Investigating Top-Down Cracking of Pavement in Recycled Waste Plastic Asphalt

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Abstract. This study investigates a new approach for the use of an alternative sustainable wearing course material on flexible pavement roads (recycled asphalt plastic pavement). Highway infrastructure plays a major key role in the domestic transportation of people, goods and services within the community and from a national perspective. Thus, highway infrastructure provides provincial and local accessibility, which promotes the growth and development of the economy. For this reason, there is a need to develop a sustainable approach to increase the efficiency of transportation infrastructure. The purpose of this study was to evaluate top-down fatigue cracking failure mode of asphaltic wearing courses for use in in pavement overlays, at high traffic intersection points and on parking sections using dual tire loads in finite element analysis. The process of developing alternative mixing materials is initiated by the need to provide a stable mixture for use on field sections different from cold mix or conventional hot mix (HMA) materials, which is subjected to stripping delamination mode with increasing moisture content. In this study, it was observed that the bonds formed between the molten plastic material has the potential to bind the bitumen and the aggregates together as a homogenous material in such a way that, when hardened at reduced temperatures, the mix is able to form a stronger bonded material that is semipervious and allows drainage of moisture or water across the surface of the asphalt plastic layer. This study adopts an alternative approach to the design of an ultrathin film asphalt concrete porous pavement layer for use in pavement surface wearing course and high-density traffic roads considering the effects of increasing temperature and moisture absorption on the asphalt plastic pavement mix

Introduction

Recently, top-down cracking along the wheel path on the surface of the asphalt layer has become a critical distress that can result in the rapid delamination and failure of the pavement. This failure, initiated at the top of the asphalt layer, propagates downwards. The rate of propagation and crack growth is subject to other service and exposure conditions of the pavement (precipitation, heavy-duty vehicles, temperature, etc.). One of the major failure modes of distress is expressed in the form of longitudinal cracks [1]. In this type of distress, failure usually does not occur until the rate of delamination exceeds the threshold that the pavement stiffness can resist (the resilient modulus). The pores become more pronounced as fissures and openings appear on the pavement surface. This study provides a surface response analysis using finite element models to design flexible pavement wearing courses using recycled waste plastic.

The issue of plastic waste has been a major threat in both urban and rural settlements. According to a report by [2], “without intervention, the amount of plastic littering the world’s oceans is expected to triple within a decade.” These plastic wastes range from used water bottles, PET bottles, electronic waste, plastic drink containers, milk jugs, cleaning product containers, and shampoo bottles. Thus, it is safe to say that our homes are filled with plastic packaging that makes shopping convenient but later poses a major threat as non-degradable waste. Experts have suggested that the increase in plastic waste in the ocean constitutes 70% of marine litter, which is a non-degradable plastic, with an estimated forecast to increase threefold between 2015 and 2025 [3,4]. However, it is almost a common subconscious act to throw away plastic items that do not seem usable. This process results in the formation of a significant percentage of landfill waste around the globe.

In a report made by [5], “Recycling, including the costs of collecting waste in tiny, mixed amounts, transporting the waste to a handling facility, sorting it, cleaning it, repackaging it, and then transporting it again, often for great distances, to a market that will buy the commodity for some actual use, is almost always more expensive than landfilling that same waste in a local facility.” The idea of waste plastic is a major discouraging factor for many waste recycling companies, considering the excessive cost of recycling, which has a low market value. For this study, waste was collected locally, sorted, and recycled in a waste plant within the same community. The recycled waste was incorporated into a modified wearing course pavement mix design (dry method). The resulting asphalt mixture is then proposed for use on surface potholes and for providing riding surfaces to gravel roads situated within rural settlements.

Recycled Plastic in Asphalt Mix

Plastic recycling faces numerous challenges, ranging from mixed plastics to hard-to-remove residues. It is estimated that plastics finding their way into the oceans contribute to the deaths of more than 100,000 marine mammals and one million seabirds every year [6,7]. The recovery and recycling of post-consumer flexible packaging is a significant recycling issue. Plastics are durable, lightweight, and inexpensive materials that can be readily moulded into various products, making them useful for a wide range of applications [8]. Every year, more than 100 million tons of plastics are produced globally, and approximately 200 billion pounds of new plastic material are thermoformed, foamed, laminated, and extruded into millions of packages and products [9]. Consequently, the reuse, recovery, and recycling of plastics are critical.

For the purpose of this study, waste plastic was categorized as follows: high-density polyethylene (HDPE – shampoo containers, milk bottles, plastic shopping bags); low-density polyethylene (LDPE – garbage bins and bags, PET bottle caps); polystyrene (PS – foam hot drink cups, plastic cutlery, foam lunch containers); plasticized polyvinyl chloride or polyvinyl chloride (PVC – squeeze bottles, cordial bottles); polyethylene terephthalate (PET – fruit juice and soft drink bottles); and electronic waste (e.g., computer casings, printer casings).

