is a byproduct of the process of manufacturing steel and serves as an exceptionally versatile construction material. BSRM Slag Chips are an environmentally friendly product that possesses comparable strength to brick chips [28]. The technical specification of slag chips is given in table II.

Table II: Technical Specification of Slag Chips [28]

Category	Slag Chips	Brick Chips
Water Absorption Capacity	1.5% – 2%	11% - 13%
California Bearing Ratio (CBR)	115% – 130%	48% - 57%
Aggregated Crushing Value (ACV)	40% – 45%	28% - 35%
10% Fines Value (TFV)	75kN – 80 kN	69kN – 100kN

1.3 Improvement of AC Mix

The enhancement of the quality of various asphalt concrete (AC) mixes can be achieved through the implementation of two distinct methods [29]the increased asphalt consumption and decreased mechanical properties induced by the incorporation of RCA limit the extensive substitution of natural aggregates with RCA in HMA. In this paper, an experimental program was carried out to investigate the potential of recycled concrete aggregate pretreated with waste cooking oil residue (WCOR:

i. Physical Strengthening - Eliminating attached components by subjecting them to heat and immersing them in acidic solutions.
ii. Chemical Strengthening - Enhancing quality through the application of various coatings using different materials.

Numerous studies have been undertaken to introduce novel materials into asphalt concrete mixes, aiming to improve both the overall quality and the effective management of waste. Slag has been studied for a long time [22], [23], [30]. Different additives have also been used to enhance binding quality. Amuchi et al. [25] used PP, LDPE has been used by [31]Indonesia is facing pavement problem due to various reasons, so it needs to improve the pavement quality and performance. The addition of plastic waste to the hot mix asphalt (HMA.

1.4 Mixing Process of Additives

Additives can be blended into asphalt mixtures using two distinct methods [15]. These additives can serve either as a coating agent or as a modifier for bitumen. The two procedures are outlined below:

- Dry Process of Mixing
- Wet Process of Mixing

1.4.1 Dry Process of Mixing

Modak and Belkhode [15] explained the procedure in this way: First, the mixture of aggregates is heated to 170°C before being moved to the mixing chamber. At the same time, bitumen is heated to a maximum of 160°C. In the mixing chamber, shredded plastic waste is added to the hot aggregates. The aggregates coated with plastic waste are then mixed with the heated bitumen. The process is shown in Fig. 1.

1.4.2 Wet Process of Mixing

The additive (E. g. plastic waste) is ground into a powder, combined with bitumen and subsequently mixed with the aggregate. Basically, bitumen is modified by an agent and then mixed with hot aggregate. The process is shown in Fig. 2.

