Received 25 May 2024
Revised 11 October 2024
24 November 2024
Accepted 2 December 2024

A sustainable approach for road pothole repair using waste plastic bottles and aggregates

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Abstract

Purpose – This study explores a sustainable method for repairing road potholes using a composite material made from waste polyethylene terephthalate (PET) plastic bottles and local aggregates. This study aims to address plastic waste management challenges and provide a cost-effective and durable road maintenance solution.

Design/methodology/approach – PET bottles were collected, sliced, cleaned and melted at 280°C. Coarse and fine aggregates were characterized per Central Materials Laboratory (CML) standards. Mixtures with varying PET and aggregate ratios were prepared, molded into specimens and tested for mechanical properties following ASTM D1559-89 and ASTM D3967 standards.

Findings – The optimal mixture (30% PET, 30% sand and 40% gravel) outperformed conventional asphalt mixtures, achieving a Marshall stability of 59.78 kN, indirect tensile strength of 5,909 kPa and a resilient modulus of 36,145 MPa, exceeding Tanzanian road construction standards.

Research limitations/implications – Although laboratory results are promising, further field trials are needed to evaluate the long-term performance and durability of the plastic-aggregate composite in real-world conditions.

Practical implications – This solution offers a cost-effective, sustainable option for road pothole repair, especially in developing countries with budget constraints and significant plastic waste.

Social implications – By repurposing plastic waste and providing durable road maintenance, this research supports the United Nations' SDGs, promotes environmental conservation and fosters economic development through improved transportation infrastructure.

Originality/value – This innovative method uses waste plastic bottles as a standalone repair material, eliminating petroleum or cementitious binders and promoting a circular economy. This approach utilizes waste streams, thereby reducing maintenance costs and addressing plastic waste issues.

Keywords Plastic waste recycling, Pothole repair, Road maintenance, Sustainable construction materials, Polyethylene terephthalate (PET) composite

Paper type Research paper

1. Introduction

Road infrastructure is a cornerstone of economic and social development, particularly in Tanzania, where a robust network of roads is essential for connecting communities and facilitating trade. However, roads are also subject to deterioration and damage due to various factors, such as traffic loads, weather conditions, poor drainage systems, quality of construction, and poor maintenance (Llopis-Castelló *et al*., 2020). Maintaining roads in good condition is necessary for ensuring efficient transportation networks and fostering economic development. Among the most prevalent and problematic pavement defects are

The author extends gratitude to Juma Masuke for his valuable contribution to the data collection process during his BSc. studies in Environmental Engineering at the University of Dodoma. Appreciation is also due to the Tanzania Roads Agency for their support with laboratory work.

Conflict of interest statement: The authors declare no conflicts of interest.

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Frontiers in Engineering and Built Environment
Vol. 5 No. 1, 2025
pp. 52-67
Emerald Publishing Limited
e-ISSN: 2634-2502
p-ISSN: 2634-2499
DOI 10.1108/FEBE-05-2024-0020

potholes—localized depressions in the road surface caused by material failure (Gupta *et al*., 2020; Liu *et al*., 2021). These hazards pose a significant threat to road users, degrade ride quality, compromise safety, increase vehicle traffic and operating costs, and heighten accident risks (Byzyka *et al*., 2018; Hafezzadeh *et al*., 2021; Yang *et al*., 2021), necessitating timely and effective repair interventions for maintaining safe and efficient transportation infrastructure.

Traditional road repair practices heavily rely on petroleum-derived binders and concrete, leading to significant environmental impacts such as an increased carbon footprint and economic burdens due to high material costs. The production process for these materials not only consumes a substantial amount of non-renewable energy but also contributes to greenhouse gas emissions and the depletion of finite natural resources (Weir *et al*., 2022). In light of the growing global emphasis on sustainability, it is imperative to innovate maintenance methods that are both environmentally friendly and cost-effective. These new approaches should effectively mitigate common road issues, such as cracks and potholes, while also addressing broader environmental concerns.

One innovative solution that is gaining traction is the utilization of plastic waste in road construction and repair (Appiah *et al*., 2017). Plastics possess desirable properties such as high strength-to-weight ratios, moisture resistance, and durability (Agarwal and Gupta, 2017; Babafemi *et al*., 2018), making them attractive materials for road construction. At the same time, the world is grappling with a plastic waste crisis, with the production and consumption of plastics skyrocketing over the past few decades. Global statistics indicate that waste plastics are predominantly discharged into the natural environment or end up in landfills (79%), incinerated (12%), or recycled (9%) (Geyer *et al*., 2017). A significant portion of plastic waste remains unrecycled or improperly disposed of, persisting in the environment for years and causing severe pollution and ecological damage. Despite efforts to mitigate plastic waste, the increasing demand for plastic and inadequate waste management practices have limited their effectiveness (Nanda *et al*., 2022).