Currently, only PET, HDPE, and PVC plastic products are recycled through curb side recycling programs (curb side or kerbside collection refers to a service provided to households, typically in urban and suburban areas, for collecting and disposing of household waste and recyclables). PS, PP, and LDPE plastics, such as bottle caps, typically face recyclability challenges because these materials often get stuck in sorting equipment at recycling facilities, causing the equipment to break or stop, making recycling difficult [10,11].

Distress in flexible pavement

One of the essential criteria for pavement mixture design assessment is determining the binder content, along with the percentage of fines and voids in the mix [12,13,14]. However, pavement practitioners have developed a more sophisticated approach to evaluating pavement durability and performance using the Superpave concept [15,16,17]. This method introduces non-conventional heterogeneous mixtures into the pavement constituent blends [18]. Furthermore, the incorporation of reclaimed asphalt and recycled materials into the pavement mix to offset the high cost of petroleum and conserve virgin materials has become a standard practice in pavement production [19].

The concept of an ultrathin friction course serves as a sustainable maintenance strategy [20]. This approach helps reduce the costs associated with producing thick asphalt surfaces, addressing the rising costs of asphalt production and life cycle assessment requirements. Consequently, it is essential to investigate the rheology, performance, and potential failure of pavement throughout its design life. Several methods have been developed to analyse and evaluate pavement deformation and predict failure responses [21,22]. This study focuses on investigating the behaviour of asphalt mixes under top-down cracking, as well as incorporating recycled materials such as reclaimed asphalt pavement (RAP) and recycled waste plastic into the asphalt mix.

Top-Down Fatigue Cracking in Flexible Pavement

Studies reveal that top-down cracking is a distress mode characterized by cracks that initiate at the pavement surface and propagate downward toward the base layer. This is commonly observed in asphalt concrete [23]. This contrasts with the traditional assumption that pavement cracks initiate at the bottom of the asphalt layer, where tensile bending stresses are greatest, and then propagate upward to the surface. However, recent analyses of asphalt deformation and computations suggest that the transfer functions used in mechanistic-empirical methods indicate multiple factors contributing to asphalt pavement surface deterioration. These factors include low stiffness in the upper layer due to temperature variations, moisture ingress, high horizontal tensile stresses from wide-base truck tire load cycles, fatigue cracking, fatigue rutting, and age hardening of the asphalt binder, which results in high thermal stresses, among others.

Since the initiation of top-down cracking in asphaltic wearing course layers can be triggered by any of these factors, it is crucial to determine the specific causes of pavement failure. Variations in stress intensity may arise depending on environmental and traffic conditions, potentially affecting pavement deformation and response in different regions [24].

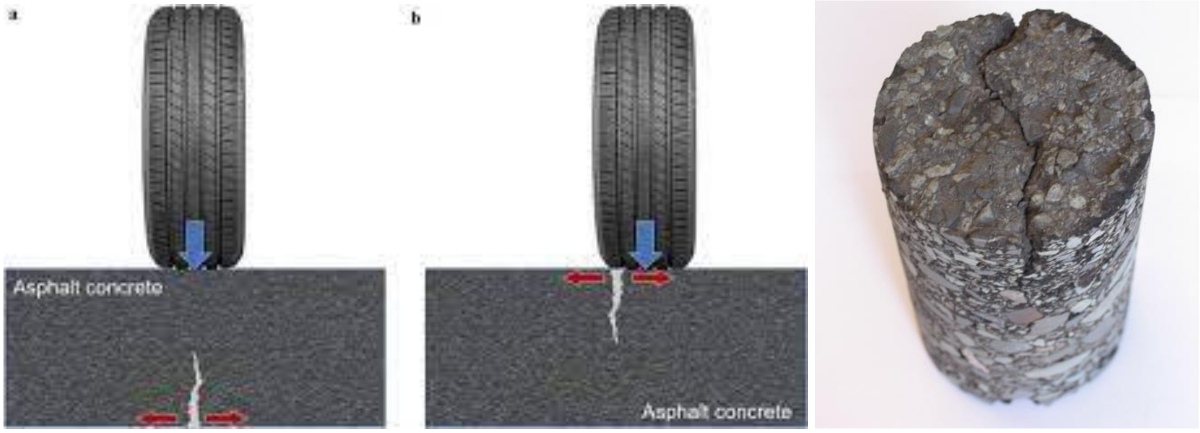

Figure 1: Illustration of different pavement cracking modes: (a) Bottom-up cracking mode, (b) Top-down cracking mode, and (c) Core sample showing a typical top-down cracking profile. [25]