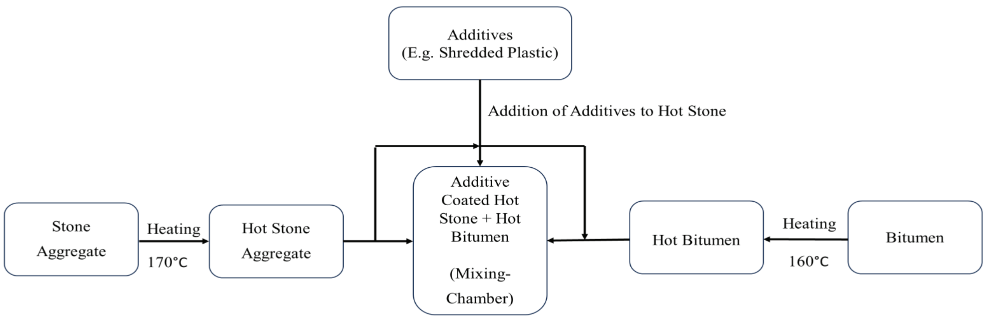

Fig. 1: Dry Process of Mixing

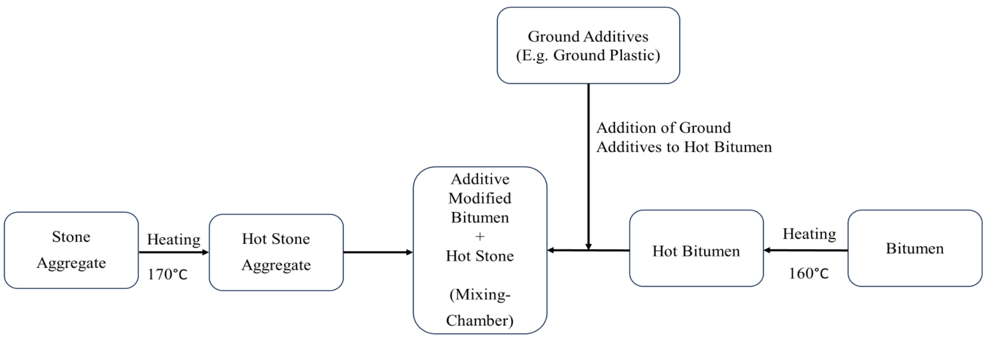

Fig. 2: Wet Process of Mixing

1.5 Approach to the Study

This study is based on a systematic review of 55 peer-reviewed articles published between 2000 and 2023. From well-known academic databases including Web of Science, Google Scholar, and Scopus, pertinent literature was found and gathered. The main emphasis was on experimental research that looked into adding steel slag and/or plastic trash to asphalt concrete mixtures. The types of waste materials employed, inclusion techniques, mix design parameters, testing procedures, and the ensuing impacts on the mechanical and durability qualities of asphalt concrete were all examined in the chosen research. This method made it possible to conduct a thorough evaluation of the field's knowledge gaps, technical developments, and current research trends.

2. LITERATURE REVIEW

Waste plastic and steel slag have long been explored as pavement materials. Several researchers [22], [23] studied AC mix by substituting stone in different percentages keeping fresh bitumen as binder. Some of them [19], [20] used waste plastic either in dry or in wet process combined with stone and bitumen. Some studies [25], [32] have also been conducted combining stone, slag, waste plastic and bitumen. Based on the materials used this portion is divided into four segments.

i. Stone - Slag - Bitumen
ii. Stone - Bitumen - Plastic Waste (PW)
iii. Stone - Slag - Bitumen – PW
iv. Other Aggregates - Bitumen – Wastes

2.1 Stone - Slag – Bitumen

Asi et al. (2007) initially evaluated the toxicity, chemical, and physical properties of steel slag. They then replaced varying percentages (0%, 25%, 50%, 75%, and 100%) of limestone coarse aggregate in asphalt concrete (AC) with steel slag aggregate (SSA). The effectiveness of SSA was assessed by improvements in AC samples' indirect tensile strength, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance. The chemical and toxicity assessments confirmed that steel slag meets safety standards for highway construction. Results showed that replacing up to 75% of limestone with SSA enhanced AC properties, though 100% slag reduced creep performance, with 25% being the optimal replacement level [22].

Ahmedzade & Sengoz (2009) investigated how steel slag affects hot mix asphalt properties. They used four asphalt mixtures with two types of asphalt cement (AC-5 and AC-10) and two coarse aggregates (limestone and steel slag) to create Marshall specimens for optimal bitumen content. Mechanical properties were tested, including Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength, along with electrical sensitivity. Results showed that using steel slag as a coarse aggregate increased stability, stiffness, and conductivity while decreasing flow values, leading to higher stiffness and resistance to deformation in the mixtures [30].

A practical on field experiment was observed by Liz Hunt (2012) replacing stone by 30 % of steel slag. An examination of in-place characteristics, field observations, skid testing, and ride testing reveals no discernible performance distinctions between the control and steel slag pavements. Both types of pavements seem to be functioning well. Although minor raveling was observed in both sections, it is not deemed a critical issue. Ongoing monitoring will be conducted to detect any potential changes in pavement performance. But slag pavement was found to be more cost efficient [23].

Ezemenike et al. (2022) explored using alternative materials, specifically waste by-products, to improve pavement properties. They tested cylindrical samples of asphalt concrete with varying amounts of steel slag (SS) replacing traditional aggregates at 2%, 4%, 6%, and 8%. The findings show that steel slag can effectively replace aggregates, enhancing mixture properties. For medium traffic roads, a 2% SS replacement achieved a stability value of 7.75 kN, while values of 8.63 kN, 9.82 kN, and 11.00 kN at 4%, 6%, and 8% SS replacements, respectively, are suitable for heavy traffic roads according to the Asphalt Institute's standards. Thus, using steel slag can significantly decrease the need for natural aggregates and lessen the pressure on these resources [33].

Chen and Wei (2016)a test road was constructed in 2012 by using three different types of asphalt mixtures as follows: stone mastic asphalt with BOF (SMA-BOF studied asphalt mixtures using basic oxygen furnace (BOF) steel slag as coarse aggregate. Laboratory tests evaluated the asphalt concrete's engineering properties. A 2012 test road featured three asphalt mixtures: stone mastic asphalt with BOF (SMA-BOF), dense-graded asphalt concrete with BOF (DGAC-BOF), and dense-graded asphalt concrete with natural aggregate (DGAC-NA). Despite heavy vehicle stress, the SMA-BOF section showed the least rutting. Both BOF mixtures performed similarly or better than the natural aggregate section in ride quality and friction. BOF steel slag met highway agency specifications and potentially enhanced asphalt mixture properties [34]a test road was constructed in 2012 by using three different types of asphalt mixtures as follows: stone mastic asphalt with BOF (SMA-BOF.