The integration of plastic waste into road construction addresses both environmental pollution and the need for durable road materials, offering a dual benefit. This method enhances the quality of roads by improving the properties of the mix, leading to an extended road life and a reduction in plastic pollution (Cirino *et al*., 2023; Rajput and Yadav, 2016; Vermo, 2008). Field tests confirm that roads containing plastic waste can better withstand stress, making this a viable option for enhancing road durability (Meghana *et al*., 2023; Vermo, 2008). Additionally, the inclusion of plastic waste in bituminous mixes increases the Marshall stability value, indicating superior road performance (Rajput and Yadav, 2016). Therefore, the use of plastic waste in road construction presents a promising avenue for enhancing road durability while mitigating the environmental impact of plastic waste. It solves disposal problems and improves the mechanical properties of road materials, contributing to sustainable development in the industry.

Numerous studies have demonstrated the technical and environmental benefits of incorporating plastic waste into traditional bituminous mixtures and concrete composites for road construction and maintenance (Ki *et al*., 2021; Wang *et al*., 2022; Wijayaningtyas *et al*., 2022). For example, the chemical processing of Polyethylene Terephthalate (PET) waste into additives like Thin Liquid Polyol PET and Viscous Polyol PET has been shown to improve asphalt properties, enhancing performance and resistance in Hot Mix Asphalt mixtures (Gürü *et al*., 2014). Recycling PET in bituminous asphaltic concrete (BAC) offers environmental and economic advantages, with polymer-coated aggregate-modified BAC showing improved air voids and Marshall stability (Sojobi *et al*., 2016). Additionally, adding plastic bottles to asphalt mixtures increases stability and flow values, reduces optimum Asphalt content, and improves fatigue resistance, indicating a potential reduction in asphalt binder use (Moghaddam *et al*., 2013). Utilizing waste plastic in bituminous mixes not only enhances mix properties but also offers an eco-friendly disposal method, potentially reducing pavement thickness (Patel *et al*., 2014). However, research on the direct use of waste plastic streams as a standalone repair material remains limited. This presents an opportunity to align with circular economy principles and reduce maintenance costs while managing waste (Athithan and Natarajan, 2023; Lamba *et al*., 2022). The quest for reuse applications that avoid extensive pre-processing or mixing is paramount to uphold the circular economy's waste reduction ethos. Investigating a new, binder-less repair material made directly from waste plastics is an innovative approach that could greatly reduce the costs associated with road maintenance. This area remains largely unexplored, presenting a research gap that, if addressed, has strong potential to advance sustainability through innovative plastic solutions.

Tanzania, like many developing countries, faces significant challenges in road maintenance. The nation allocates substantial resources to road upkeep, emphasizing the need for cost-efficient solutions (The Citizen, 2020). Current practices primarily involve traditional methods using asphalt and concrete for pothole repairs, which, while effective, are often costly and resource-intensive (URT, 2023). The Tanzania National Roads Agency (TANROADS) is responsible for maintaining a vast network of roads, with a significant portion of their budget dedicated to routine maintenance and repairs (URT, 2023). The high costs and environmental impact of these traditional methods underscore the need for innovative, sustainable solutions in road maintenance (Hoy *et al*., 2023). The exploration of alternative materials, such as recycled plastics, presents an opportunity to address both economic and environmental concerns in road infrastructure management (Hasheminezhad *et al*., 2024). Amidst increasing plastic waste, developing viable reuse strategies that address infrastructural and environmental issues has become necessary (Athithan and Natarajan, 2023). This study proposes a transformative and scalable road maintenance solution utilizing waste plastic bottles. By using these bottles in their original molecular state, the approach bypasses expensive preprocessing steps, promoting broader adoption and supporting a circular economy (Lamba *et al*., 2022). This innovative application signifies a shift towards sustainable construction practices, fostering environmental conservation through efficient waste management while offering economic benefits by potentially lowering maintenance costs (Sparrevik *et al*., 2021). The research aligns infrastructure development with sustainable materials management, contributing to progress towards the United Nations Sustainable Development Goals (Bernstein, 2017). The findings hold promise for advancing cost-effective, environmentally friendly construction methods, addressing critical sustainability challenges in road maintenance and plastic waste management.