Therefore, this study investigates pavement failure propagators as essential for differentiating top-down or bottom-up cracking, as shown in Fig. 1a and 1b. The deformation response classification serves as a useful tool for predicting and providing the most efficient maintenance needed. In many cases, cores are usually taken to categorize the type of cracking developed resulting from the service load conditions experienced. Fig. 2 displays the crack phenomena when subjected to PT testing and loading passes. Fig. 2 shows that shallow cracks from the top of the pavement under loading are a common expression of distress during the wearing course. However, as the stresses increase, the magnitude of the crack increases, and the crack propagates downwards. Over time, the resulting distress may result in peeling or wearing away of the surface layer.

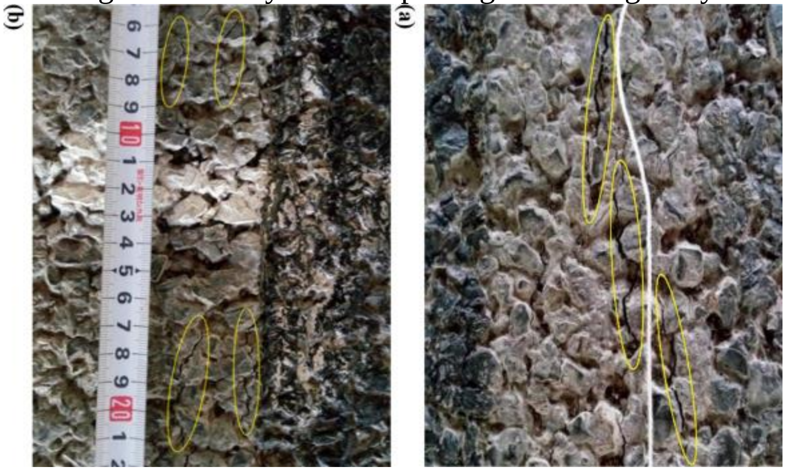

Figure 2: Pavement cracking phenomenon: (a) Cracks between two-wheel paths at approximately 237,000 APT loading passes and (b) Cracks near the outer edge of the wheel path at approximately 550,000 APT loading passes. [23]

This study proposes a hypothesis stating that the material stiffness (resilient modulus) developed within the asphalt mix is directly proportional to the fracture energy stored within the asphalt matrix mix. This indicates that a reduction in the potential energy stored within the asphalt mix results in a reduction in the stiffness of the pavement mix. When subjected to dynamic traffic loads as well as moisture ingress. In addition, the probability of the pavement experiencing deformation at the contact point of the tire load will result in induced stresses, which can potentially initiate a Mode I crack [26,27] at the crack tip opening, which continues to propagate downwards with increasing load cycle and moisture ingress [28]. [29] revealed that top-down cracking can evolve on pavement in three stages (i.e., single crack, sister cracks, alligator cracks).

There are several top-down cracking models based on deformation mechanics (e.g., continuum damage mechanics and fracture mechanics) [29]. This deformation method, however, provides rigorous inferences of crack initiation and stress intensity propagation within the asphalt mixture [30]. Consequently, there is a need to identify a reliable and feasible superpave testing method, among those proposed in the literature, to strictly evaluate and analyse the top-down cracking performance of asphalt mixtures incorporated with recycled plastic material. This paves the way for the implementation of top-down cracking analysis on the use of recycled plastic in asphalt pavement solely in pavement management systems (PMSs) through proper identification to minimize top-down cracking asphalt mixes and fatigue cracking.

Material Mix Design of Recycled Plastic Asphalt

The material specification mix design consideration for the recycled asphalt plastic Mix is as proposed. The material composition based on the sieve sizes is presented from the data obtained from the particle size distribution for the recycled asphalt mix. The Asphalt Mix Boundary sieve sizes ranged from 85-100 (10 mm), 65-86 (7.10 mm), 55-70 (5.0 mm), 30-49 (2.0 mm), 24-42 (1.0 mm), 15-25 (0.60 mm), 9-19 (0.30 mm), 7-14 (0.150 mm), 3-8 (0.075 mm) and 13-26 (<0.075 mm). This bracket was used to derive the mixture for the sample used. The recycled plastic was within the 55–70th zone.

Experimental analysis was performed on a sample mixture of asphalt incorporating recycled plastic into the asphalt mix, recycled asphalt plastic pavement (RAPP), and a cold mix without the presence of recycled plastic. The presence of fines and filler material in the RAPP mix from the Marshall test results indicates an improvement in the heterogeneous bond developed within the mix. The material characterization table for the design is presented in Table 1.