According to Shatnawi et al. (2008) research, steel slag sourced from a Jordanian steel factory was employed in Asphalt Concrete Hot Mixes (ACHM). Control specimens were created with 100% limestone dense-graded aggregates at varying bitumen contents (4.5%, 5%, 5.5%, and 6% by weight of aggregate). Another set of Marshall Specimens was prepared using full Steel Slag Aggregates (SSA), a third set involved combination of limestone and SSA, all maintaining the same grading and bitumen contents. The research observed a potential reduction in the optimum bitumen content (OBC) value and enhanced performance of asphalt concrete when employing SSA in. The study recommends that producers and users of asphalt concrete hot mixes (ACHM) in Jordan consider incorporating SSA for improved performance [35].

Ameri et al. (2013) evaluated the use of electric arc furnace (EAF) steel slag (SS) as a substitute for natural limestone (LS) in warm mix asphalt (WMA) and hot mix asphalt (HMA) mixtures. SS was used as both fine and coarse aggregate in HMA blends and as coarse aggregate in WMA. The Marshall test results showed that substituting coarse LS with SS improved Marshall stability, flow, and the MQ parameter in HMA mixtures [36].

Nguyen et al. (2018)a by-product of steelwork industry, under Vietnamese's law, was considered as a deleterious solid waste which needed to be processed and landfilled. However, this has changed recently, and steel slag is now seen as a normal or non-deleterious solid waste, and has been studied for reuse in the construction industry. In this study, steel slag was used, as a replacement for mineral aggregate, in hot mix asphalt. Two hot mix asphalt mixtures with an equivalent nominal aggregate size of 12.5 (C12.5 investigated using steel slag as a replacement for mineral aggregate in hot mix asphalt. They created two asphalt mixtures with steel slag, one with a nominal aggregate size of 12.5 mm and another with 19 mm, and compared them to a conventional mixture of 19 mm mineral aggregate. Steel slag showed comparable physical properties to mineral aggregate, despite being heavier, and demonstrated good water stability. The steel slag mixtures met Vietnamese standards for Marshall Stability and flow, and both sizes exhibited adequate skid resistance, making them suitable for surface courses [37] a by-product of steelwork industry, under Vietnamese's law, was considered as a deleterious solid waste which needed to be processed and landfilled. However, this has changed recently, and steel slag is now seen as a normal or non-deleterious solid waste, and has been studied for reuse in the construction industry. In this study, steel slag was used, as a replacement for mineral aggregate, in hot mix asphalt. Two hot mix asphalt mixtures with an equivalent nominal aggregate size of 12.5 (C12.5.

H M (2014) conducted a study to examine the impact of incorporating iron slag powder into hot mix asphalt on Marshall Stiffness and indirect tensile strength. Three different hot mix asphalt compositions were investigated, each containing varying percentages of iron slag (0%, 10%, and 20% by weight of the total mixture). The test results demonstrated enhancements in both Marshall stability and indirect tensile strength when iron slag powder was included as part of the fine aggregate in the mixtures. Across the range of iron slag content tested (0% to 20% of the total mixture), both Marshall stability and indirect tensile strength exhibited a positive correlation with increasing iron slag content. Additionally, it was observed that other Marshall properties such as density, air voids, and VMA also increased with higher iron slag contents [38].

Sridhar & Sastri (2021) assessed Steel Slag Aggregate (SSA) for use in Hot Mix Asphalt (HMA) and flexible pavements, aiming to reduce reliance on natural resources. They prepared four HMA mixes with increasing SSA content from 25% to 75% of natural aggregates. SSA improved mix density and stability, enhancing resistance to deformation. The Marshall Stability Test showed the optimum bitumen content increased from 5.2% with natural aggregates to 5.7% with 75% SSA. Using steel slag not only boosts asphalt quality but also supports environmental conservation by decreasing the need for natural aggregates [39]. Table III shows the summary of Stone – Slag – Bitumen. Here Optimum Steel Slag Content and Optimum Bitumen Content are abbreviated by OSC and OBC.

Several studies have explored the replacement of conventional stone with steel slag in proportions ranging from 0% to 100%. The optimum slag content was found to be around 25%. Findings indicate that slag can be used in both coarse and fine aggregates. Its inclusion improves various properties of Hot Mix Asphalt (HMA), such as stability and creep resistance, while also reducing overall costs.

Table III: Summary of Stone - Slag – Bitumen

Reference	Stone %	Slag %	Major Findings
[22]	100−0	0−100	OSC = 25%; slag improved mechanical properties; reduced creep
[30]	100, 65	0, 35	High stability and strength; low flow
[23]	100, 70	0, 30	Satisfactory quality; cost-effective
[33]	98−92	2−8	Marshal stability increased up to 8% SS replacement
[34]	Not Specified	Not Specified	Improved engineering properties
[35]	100−0	0−100	SSA lowered asphalt mix OBC
[36]	FA, CA, 0	CA, FA, Both	SS improved Marshall properties in HMA mixtures
[37]	100, 0	0, 100	Steel slag HMA met Vietnam standards
[38]	100−80	0−20	Iron slag improved stability and strength
[39]	75−25	25−75	OBC increased from 5.2% to 5.7%

2.2 Stone - Bitumen - Plastic Waste (PW)

PET, ranging from 0 to 10% by the weight of 80/100 grade bitumen, has been incorporated into Stone Mastic Asphalt (SMA) through a dry process additive addition by Ahmadinia et al.(2012). Utilizing 4-6% PET demonstrates reduced drain down of binder, heightened resistance against permanent deformation, and increased stiffness. This method enables the eco-friendly and economical reuse of waste materials [18].