2. Material and methods

2.1 Study area

This study was conducted at the University of Dodoma, Tanzania, in collaboration with the Tanzania National Roads Agency (TANROADS). Dodoma serves as a strategic location in Tanzania's extensive road network, which spans over 86,472 km (Logistics Cluster, 2022). The study focuses on developing sustainable and cost-effective road maintenance strategies suitable for local conditions, addressing both infrastructure maintenance needs and plastic waste management challenges.

2.2 Materials

2.2.1 Waste plastic bottles. The study utilized polyethylene terephthalate (PET) waste bottles collected from the University of Dodoma campus. PET bottles were selected due to their abundance, high tensile strength, and chemical resistance (Rajput and Yadav, 2016). In Tanzania, PET bottles constitute a significant portion of plastic waste, making them readily available for recycling (Kombe and Shemsanga, 2024). Moreover, PET's thermoplastic properties allow for easy melting and remolding, which is necessary for application in road repair (Lapina and Baurova, 2018). The choice of PET also aligns with global efforts to find sustainable solutions for plastic waste management, particularly for single-use plastics like beverage bottles (UNEP, 2021). Previous studies have shown promising results in using PET in road construction, demonstrating improvements in the mechanical properties of asphalt mixtures (Gürü *et al*., 2014; Moghaddam *et al*., 2013). The bottles underwent cleaning with local tap water, manual cutting into 10–20 mm flakes, and sun-drying for 24 h. These preparation methods were chosen to reflect realistic conditions in resource-constrained settings. Plate 1 illustrates the waste plastic bottles' collection and preparation process.

2.2.2 Aggregates. **Coarse** aggregates (crushed stone) and fine aggregates (natural river sand) were sourced locally from Dodoma quarries and the Makulu stream, respectively. Both materials were characterized according to Central Materials Laboratory (CML) standards, with particle size distribution analysis conducted per CML test 2.3 (BS 812: Part 103.1:1985) (URT, 2000a). Table 1 presents the sieve analysis results, with detailed gradation curves provided in Supplementary Figure S1(a,b).

The aggregates demonstrated suitable mechanical properties with an aggregate crushing value below 7.1% (maximum limit 30%), Ten Percent Fines Value exceeding 110 kN, and Los Angeles abrasion test value of 7.1%, indicating high wear resistance.

2.3 Methods

As illustrated in Figure 1, the study's methodology encapsulates a novel approach to enhancing road maintenance using recycled PET plastic material. It illustrates the step-by-step process of experimental approach, from material collection to final testing. Each box

Source(s): Author's own work

Plate 1. Waste plastic bottles collection, slice and washing process

Table 1. Coarse and fine aggregates sieve analysis

Fine aggregate Sieve size (mm)	Passing (%)	Coarse aggregates Sieve size (mm)	Passing (%)
14		37.5	100.0
10	100.0	20	100.0
5.0	100.0	14	97.3
2.360	99.4.0	10	77.3
1.180	95.2	6.3	18.4
0.600	61.8	5.0	1.9
0.300	21.5	2.36	0.1
0.15	5.2		

Source(s): Author's own work

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Figure 1. Study's methodology

represents a key stage in the research, with arrows indicating the progression and relationships between stages. This visual representation succinctly outlines the experimental process, from the initial collection of waste plastic bottles and aggregates to the final mechanical testing of the formulated mixtures. The subsequent sections delve into the specifics of each step, providing a comprehensive understanding of the methods employed to evaluate the viability of this eco-friendly innovation for road repair applications.

2.3.1 Preparation of plastic-aggregate mixtures. 2.3.1.1 Melting of waste plastic bottles. Sliced plastic bottles were subjected to a melting process in a furnace oven. A consistent temperature of **280°C** was maintained to ensure complete melting, resulting in a homogenous molten plastic liquid. This step was critical to render the plastic into a flowable state, facilitating its subsequent mixing with aggregates.

2.3.1.2 Determination of mixing ratios. The molten plastic served as the binding agent in the preparation of trial mixtures with coarse aggregates and sand. A systematic trial-and-error method was employed to ascertain the optimal material ratios, aiming to achieve mixtures with superior mechanical and structural properties suitable for road maintenance. Initial mixtures were crafted by altering the material percentages according to Table 2, which shows the mixing ratio design tested. The 'Mixing Ratio Label' column identifies each unique mixture. Subsequent columns show the percentage and actual weight of each component (PET, fine aggregate, and coarse aggregate) used in preparing the 1.2 kg Marshall specimens. This systematic variation in composition allowed for determination of the optimal mixture for pothole repair applications.