Table 1: ITS response data and material characterization

	No. of Briquettes	ITS Data	Bulk Density	Binder Content %	Void in Mix %	Flow	Poisson's ratio	Ave. Elastic Modulus (MPa)
HMA	Thickness of Briquettes (mm)	63.00	2543	4.6	4.0	4.0	0.44	5490
	Reading (kN)	13.43						
	Δ Thickness (mm)	2.24						
	ITS (kPa)	1336.34						
RAPPC (Crumbs)	No. of Briquettes							
	Thickness of Briquettes (mm)	65.40	1668.7	5.6	11.4	13.4	0.44	8471
	Reading (kN)	24.0						
	Δ Thickness (mm)	2.55						
	ITS (kPa)	2330.46						
RAPPP (Pellets)	No. of Briquettes							
	Thickness of Briquettes (mm)	65.40	1848.4	5.3	8.9	9	0.44	10029
	Reading (kN)	26.50						
	Δ Thickness (mm)	2.47						
	ITS (kPa)	2541.45						

Laboratory Testing of the Mixtures

A full Marshall test was performed on the sample. The test focused primarily on the indirect tensile strength test results, percentage of voids in the mixture and binder content. The deformation results were compared with those of a hot mix using the same material mix design specification. Fig. 3a shows the mix design using plastic pellets, and 3b shows the mix design using plastic crumbs. The source of the plastic used was standard LDPE (low-density polyethylene) plastic from a wash plant. Furthermore, the recycled asphalt plastic pavement (RAPP) mixture was a hot mix that was mixed at a temperature of 160°C. In this study, to investigate the mechanisms of top-down cracking incorporating plastic waste materials as aggregate replacement, it was essential to accurately determine the stress or strain response at the surface using a Finite Analysis Mesh design which takes account of aggregate composition hence the proposed sieve analysis distribution for the mix design presented in Fig. 4.

Figure 3: Different forms of waste plastic used in asphalt mixtures (a) Waste plastic pellets: Uniformly sized and (b) Waste plastic crumbs: Irregularly shaped particles

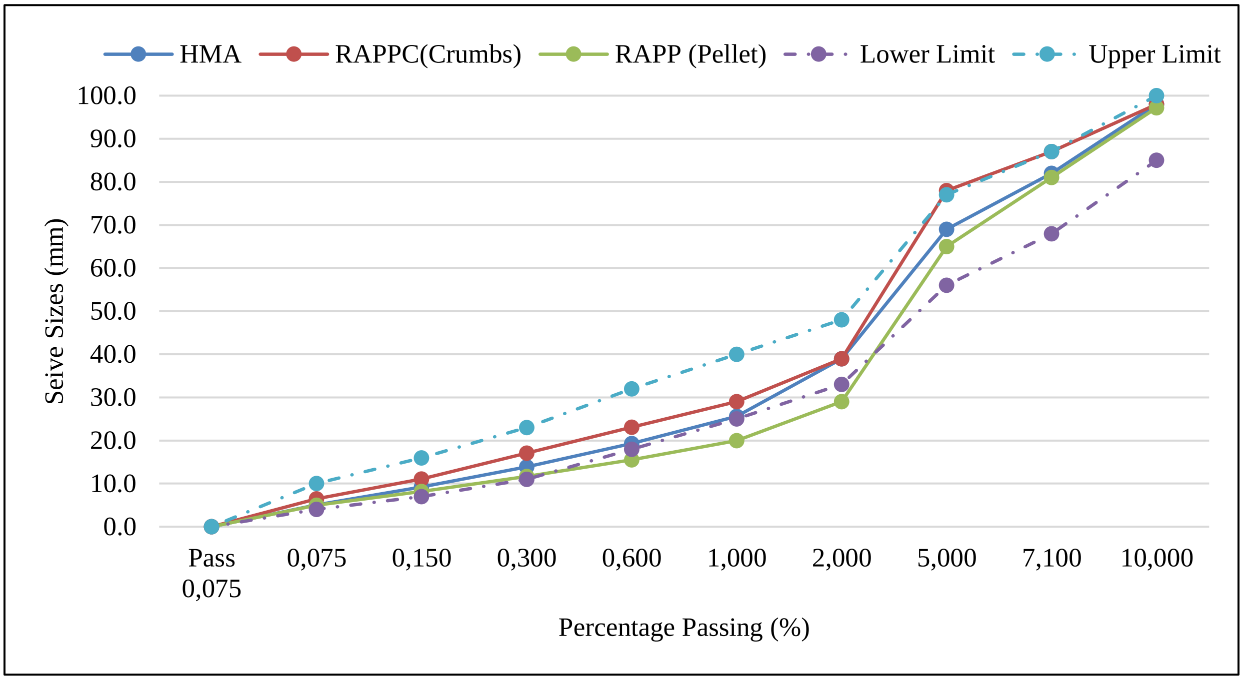

Figure 4: Grain size distribution analysis for different asphalt mixtures

Research Methodology

In this study, finite element analysis was employed to investigate the pavement's response to top-down cracking, considering the complexities associated with this phenomenon [31,32]. This study focused on the impact of rutting and fatigue cracking on the pavement response, particularly emphasizing the horizontal tensile strain at the asphalt bottom and bond development with interlayers. Previous research by [33], highlighted the initiation of longitudinal surface cracks due to near-surface stress, which evolve into deep cracks, causing critical tensile strain and ultimately leading to top-down cracking failure.