Awwad and Shbeeb (2007) used HDPE and LDPE polyethylene to coat aggregates in either grinded or not grinded forms. They prepared 105 samples, with 21 for binder content determination and the rest for studying asphalt modification. The optimum binder content was 5.4%. Seven weight percentages of each polyethylene type (6%-18%) were tested. The best results were achieved with 12% ground HDPE, leading to higher stability, lower density, and a slight increase in voids. The asphalt mix with grinded HDPE showed the highest stability (2347 kg), outperforming the not grinded variant [20].

Musa (2014) gathered, cleaned, shredded, and then blended low-density polyethylene (LDPE) carry bags discarded from supermarkets with asphalt hot mix at a temperature of 150°C in the Roads. The alterations in marshal stability, flow, and voids resulting from the inclusion of low-density polyethylene carry bag waste (at concentrations of 4 %, 6 %, 8 %, 10 %, 12 %, 14 %, 16 %, and 18 % of the asphalt weight) were assessed. The findings revealed enhancements in the properties of asphalt hot mix design, particularly when a 10 % concentration of low-density polyethylene waste, relative to the asphalt weight, was utilized, thereby contributing to an improvement in environmental pollution [19].

Suaryana et al. (2018)Indonesia is facing pavement problem due to various reasons, so it needs to improve the pavement quality and performance. The addition of plastic waste to the hot mix asphalt (HMA developed three Asphalt Concrete Wearing Course (AC-WC) mixtures with 0%, 5%, and 10% LDPE plastic waste. Tests showed that adding plastic improved Marshall stability, resilient modulus, and resistance to stripping, moisture, and rutting. While moderate plastic content boosts fatigue life and raveling resistance, too much plastic reduces these benefits compared to traditional HMA [31]Indonesia is facing pavement problem due to various reasons, so it needs to improve the pavement quality and performance. The addition of plastic waste to the hot mix asphalt (HMA.

Sojobi et al. (2016) used PET as an additive in HMA by both wet and dry process. The plastic content was adjusted across different proportions, including 0% as a control, 5%, 10%, and 20% for polymer-modified bituminous (PMB) asphaltic concrete, and 10%, 20%, and 30% for polymer-coated asphaltic (PCA) mix. It was found to be eco-friendly and more benefitable in terms of stability. Optimum plastic waste content (OPC) was observed to be 16.7 % by weight of total aggregate. The use of PCA-modified AC mix maximizes PET recycling, achieving a higher optimal plastic content of 16.7%, in contrast to the 9% optimal plastic content achieved with PMB-modified. [17].

Plastic waste, including items like cups and bags made from PE, PP, and PS, was processed through a shredding machine to achieve a size range between 2.36 mm and 4.75 mm to mix with HMA by dry process. When these plastics coat the aggregates, Mir (2015) observed that it enhances the surface properties of the aggregates. This coating results in a doubling of the binding property of the aggregates and an increase in their overall strength. Remarkably, roads constructed with this method exhibit no degradation even after several years. Additionally, there is a reduction in the required bitumen by approximately 10 %, allowing for the utilization of waste plastic exceeding 15 %. The cost difference for roads constructed with this compound, as opposed to without it, amounts to Rs. 500 per cubic meter [16].

Modak and Belkhode (2022) incorporated plastic waste ranging from 2.36 mm to 4.75 mm into bitumen at varying percentages (8%, 10%, 12%, and 20%). The resulting mixture exhibited increased Marshall Stability values and an appropriate Marshall Coefficient. Consequently, utilizing waste plastics in pavement construction emerges as a highly effective approach for the convenient disposal of plastic waste [15].

Jegatheesan et al. (2018) explored adding PET fibers to Hot Mix Asphalt Concrete (HMAC) to reduce costs. PET fibers (0.5 mm in diameter and 4.0-6.0 mm in length) were mixed into HMAC using a wet process in varying amounts (5%-40% of bitumen weight). The study found that PET fibers significantly improve Marshall stability and bulk properties, with stability peaking at 30% PET content and Marshall flow increasing with fiber addition [40].