The ratios varied the percentage composition of polyethylene terephthalate (PET) plastic bottles, sand, and coarse aggregates, with two specimens prepared for each mixing ratio. The molten plastic, at 280°C, was blended by hand with predetermined proportions of sand and gravel according to the mixing ratio, ensuring a thorough mix as depicted in supplementary Figure S2, which illustrates the blending process. During this phase, the temperature was carefully controlled between 270–280°C to maintain mixture homogeneity. The mixing ratios tested ranged from R1 with 100% plastic to R10 with varying combinations of plastic (25–70%), sand (0–30%), and coarse aggregates (20–50%) by weight, based on a standard Marshall specimen weight of 1200g.

2.3.1.3 Compaction and molding of specimens. After mixing, the homogeneous mixtures were firmly packed into cylindrical steel molds measuring 100 mm in diameter and 63 mm in height, using a compaction hammer. The hot mixture was evenly layered into the mold, which was then compacted to simulate field conditions and ensure void elimination. This process produced cylindrical specimens replicating the dimensions of the Marshall test method. The molded specimens were then cured at room temperature for 24 h to solidify before undergoing mechanical property testing. Specimen heights were accurately measured using Vernier calipers prior to testing. Supplementary Figure S3 illustrates the sample specimens produced and the molding and compaction process. This molding process produced test specimens representing the different material formulations. Allowing the mixtures to cure ensured they had sufficient strength and cohesion for subsequent performance evaluation.

Table 2. Mixing ratios of PET, sand and gravel

Mixing ratio label	% PET	Fine aggregate (%)	Coarse aggregate (%)	Actual percent by 1.2 kg/marshal specimen PET (g)	Fine aggregate (g)	Coarse aggregate (g)
R1	100	0	0	1,200	0	0
R2	70	0	30	840	0	360
R3	60	0	40	720	0	480
R4	50	0	50	600	0	600
R5	40	0	60	480	0	720
R6	30	0	70	360	0	840
R7	70	10	20	840	120	240
R8	50	20	30	600	240	360
R9	30	30	40	360	360	480
R10	25	35	40	300	420	480

Source(s): Author's own work

2.3.2 Evaluation of mechanical and physical properties of mixture. The molded specimens produced from each mixing ratio were subjected to laboratory testing to evaluate and compare the performance of different mixtures based on stability, strength, and deformation resistance at the Central Materials Laboratory (CML), TANROADS in Dodoma. Marshall stability of the specimens was determined in accordance with CML Test 3.18, ASTM D1559 to evaluate load resistance. The selection of the Marshall stability test (ASTM D1559) was based on its widespread use in evaluating the strength and flow of bituminous mixtures. This test is particularly relevant for plastic-aggregate composite as it simulates the loading conditions experienced by road surfaces.

The indirect tensile strength (ITS) of the specimens was then measured based on CML Test 3.21, ASTM D3967 by applying a diametrical compressive load until failure. The Indirect Tensile Strength test (ASTM D3967) was chosen to assess the material's resistance to cracking, which is vital for long-term durability in pothole repairs. These standardized tests allow for direct comparison with conventional materials and provide a comprehensive evaluation of the composite's mechanical properties. The material's E-modulus was a derived from the ITS value using Equation (1) (URT, 2000a) to analyze tensile strength and deformation resistance properties.

$$E_{mod} = 6.1S_t + 100\,(Mpa) \tag{1}$$

Where: S_t = indirect tensile strength (kPa).

The test results were used to evaluate and compare the performance of different mixtures based on stability, strength, and deformation resistance. This allowed for identifying the optimum mixing ratio that produces specimens with the highest mechanical strengths for effectively resisting tensile and compressive stresses experienced in road patching applications.

3. Result and Discussions

3.1 Marshall stability

The Marshall stability test is a crucial indicator of the performance of plastic-aggregate mixtures for road maintenance applications. Figure 2 presents the Marshall stability values for the various mixing ratios evaluated in this study, revealing a clear trend: the stability of the

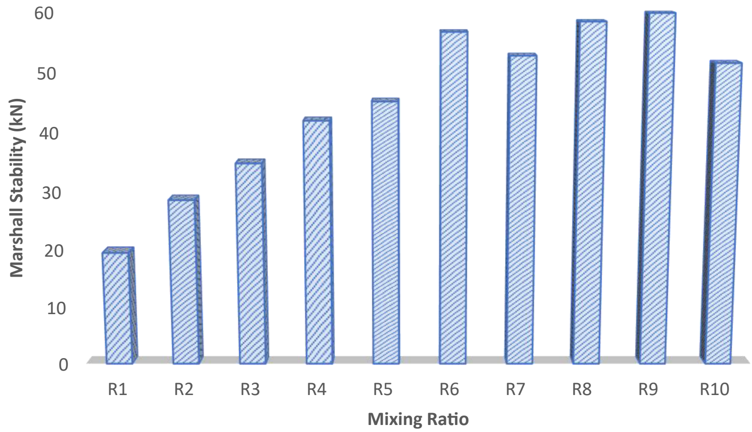

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Figure 2. Marshall stability of the various mixtures