Model Geometry

For economic and computational efficiency, a 2D axisymmetric model in Abaqus software was chosen over a 3D model, despite the latter's accuracy [34]. The pavement structure, representing a region near the tire contact, was modelled in 2D with a 3000 mm transverse direction and a 2000 mm subgrade depth [35]. The pavement design features layers such as beams with a 150 mm thick stabilized base, an in situ treated subgrade at 2000 mm depth, and an asphalt surface layer with a depth of 50 mm using HMA, RAPPC, and RAPPP.

Material characterization. Drawing on previous works [35,36], material characterization, including the resilient modulus, utilized findings from the indirect tensile strength test (ITS) employing the correlation formula method (CFM), as presented in Table 1.

Model Interactions and Boundary Conditioning

The boundary conditions used rollers to limit the degrees of freedom, simulating real-world situations. Transversal and longitudinal movement of the layers were restricted, and the subgrades were subjected to further vertical constraints. The requirements for substantial deformation and material linearity were balanced by fine and coarse meshing, which was based on axisymmetry with reduced integration elements. Under the assumption of a circular contact area with a radius of 192.108 mm and a total area of 28985.5 mm^2, a standard equivalent wheel load of 80 kN was applied uniformly. It was determined that the tire pressure against the pavement surface was 690 kPa (0.69 MPa). Instead of taking into consideration the influence of many load cycles on the same place, as suggested by [37,38], the loading scenario concentrated on the impact of repeated load cycles. The simulation considered the load remaining on the area of interest for 0.1 s with a subsequent 0.9 s of rest, aligning with previous studies [37].

Crack Propagation Modelling

The extended finite element method (X-FEM) is used to represent stable and evolving discontinuities with geometries independent of the finite element mesh. The X-FEM approach uses interpolation functions to characterize the displacement field near a crack [39,40,41]. As a result, this approach has emerged as an effective method for studying the genesis and evolution of cracks. A refinement mesh was required near the fracture end to capture the necessary singular asymptotic fields. The mesh must be regularly updated to reflect the discontinuity of the crack geometry as it grows from small to larger opening cracks [41]. Furthermore, using the X-FEM tool, crack development was modelled at 5 mm, 10 mm and 15 mm from the top of the asphalt layer.

Results and Discussion

The laboratory test results revealed three components: a control mixture with 0% plastic following HMA design (HMA), a second mixture with 15% replacement of the 5 mm grain size fraction using waste plastic crumbs and 20% RAP (RAPPC), and a third mixture with 15% replacement of the 5 mm grain size fraction using waste plastic pellets and 20% RAP (RAPPP). The damage criterion for each model illustrates the pavement delamination rate under loading conditions. However, these results are exclusively applicable within a simulated environment.

Interaction Mechanisms between Recycled Plastic and Bitumen

The adhesion between bitumen and recycled plastic is influenced by chemical compatibility and physical interactions. In the laboratory mix, RAPPC (a combination of LDPE and HDPE) indicated weaker bonding than RAPPP, which is based on PET. RAPPP indicated better adhesion at higher temperatures due to its polar ester groups, whereas RAPPC showed minimal contact [42]. However, at higher temperatures, the plastics in RAPPC partially melt, resulting in a semi-fused matrix that improves bonding and minimizes stripping susceptibility. In terms of physical interactions (Fig. 4), RAPPP fit the grain size envelope well, whereas RAPPC surpassed the upper limit of sieve sizes, resulting in more air voids and a lower density (Table 1). Furthermore, microstructural analysis, such as scanning electron microscopy, which could provide a more detailed understanding of the bonding and interface characteristics between plastic and bitumen.