Baghaee Moghaddam et al. (2014) aimed to assess the impact of incorporating waste Polyethylene Terephthalate (PET) as a modifier on the characteristics of asphalt mixtures. In a dry process, post-consumer PET bottles with a size of 2.36 mm and below were utilized in varying quantities ranging from 0% to 1% by weight of mixed aggregates. The bulk specific gravity and stiffness of the asphalt mixture initially increase with lower amounts of PET, but decrease with higher PET contents. The application of PET leads to a reduction in Marshall Quotient and indirect tensile strength values, with higher amounts of PET resulting in lower values for both Marshall Quotient and tensile strength [41].

Hassani et al. (2005)more than 1 million m3 landfill space is needed for disposal every year. The purpose of this experimental study was to investigate the possibility of using PET waste in asphalt concrete mixes as aggregate replacement (Plastiphalt examined the use of PET waste in asphalt concrete, called “Plastiphalt,” to reduce environmental impact. PET granules (3 mm in diameter) replaced 20%-60% of coarse aggregates (2.36–4.75 mm) in the mix through a dry process. The study found that replacing 5% of aggregate with PET improved Marshall quotient, lowered flow, and minimized stability reduction, offering economic and environmental benefits. Using Plastiphalt could save 625 tons of natural resources and use 315 tons of PET, making it a viable option for pavements and bridge overlays [42]more than 1 million m3 landfill space is needed for disposal every year. The purpose of this experimental study was to investigate the possibility of using PET waste in asphalt concrete mixes as aggregate replacement (Plastiphalt.

Zoorob and Suparma (2000)predominantly composed of low density polyethylene (LDPE studied adding recycled LDPE pellets to dense bituminous mixes, replacing 30% of aggregates (5.00-2.36 mm). This substitution reduced mix density by 16%, lowering haulage costs. It also led to a 250% increase in Marshall stability and improved resistance to deformation. While the mix’s stiffness was lower than the control, its tensile strength was significantly higher [43]predominantly composed of low density polyethylene (LDPE.

Punith and Veeraragavan (2007) investigated using reclaimed low-density polyethylene (PE) from household carry bags as an additive in asphalt mixtures. They tested PE in various amounts (2.5%-10% by asphalt weight) with 80/100-grade asphalt. Results showed that PE-modified mixtures had less plastic deformation, higher shear resistance, and improved tensile strength at low temperatures, reducing pavement cracking risks. This approach effectively repurposes LDPE bags at a reasonable cost while enhancing asphalt properties [44].

Hinislioglu and Agar (2004) studied using HDPE plastic waste as an additive in asphalt concrete. They blended HDPE (4%-8% of bitumen weight) with AC-20 at 145-165°C for 5-30 minutes. HDPE-modified asphalt showed improved Marshall Stability and resistance to deformation. The best results came from mixing 4% HDPE at 165°C for 30 minutes, yielding the highest stability and Marshall Quotient, indicating stronger mixes than the control [45].

Attaelmanan et al. (2011) investigated using HDPE as an asphalt modifier. They tested 1%, 3%, 5%, and 7% HDPE with 80/100 grade asphalt. Adding 5% HDPE increased the Marshall Quotient by 55%, indicating better resistance to deformation. HDPE-modified asphalt showed high tensile strength and durability, making it suitable for military airfields and flexible pavements [46].

Ahmadinia et al. (2011) investigated using PET plastic bottles in stone mastic asphalt (SMA). Various PET percentages (0%-10%) were added, and the mixtures were tested for their properties. Results showed that PET initially improved Marshall Stability, peaking at 6%, but then decreased. Marshall Flow dropped initially and then increased with more PET. PET improved mix stiffness, resulting in a higher Marshall Quotient and better deformation resistance, with properties meeting standards [47].

Panda & Mazumdar, (2002 employed reclaimed polyethylene (PE) derived from LDPE carry bags to modify asphalt cement in his study. LDPE carry bags with dimensions of 3 mm by 3 mm were utilized at proportions of 2.5%, 5.0%, 7.5%, and 10% by weight of bitumen through a wet process. After evaluating the properties of both the modified binders and the mixes, it was determined that the optimal quantity of reclaimed polyethylene by weight of the binder was 2.5%. Under specific temperature and stress conditions, polymer modification resulted in an increase in the resilient modulus and fatigue life of the mixes. Furthermore, the modification contributed to an enhancement in resistance to moisture susceptibility [48]. Table IV shows the summary of Stone - Bitumen - Plastic Waste (PW). Here Optimum Plastic Content, Optimum Steel Slag Content and Optimum Bitumen Content are abbreviated by OPC, OSC and OBC. In addition, PW (Plastic Waste) % is shown by weight of bitumen.

Various types of plastic waste, including PET, HDPE, LDPE, PE, PP, and PS, have been incorporated into HMA using both dry and wet processes. While some studies used plastic waste up to 60%, the optimal range was typically 4-16%. Most plastics used were in the size range of 2.36-4.75 mm. The inclusion of plastic waste enhanced several mechanical properties such as stability, Marshall Quotient, tensile strength, rutting resistance, and stiffness-alongside offering cost savings and environmentally friendly benefits.