specimen mixtures, comprising waste plastic bottles (PET) and aggregates, increases with a higher proportion of aggregates and a lower PET content. Specifically, the stability values incrementally rise from Ratio 1 (100% PET) to Ratio 6 (30% PET and 70% coarse aggregates). This increase is attributed to the reduction in plastic content and the corresponding increase in aggregate quantity, which collectively enhance the overall stability and resistance to deformation under loading.

The addition of fine aggregates (sand) to the mixtures in Ratios 7, 8, and 9 resulted in a notable increase in stability compared to their counterparts without fine aggregates (Ratios 2, 5, and 6, respectively). This enhancement indicates that fine aggregates create a denser, more compact matrix. As a result, they improve the overall stability of the mixtures. The highest Marshall stability value of 59.776 kN was observed for Ratio 9, comprising 30% PET, 30% fine aggregates (sand), and 40% coarse aggregates. This stability value significantly exceeds the typical range of 7–15 kN for conventional asphalt mixtures and the minimum requirement of 9 kN specified by the Tanzania road construction standards (URT, 2000b). The use of such a mixture for road pothole repair can potentially provide superior resistance to deformation under heavy traffic loads, thereby extending the lifespan of the repaired road surface.

It is important to note that mixtures with very high PET content, such as Ratio 1 (100% PET) and Ratio 2 (70% PET, 30% aggregates), exhibited the lowest stability values. This reduction in stability can be attributed to the predominance of plastic material, which tends to accelerate surface cracking and reduce the overall stability under loading conditions. Additionally, Ratio 10 (25% PET, 35% fine aggregates, and 40% coarse aggregates) demonstrated a deterioration in stability compared to Ratio 9, suggesting that a plastic content below 30% may weaken the binding between aggregates, adversely affecting the mixture's stability. Ratio 7 (70% PET, 10% fine aggregates, and 20% coarse aggregates) demonstrates a notable trend. It shows a rapid decrease in stability due to the high proportion of plastic material relative to the aggregates.

This study, while unique in its exclusive use of plastic waste, fine aggregates, and coarse aggregates for pothole repair, aligns with similar observations on the Marshall stability test reported in other studies which use plastic waste, bitumen, and aggregates. Research has consistently shown that the Marshall stability values increase with the addition of PET up to a certain threshold, after which the stability begins to decrease. For instance, Ahmadinia *et al.* (2011) observed that the Marshall stability values increased with the addition of PET until a maximum level was reached at 6% PET content, after which the stability started to decrease. Similarly, Moghaddam *et al.* (2013) reported an increase in Marshall stability up to an optimum PET content of 0.6% by weight of aggregate particles, beyond which higher plastic content reduced the stability. Köfteci (2016) found that the addition of HDPE-based waste material as a bitumen modifier led to a slight increase in Marshall stability at 2% and 3% HDPE content. Hinislioglu *et al.* (2005) also reported an increase in Marshall stability with the incorporation of HDPE, with the maximum increase observed at 4% HDPE content. Jassim *et al.* (2014) investigated the effect of replacing a portion of aggregates with plastic waste and observed an increase in Marshall stability, with the optimum value achieved at 15% aggregate replacement.

The incorporation of waste plastic bottles (PET) and aggregates in appropriate proportions has yielded mixtures with superior stability compared to conventional asphalt mixtures, as indicated by the findings from the Marshall stability test. Ratio 9 stands out as the optimal blend, exhibiting the highest stability value. This sustainable approach promises to enhance the durability and longevity of road pothole repairs while promoting the efficient utilization of waste materials. The utilization of waste plastic bottles within aggregates for road pothole repair has the potential to enhance the road surface's resistance to deformation from repetitive heavy traffic loads. The superior mechanical performance of Ratio 9, relative to customary asphalt formulations, suggests that plastic-aggregate mixtures produced at this optimized blend ratio may present a sustainable solution for maintenance applications seeking cost-effective road repair using available waste materials. By carefully blending materials, one can harness the potential of waste plastic incorporation to improve critical mechanical properties essential for durable road repair applications.