Effect of Plastic Type on the Stress and Strain Responses

The integration of various plastics as partial replacement for aggregate grain size in asphalt mixtures not only offers an opportunity to reduce environmental impact but also ensures the long-term performance and stability of the pavement structure. Fatigue cracking analysis revealed a decrease in horizontal strain (Fig. 5) at the bottom of the asphalt layer with the introduction of plastics (crumbs and pellets). Similar trends are observed for the vertical strains within the asphalt layer (Fig. 6), with the waste plastic pellet (RAPPP) exhibiting superior performance compared to that of the waste plastic crumb (RAPPC). This discrepancy is attributed to the greater excess void density in the plastic crumb mixture (11.4%) than in the RAPPP mixture, where the void density was 8.9% (Table 1). These findings underscore the significance of plastic type in influencing stress and strain responses in asphalt mixtures.

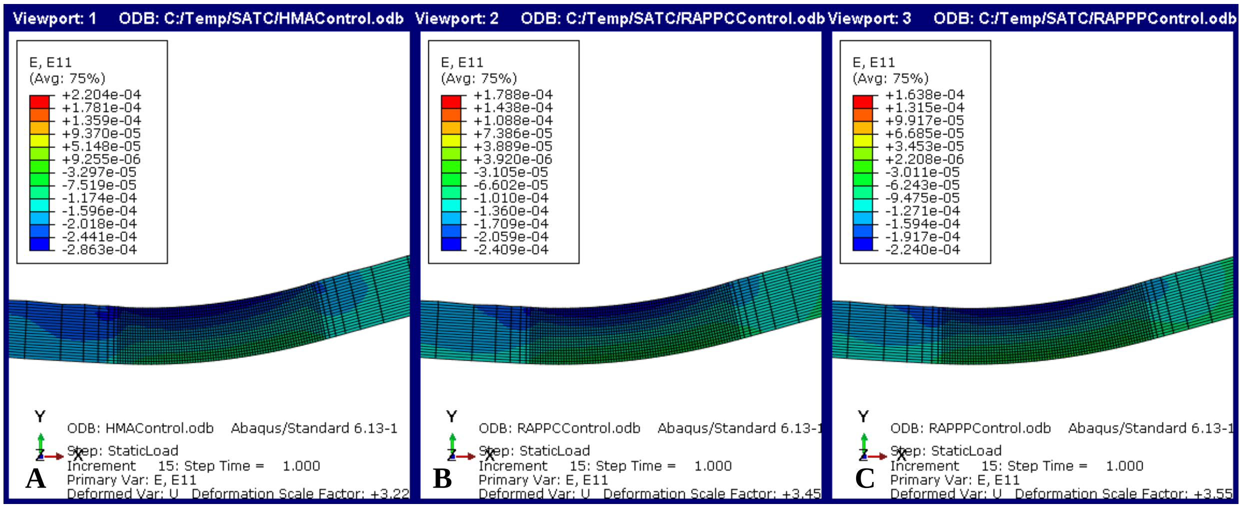

Figure 5: Horizontal strain on the asphalt mix during HMA control crack growth (a) HMA (b) RAPPC and (c) RAPPP

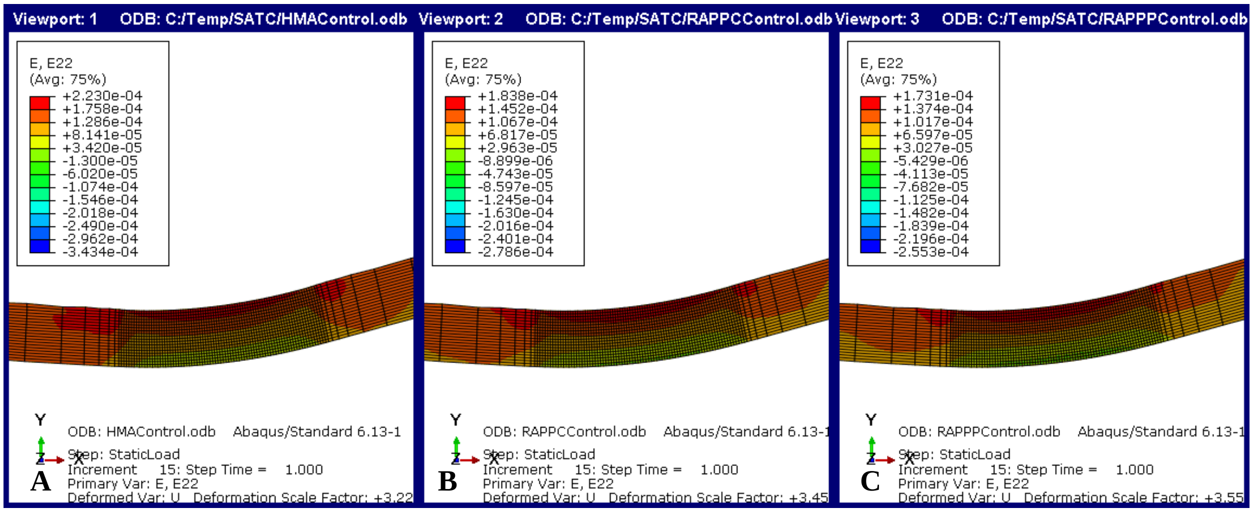

Figure 6: Vertical strain on the asphalt mix during HMA control crack growth (a) HMA (b) RAPPC and (c) RAPPP