Table IV: Summary of Stone - Bitumen - Plastic Waste

Ref.	PW Type	PW %	PW size (mm)	Process	Major Findings
[18]	PET	0−10	2−3	Dry	OPC = 4−6 %; Resist rutting; Increase stiffness
[20]	HDPE, LDPE	6−18		Dry	OBC = 5.4%; OPC = 12%; HDPE modifier achieved highest stability
[19]	LDPE	4−18		Wet	OPC = 10 %; High stability; Minimum VFA; Improved environment.
[31]	LDPE	0−10	0.6 – 9.5	Dry	LDPE enhances asphalt properties
[17]	PET	Wet: 5 − 20 Dry: 10 − 30		Wet & Dry	Eco friendly solution; OPC = 16.7%
[16]	PE, PP, and PS	6 - 8	2.36 – 4.75	Dry	Enhanced binding property; OPC = 15%; Rs. 500 savings per cum.
[15]	PW	8 − 20	2.36 – 4.75	Wet	Improved Marshall mix
[40]	PET fibers	5−40	4−6	Wet	PET boosted asphalt properties
[41]	PET	0−1.0	2.36	Dry	PET decreased Marshall Quotient and tensile strength
[42]	PET	20−60	2.36–4.75	Dry	PET reduced stability; increased flow
[43]	LDPE		2.36−5	Dry	LDPE reduced density; boosted strength
[44]	LDPE	2.5−10	2	Wet	5% PE improved asphalt performance
[45]	HDPE	4 – 6 and 8	0.935 g/c^3.	Wet	HDPE boosted asphalt strength
[46]	HDPE	1−7	solid form	Wet	HDPE increased softening point and strength
[47]	PET	0−10		Dry	PET initially increased stability, then decreased; flow decreased, then increased
[48]	LDPE carry bags	2.5−10	3	Wet	Marshall mix meets IRC criteria; optimum quantity of reclaimed polyethylene = 2.5%

2.3 Stone - Slag - Bitumen – PW

Rajabi (2022) assessed the impact on pavement performance combining steel slag and recycled polyethylene in various proportions. The study involved conducting resilience modulus tests, Marshall Resistance tests, dry and wet indirect traction tests, and moisture sensitivity tests. Both dry and wet ITS, MR, water susceptibility showed better value in increase in slag content. rPET influenced in dry but a little in wet ITS and lowered down water susceptibility. The findings also indicated that utilizing a blend of both materials in the mix yielded superior results compared to employing each material separately [32].

Amuchi et al. (2015) studied modified SSAC (Steel Slag Asphalt Concrete) samples using three different lengths of PP fibers—6 mm, 12 mm, and 19 mm—at varying mass percentages of 2 %, 4 %, and 6 %, relative to the total weight of bitumen. The inclusion of 2% - 19 mm PP fibers results in a reduction of approximately 15% in the optimized asphalt content when compared to the neat mixture steel slag asphalt concrete. Furthermore, there is an increase in both indirect tensile strength and resilient modulus (MR) [25].

Hasban et al. (2022) tested Marshall specimens with bitumen content between 4.0% and 5.0% by weight to find the ideal amount. The specimens included various percentages of P.E.T. (0%, 4%, 6%, 8%, 10%) relative to bitumen weight and steel slag aggregate at 5%, 10%, and 15%. They assessed parameters such as Marshall Stability, Flow value, Marshall Quotient, Air voids (Vv), Voids in Mineral Aggregates (VMA), Voids Filled with Bitumen (VFB), and Retained Stability using the wet process and compared these with standard bituminous mixes. The results showed significantly higher Marshall Test values for modified mixes compared to conventional ones. The optimal bitumen content was found to be 4.5%. Utilizing up to 8% plastic and 15% steel slag can be beneficial and reduce overall road construction costs [24]. Table V shows the summary of Stone - Slag - Bitumen - PW. Here Optimum Plastic Content, Optimum Steel Slag Content and Optimum Bitumen Content are abbreviated by OPC, OSC and OBC. In addition, PW (Plastic Waste) % is shown by weight of bitumen.

Different plastic wastes like PET and PP were used up to 15% by wet mixing, with the optimum plastic content found to be around 8% and optimum slag content at 15%. The simultaneous inclusion of slag and plastic in HMA contributed to reduced optimum bitumen content and enhanced cost-effectiveness.