3.2 Indirect tensile strength

The indirect tensile strength (ITS) is a critical parameter that influences the cracking resistance and overall performance of asphalt concrete mixtures. This study investigated the ITS of various mixtures comprising waste plastic bottles, fine aggregates (sand), and coarse aggregates. The aim was to develop a sustainable method for road pothole repair. The mixture compositions tested ranged from R2, which included 70% plastic, 0% sand, and 30% coarse aggregate, to R10, with 25% plastic, 35% sand, and 40% coarse aggregate, among other varied ratios.

An increase in ITS values was observed as the plastic content decreased and the coarse aggregate proportion increased (refer to Figure 3). Mixtures R2 to R6, which consisted only of plastic and coarse aggregates, showed an increase in ITS. This trend is due to the enhanced interlocking and load distribution among the coarse aggregate particles, which strengthens the overall mixture. However, the high plastic content in R2 (70%) resulted in a notably lower ITS of 2,813 kPa. This is likely due to the mismatched thermal expansion and contraction rates between the plastic and aggregates, leading to cracking and reduced integrity.

The inclusion of fine aggregate (sand) in the mixtures (R7, R8, and R9) resulted in a further increase in ITS compared to their counterparts without sand (R2, R5, and R6). This enhancement is attributed to the improved particle packing and increased surface area for adhesion provided by the sand particles. The highest ITS of 5,909 kPa was achieved by R9, which comprised 30% plastic, 30% sand, and 40% coarse aggregate. This value exceeds the minimum ITS requirement of 800 kPa for asphalt concrete mixes as per the Tanzania Road Construction Specifications (URT, 2000b). These findings align with previous studies (Ahmadinia *et al.*, 2011; Moghaddam *et al.*, 2013) that reported an increase in ITS with the optimal addition of polyethylene terephthalate (PET) to asphalt mixtures. However, an excessive amount of PET can negatively affect the ITS due to the agglomeration of PET on the aggregate particles' surfaces, which weakens the asphalt-aggregate adhesion.

A decrease in ITS was noted for R10, where the plastic content was reduced to 25%. This reduction may have compromised the adhesive capacity of the mixture, resulting in weaker aggregate interlocking and a lower ITS of 5,189 kPa. The observed decrease in indirect tensile

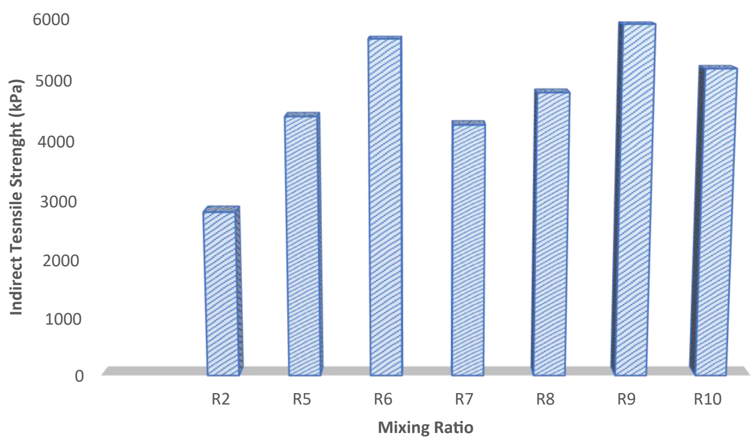

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Figure 3. Indirect tensile strength for various mixtures

strength from R9 (5,909 kPa) to R10 (5,189 kPa) can be attributed to the reduction in PET content from 30% to 25%. This decrease suggests that a minimum threshold of PET is necessary to maintain optimal binding between aggregate particles. With less PET, the interfacial adhesion between the plastic matrix and aggregate particles may be compromised, leading to reduced tensile strength (Nonato and Bonse, 2016). Additionally, the increased proportion of fine aggregates in R10 may have altered the overall particle packing, potentially creating more void spaces that weaken the composite structure.

Although no similar studies focused exclusively on plastic waste and aggregates, this finding is consistent with Ameri and Nasr (2017), observation that the ITS of a standard asphalt mixture was higher than that of modified mixtures containing waste PET, with the highest ITS of the modified mixtures being 1,049 kPa (8% plastic). These results suggest that while the addition of PET can improve the ITS compared to control mixtures without PET, the optimal proportion and mixture design require careful consideration to achieve ITS values that are comparable to or better than those of traditional asphalt mixtures.

It is important to note that ITS is affected by various factors, including temperature. Ahmadinia *et al*. (2011) highlighted that ITS decreases with an increase in temperature, emphasizing the need for a thorough evaluation under different environmental conditions to ensure the long-term effectiveness of these mixtures.