Effect of the Initial Crack on the Stress and Strain Responses

The introduction of an initial crack, facilitated by the X-FEM development tool in Abaqus, revealed a progressive increase in horizontal strain at the bottom of the asphalt layer. This phenomenon was observed for crack lengths of 5 mm, 10 mm, and 15 mm, indicating a correlation between the fatigue cracking performance of the asphalt mixture and adherence to proper construction practices. Notably, despite the introduction of initial cracking, the RAPPP continued to outperform the other variants. Fig. 7-9 illustrate that the development of rutting in the asphalt layer is significantly influenced by induced cracks. While top-down cracking may not substantially impact the fatigue resistance of the asphalt layer, continuous exposure to traffic loads and environmental factors could lead to a notable reduction in rutting resistance, potentially resulting in pavement failure. These findings emphasize the critical role of initial crack length in shaping stress and strain responses, highlighting the importance of robust construction practices for long-term pavement performance.

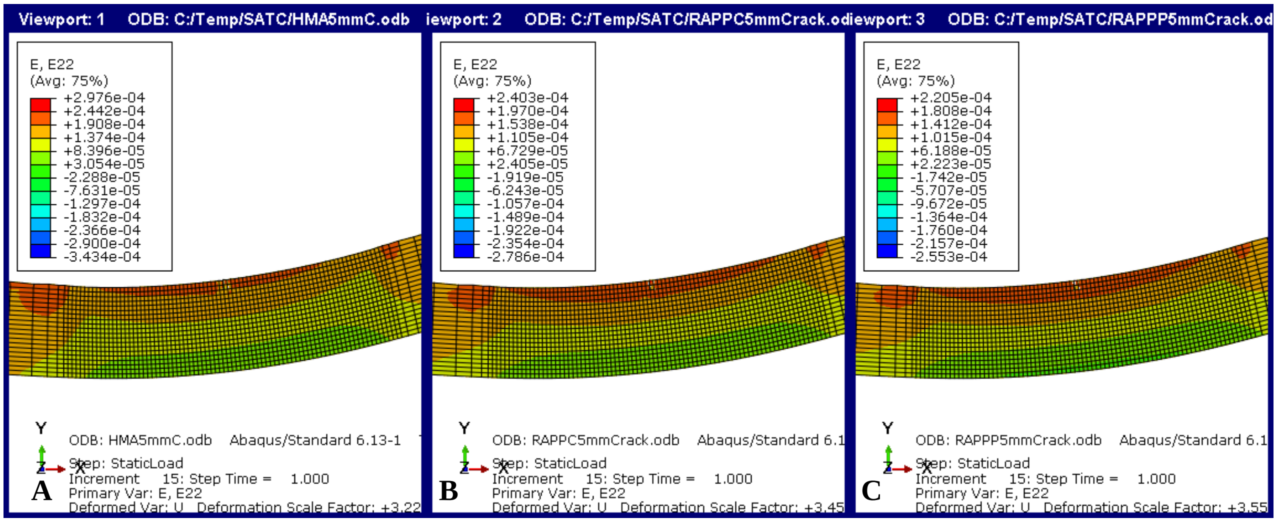

Figure 7: Vertical strain in the asphalt mixture at 5 mm crack growth (a) HMA (b) RAPPC and (c) RAPPP