Table V: Summary of Stone - Slag - Bitumen – PW

Ref.	Slag %	PW Type	PW%	PW size	Process	Major Findings
[32]	0-100	rPET	0−15		Wet	Slag and rPET improved all the properties
[25]		PP	2−6	6, 12, 19	Wet	OPC = 2%; Optimum size = 19 mm; 15% reduction of OBC
[24]	5-15	PET	0−10		Wet	OBC = 4.5%; OPC= 8%; OSC = 15%; Cost efficiency

2.4 Other Aggregates - Bitumen – Wastes

Ma et al. (2019) investigated using recycled concrete aggregate (RCA) treated with waste cooking oil residue (WCOR) to lower asphalt use and enhance Hot Mix Asphalt (HMA) performance. Their lab analysis involved HMA with 40% coarse RCA and 20% fine RCA treated with WCOR. Results showed that treating RCA with WCOR reduced the optimum asphalt content from 5.4% to 4.5% for 40% coarse RCA and from 5% to 4.5% for 20% fine RCA. This treatment improved the fatigue life and low-temperature performance of HMA but slightly affected moisture sensitivity, resistance to permanent deformation, and dynamic modulus [29]the increased asphalt consumption and decreased mechanical properties induced by the incorporation of RCA limit the extensive substitution of natural aggregates with RCA in HMA. In this paper, an experimental program was carried out to investigate the potential of recycled concrete aggregate pretreated with waste cooking oil residue (WCOR.

Azarhoosh et al. (2021) tested CRCA (Coarse Recycled Concrete Aggregate) surfaces coated with waste plastic bottles (WPB) at 15%, 30%, and 50% to evaluate their rutting resistance in hot mix asphalts. Results showed that untreated CRCA reduced both the Marshall quotient and rutting resistance, increasing permanent deformation. In contrast, treated CRCA with WPB reduced permanent deformation by enhancing CRCA stability through void filling and cement mortar reinforcement. Elevated temperatures lowered the stiffness modulus of all asphalt concretes, with a more significant decrease in the modified specimens [21].

Using waste materials in pavement can reduce waste, environmental pollution, and costs. Arabani & Azarhoosh (2012) tested six asphalt mixtures with different aggregates (dacite, recycled concrete, steel slag) to find the best asphalt binder content. Replacing coarse dacite with recycled concrete aggregates (RCA) worsened mechanical properties due to weak cement mortar removal. However, using RCA as fine aggregate and steel slag as either fine or coarse aggregate improved Marshall stability and reduced flow. The optimal mix was RCA as fine aggregate, steel slag as coarse aggregate, and dacite as filler, which showed strong mechanical properties [49].

Paranavithana and Mohajerani (2006) studied the use of Recycled Concrete Aggregates (RCA) in asphalt concrete. They compared control mixes with fresh basalt aggregates and varying bitumen percentages (5.0%, 5.5%, 6.0%) to modified mixes with RCA and different bitumen contents (5.1%, 5.5%, 6.0%, 6.5%). Results showed that RCA-containing asphalt had lower bulk density, voids in mineral aggregates, and film thickness, but higher air voids compared to the control mix. This was due to the porous, low-density cement mortar on RCA particles, which increased water absorption and decreased particle density [50].

Mills-Beale and You (2010)pressing demand on existing landfill sites, rising dumping fees, and reduced emissions into the environment. Recycled Concrete Aggregates (RCA evaluated the mechanical properties of asphalt mixtures with recycled concrete aggregates (RCA) for low-volume roads. RCA replaced Michigan traprock aggregates in hot mix asphalt (HMA) at 25%, 35%, 50%, and 75% substitution rates. The VA-RCA HMA met SuperpaveTM performance standards and proved effective for low-traffic roads. Temperature had a greater effect on the resilient modulus than RCA levels, and the dynamic modulus increased as RCA content decreased [51]pressing demand on existing landfill sites, rising dumping fees, and reduced emissions into the environment. Recycled Concrete Aggregates (RCA.

Arabani et al. (2017) examined how waste materials as fillers affect hot mix asphalt (HMA) performance. They tested mixtures with waste glass powder (WGP), waste brick powder (WBP), rice husk ash (RHA), and stone dust (control) to find the optimal asphalt binder content. Tests showed WGP had the highest stability and lowest flow, followed by WBP, stone dust, and RHA. Mixtures with these fillers had progressively lower air voids. The study suggests that these waste materials could be useful in road construction due to environmental and resource concerns [52].

Gautam et al. (2018) investigated using limestone mining waste (Kota stone) as aggregates in bituminous concrete (BC) and dense bituminous macadam (DBM), replacing traditional basalt aggregates. They tested ten mix combinations with LSA replacing 0% to 100% of conventional aggregates, assessing strength, durability, moisture resistance, and rutting resistance. The Marshall mix design method, with 75 blows per side, showed that all LSA mixes met the criteria for low-volume roads. However, increasing LSA content led to lower stability and higher flow values, reducing the Marshall Quotient [53].