3.3 Stiffness modulus

The stiffness modulus is a critical parameter that reflects a material's capacity to withstand deformation when subjected to applied forces. In the context of road construction and pothole repair, materials with a higher stiffness modulus are preferred due to their superior load-bearing capabilities and resistance to rutting and cracking. Nonetheless, an excessively high stiffness modulus may induce fatigue cracking, underscoring the importance of achieving an optimal balance (Shah *et al*., 2023).

Supplementary Figure S4 illustrates mixtures containing 30% polyethylene terephthalate (PET) with varying proportions of gravel and sand exhibit elevated stiffness modulus values compared to other compositions. The R9 mixture (30% PET, 30% sand, 40% gravel) demonstrated the highest stiffness modulus of 36,145 MPa, surpassing the R6 mixture (30% PET, 70% gravel) at 34,699 MPa. The superior performance of R9 can be attributed to its optimized particle size distribution. The inclusion of sand leads to better particle packing, effectively filling voids between larger gravel particles and creating a more cohesive structure (Xiao and Tutumluer, 2017). Sand particles act as a bridge between the PET matrix and gravel aggregates, enhancing load transfer and distribution (Pukánszky and Vörös, 1996). This synergistic effect demonstrates that overall composition and particle interaction are more critical to stiffness than merely the quantity of coarse aggregates. The optimal R9 mixture (30% PET, 30% sand, 40% gravel) achieves a balance between the binding properties of PET and the structural integrity provided by aggregates. The 30% PET content ensures sufficient polymer chains to create a robust binding network, while the equal proportion of sand provides optimal particle packing. The 40% gravel content contributes to the composite's load-bearing capacity and deformation resistance. This composition aligns with principles of composite material design, where an optimal balance between matrix (PET) and reinforcement (aggregates) is important for maximizing mechanical properties (Shubham and Ray, 2024). Notably, the R10 mixture, with a PET content below 30%, showed a decline in stiffness. This observation underscores the importance of maintaining an optimal PET content (approximately 30%) to ensure a robust bond between aggregates. Insufficient PET content appears to weaken this bond, diminishing the overall stiffness of the mixture.

This study is distinct in its exclusive use of plastic waste, fine aggregates, and coarse aggregates for pothole repair and aligns with similar findings from stiffness modulus tests in other studies that included plastic waste, bitumen, and aggregates. Various research initiatives have investigated the effects of incorporating waste plastics, particularly PET, on the stiffness modulus of asphalt mixtures. Moghaddam and Karim (2012) observed that the stiffness of PET-augmented mixtures lessened at elevated stress levels, indicating that PET incorporation bolsters the mixture's flexibility. Remarkably, mixtures fortified with 1% PET displayed consistent stiffness values across different stress levels. Moghaddam *et al*. (2013) noted a 3.88% increase in stiffness when a precise 0.2% PET (by aggregate weight) was added to the mixture under stress levels of 250 kPa, 350 kPa, and 450 kPa. However, they remarked that an escalation in PET content beyond the optimal threshold resulted in a reduction of specimen stiffness. Ameri and Nasr (2017) reported a 4% and 6% increase in the stiffness of modified asphalt mixtures with the addition of 0.4% and 1% plastic, respectively. Yet, a further increment in plastic content to 8% and 10% led to a stiffness decrement. This pattern suggests that plastics can amplify stiffness to a certain extent, after which the stiffness diminishes.

Remarkably, the stiffness of PET mixtures surged by an impressive 539.5% upon the addition of an optimal 6% PET (by mixture weight) (Shah *et al*., 2023). These collective insights affirm that the integration of waste plastics, particularly PET, can substantially elevate the stiffness modulus of asphalt mixtures, contingent on the optimization of plastic content. An ideal plastic quantity boosts stiffness and rutting resistance, whereas an excessive amount may reduce stiffness. The precise optimal plastic percentage may fluctuate based on the plastic variety, asphalt mixture formulation, and test conditions.

The strategic incorporation of recycled plastic bottles (PET) and judicious aggregate selection (gravel and sand) was pivotal in enhancing the stiffness modulus and overall efficacy of the mixtures examined in this study. The optimal mixture proportion (R9: 30% PET, 30% sand, 40% gravel) attained the highest stiffness modulus, surpassing the traditional asphalt mixture employed for pothole repair in Tanzania. These results propose that the innovative, sustainable method utilizing waste plastic bottles and aggregates could offer a feasible and eco-friendly alternative for road pothole repair, potentially addressing both infrastructure upkeep and waste management issues.