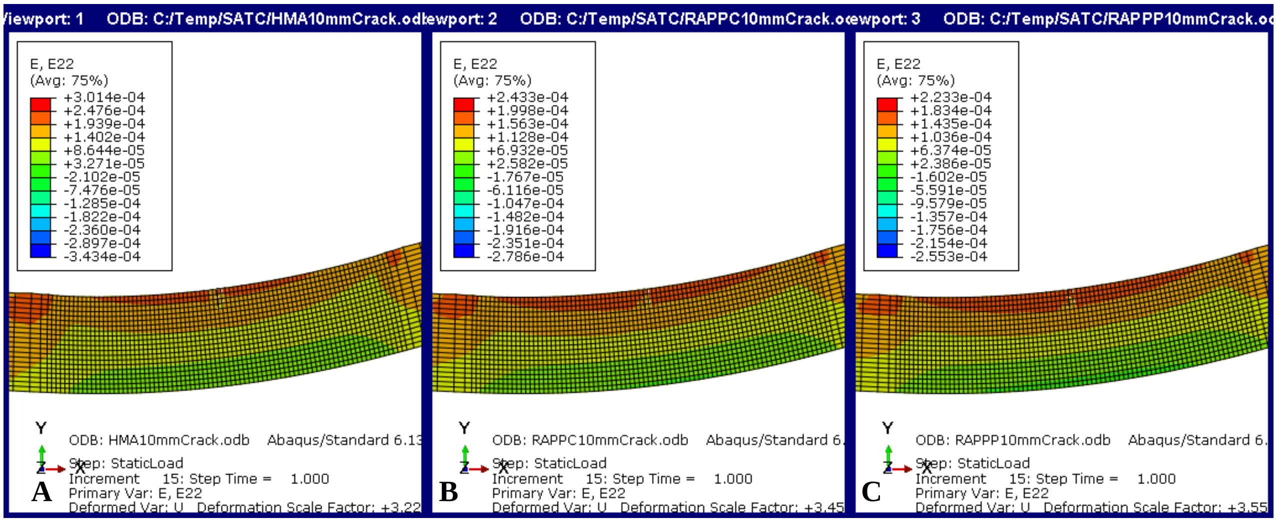

Figure 8: Vertical strain in the asphalt mixture at 10 mm crack growth (a) HMA (b) RAPPC and (c) RAPPP

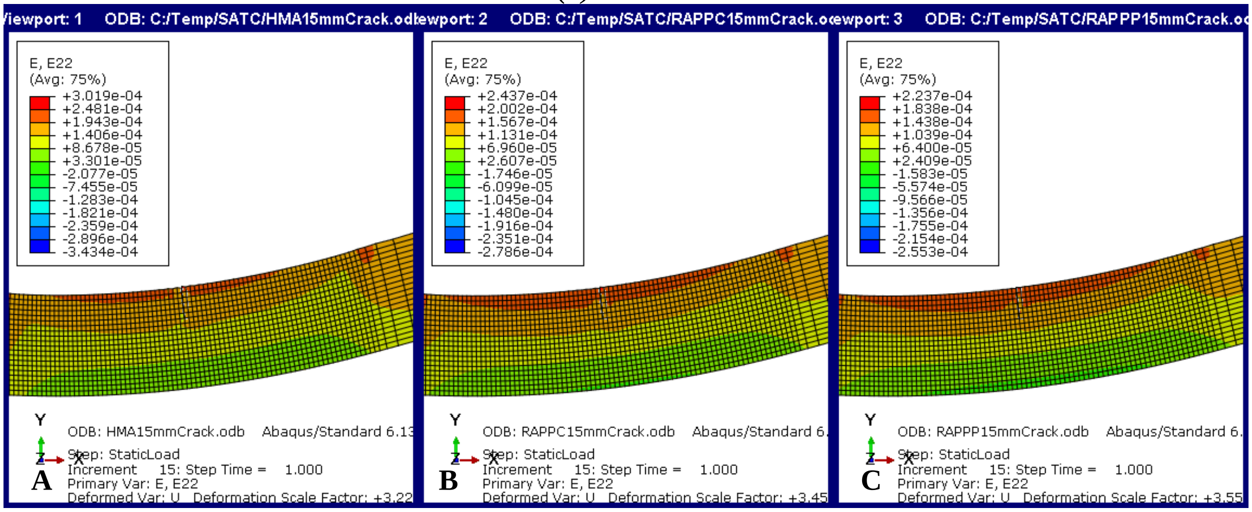

Figure 9: Vertical strain in the asphalt mixture at 15 mm crack growth (a) HMA (b) RAPPC and (c) RAPPP

Summary

In conclusion, investigating the effects of plastic type and initial crack length on the stress and strain responses of asphalt mixtures provides valuable insights into the optimization of pavement performance. The incorporation of plastics as aggregate substitutes not only offers environmental benefits but also significantly influences fatigue cracking and rutting resistance. The superior performance of waste plastic pellets (RAPPPs) over waste plastic crumbs (RAPPCs) underscores the importance of the plastic type in enhancing the long-term stability of pavement structures.

Additionally, the fracture energy stored within the recycled asphalt plastic mix surpasses that of conventional HMA, indicating the potential for increased resilience. The semi molten state of the modified plastic mix results in increased potential energy, reduced crack initiation and top-down crack development. Although crack formation occurs, the presence of molten plastic molecules that crystallize with bitumen contributes to an enhanced waxy structure with aggregate particles, mitigating immediate failure propagation within the plastic mix. In essence, these findings underscore the multifaceted nature of the factors influencing the asphalt mix behaviour.

Implementing environmentally conscious practices and ensuring proper construction methods are essential for optimizing the longevity and performance of asphalt pavements in real-world scenarios.

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