Arabani et al. (2013) studied hot mix asphalt concrete using dacite and recycled concrete aggregates (RCA). They tested RCA as a partial or full replacement for dacite in coarse aggregate (CA), fine aggregate (FA), and filler. RCA as CA worsened mechanical properties due to particle breakage and weak cement mortar disruption. The best mix used RCA as FA, with dacite as CA and filler. Although RCA increased CaOH levels, raising environmental concerns, using RCA as fines and filler improved Marshall Stability [54].

Haritonovs and Tihonovs (2014)where local crushed dolomite and sandstone do not fulfill the requirements for mineral aggregate in high and medium intensity asphalt pavements roads. Annually 100–200 thousand tons of steel slag aggregates are produced in Latvia. However, it has not been used extensively in asphalt pavement despite of its high performance characteristics. Dolomite sand waste, which is a byproduct of crushed dolomite production, is another widely available polydisperse by-product in Latvia. Its quantity has reached a million of tons and is rapidly increasing. This huge quantity of technological waste needs to be recycled with maximum efficiency. Various combinations of steel slag, dolomite sand waste and conventional aggregates were used to develop asphalt concrete AC 11 mixtures. The mix properties tests include resistance to permanent deformations (wheel tracking test, dynamic creep test investigated using dolomite sand waste as filler or sand and blast furnace steel slag as aggregate in high-performance asphalt concrete. They created AC 11 mixtures with various combinations of these materials and traditional aggregates, testing them for resistance to permanent deformations and fatigue. Results showed that mixtures with steel slag and limestone in the coarse aggregate, and dolomite sand waste in the sand

and filler, had strong resistance to plastic deformations and fatigue failure [55]where local crushed dolomite and sandstone do not fulfill the requirements for mineral aggregate in high and medium intensity asphalt pavements roads. Annually 100–200 thousand tons of steel slag aggregates are produced in Latvia. However, it has not been used extensively in asphalt pavement despite of its high performance characteristics. Dolomite sand waste, which is a byproduct of crushed dolomite production, is another widely available polydisperse by-product in Latvia. Its quantity has reached a million of tons and is rapidly increasing. This huge quantity of technological waste needs to be recycled with maximum efficiency. Various combinations of steel slag, dolomite sand waste and conventional aggregates were used to develop asphalt concrete AC 11 mixtures. The mix properties tests include resistance to permanent deformations (wheel tracking test, dynamic creep test. Table VI shows the summary of Other Aggregates - Bitumen - Wastes.

Unconventional aggregates such as recycled concrete aggregate (RCA), along with various waste materials like plastic bottles, waste cooking oil residue (WCOR), waste glass powder (WGP), waste brick powder (WBP), rice husk ash (RHA), and stone dust, were introduced in HMA primarily through the dry mixing process. These inclusions generally led to a reduction in optimum bitumen content (OBC), improved fatigue life, and lower mix density. However, some materials like RCA raised environmental concerns due to increased calcium hydroxide (CaOH) content.

Table VI: Summary of Other Aggregates - Bitumen – Wastes

Ref.	Aggregate With % used	Waste Type	Process	Major Findings
[29]	RCA	WCOR	Dry	OBC decreased; improved fatigue life
[21]	Stone and CRCA (0−50)	PET	Dry	Treated CRCA improved performance
[50]	Stone and RCA			RCA reduced mix density, voids, voids filled with binder, and film thickness.
[51]	Stone and RCA (25−75)			RCA reduced mix stiffness
[52]	Stone, WGP, WBP, RHA			WGP showed highest stability value as compared to WBP, SD, and RHA
[53]	Stone and LSA (0−100)			Declining stability, increasing flow with LSA
[54]	Dacite Stone and RCA			RCA increased CaOH, causing environmental concerns.

3. CONCLUSIONS

After reviewing the literatures, these key factors can be concluded:

- Both steel slag and waste plastic demonstrate their suitability for use in AC mixtures.
- Waste plastic can be applied in both dry and wet processes, meaning it can be used to coat aggregates and modify bitumen.
- When utilized as a coating agent, plastic waste exhibits superior results compared to its role in modifying bitumen.
- Based on the optimal findings for slag and plastic content, it is advisable to limit slag content to no more than 30% of the total aggregate weight and plastic content to no more than 20% of the bitumen weight.
- Among plastic types, PET and HDPE show greater potential.
- In conclusion, for promising research, it is recommended to substitute stone aggregate with PET-coated steel slag (using the dry mixing process) combined with bitumen as a binder in AC mixtures.
- PET-coated steel slag is expected to reduce the optimum bitumen content and overall costs, while enhancing Marshall properties. It also presents an environmentally friendly solution.
- Large-scale field testing for the inclusion of steel slag and plastic waste in HMA has yet to be conducted.

- ❖ Life-cycle environmental impact (LCA) analysis and assessments under extreme weather conditions could be valuable areas for future research.
- ❖ The adoption of waste plastic and steel slag in public infrastructure can significantly reduce the environmental impact associated with these materials.

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