3.4 Socio-economic and environmental implications

The integration of recycled polyethylene terephthalate (PET) plastic bottles with locally sourced aggregates for pothole repair is a forward-thinking strategy that promotes environmental sustainability and economic efficiency. This method is anchored in the principles of the circular economy, which aims to convert waste into valuable resources, thereby reducing PET bottle waste in landfills and addressing plastic pollution (Lamba *et al*., 2022). The plastic-aggregate composite minimizes the need for virgin materials and lessens the ecological impact associated with road maintenance (Sparrevik *et al*., 2021). Implementing this composite material supports several United Nations Sustainable Development Goals (SDGs), particularly those related to Industry, Innovation, and Infrastructure (SDG 9), Sustainable Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13) (Bernstein, 2017). Utilizing local plastic waste and aggregates can significantly lower carbon emissions and energy consumption that are typically associated with the extraction and transportation of raw materials, thereby lessening the overall environmental footprint of road construction (Zhong *et al*., 2021). Economically, the enhanced durability and performance of the plastic-aggregate composite indicate a potential for a longer service life and reduced maintenance needs for road infrastructure, leading to considerable cost savings by decreasing the frequency of repairs and related traffic disruptions (Okte and Al-Qadi, 2020). The material's resistance to wear and deformation suggests a lower life-cycle cost for road infrastructure, offering a cost-effective solution, especially for developing regions where traditional repair materials may be less accessible (Riekstins *et al*., 2020). Moreover, the application of this composite has the potential to create new economic opportunities within the waste management and construction industries, fostering job creation and sustainable economic growth (Ogundana, 2023). This aligns with the circular economy's ethos, where waste is transformed into a resource, promoting sustainable development.

3.5 Limitations and future research directions

While this study yielded promising results, several limitations were identified, highlighting critical areas for future research to advance the application of plastic waste in sustainable road construction.

(1) Scope of Laboratory Tests: This study relied on specific tests like Marshall stability, indirect tensile strength, and stiffness modulus. However, aspects such as fatigue resistance, thermal stability, and water sensitivity were not evaluated. Future research should include these properties and conduct comprehensive field trials under various conditions to better understand long-term performance and durability.

(2) Focus on PET Plastic: The study concentrated solely on polyethylene terephthalate (PET) plastic. This narrow focus limits the generalizability of results to other types of plastic waste. Future research should explore a wider range of plastic types or mixtures to provide a more comprehensive solution to plastic waste management in road construction.

(3) Controlled Laboratory Conditions: Evaluations were conducted under controlled conditions, which may not fully represent real-world scenarios. Field performance and durability evaluations under actual traffic loads, varying weather conditions, and exposure to environmental factors are necessary to predict long-term performance in real-world applications.

Addressing these limitations through targeted future research will be essential for transitioning this innovative approach from a laboratory concept to a widely adopted, sustainable solution for road maintenance. The potential benefits in terms of waste management, resource conservation, and infrastructure durability make this a promising area for continued investigation and development.

4. Conclusions

This study explored the use of a plastic-aggregate composite mixture as a sustainable material for repairing road potholes, demonstrating both technical and environmental advantages over conventional asphalt. The optimized mixture, comprising 30% recycled PET plastic, 30% sand, and 40% gravel, exhibited superior mechanical properties. Laboratory tests conducted according to Tanzanian Central Materials Laboratory standards (ASTM D1559-89 and ASTM D3967) revealed remarkable results: Marshall stability of 59.78 kN (far exceeding the minimum requirement of 5.34 kN for road construction), Indirect Tensile Strength of 5,909 kPa, and a Resilient Modulus of 36,145 MPa. These values indicate exceptional strength, durability, and stiffness, surpassing typical performance requirements for road infrastructure in Tanzania. This plastic-aggregate composite offers a simple and economical solution to the dual challenges of plastic waste management and infrastructure repair in developing nations, aligning with circular economy principles and contributing to progress towards the United Nations Sustainable Development Goals. Despite acknowledged limitations, the study underscores the promising potential of this composite as a sustainable road repair alternative, highlighting the importance of innovations that utilize local materials and promote circular economy principles. This approach transforms a prevalent waste stream into a valuable resource. In doing so, it paves the way for infrastructure development that is cost-effective, environmentally friendly, and socially responsible. This is particularly beneficial for regions facing budgetary constraints and plastic pollution challenges. The findings are served as a foundation for future research in sustainable road maintenance practices, with the vital need for multifaceted solutions emphasized as infrastructure degradation and plastic waste management. are grappled with. The potential of this plastic-aggregate composite is extended beyond mere road repair, representing a step towards more sustainable, resilient, and economically viable infrastructure systems.

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Supplementary material

The supplementary material for this article can be found online.

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