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Innovative Integration of Recycled Plastics for Flexible Pavement Design

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Plastic waste is a major problem due to its non-biodegradable nature. Incorporating recycled plastic in road construction enhances mechanical properties effectively. This paper encompasses methods to solve two major issues in Nepal, largely focused in major cities of Nepal: primarily, the management of solid waste, specifically with consideration of used plastics which have engulfed main cities; secondarily, the development of potholes on roads due to heavy traffic weight and some environmental factors such as excessive precipitation and infiltration, flooding conditions. This study inspects the effect of combining waste thermoplastic polymers like High-density polyethylene (HDPE), Polyethylene Terephthalate (PET), and Polypropylene (PP) in flexible pavement design, at various plastic compositions. The plastics were grinded and mixed with the bitumen at a temperature range of 160 °C–170 °C. Various tests such as the Marshall Stability test, Penetration test, Ductility test, and, Softening Point test were carried out to find the resulting modifications from base bitumen. It was observed that the plastic mixed sample upto 10% by weight shows sufficient mechanical properties of pavements. Being a cheap and effective way of improving the capacity of flexible pavement, It is one of the alternative ways to use plastic waste.

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1. INTRODUCTION

1.1 Background

Roads are the predominant mode of transportation in Nepal. Nepal's road network consists of about 64,500 KM of road. The road network density is very low, at 14 KMs per 100 KM2 and 0.9 KM per 1000 people as per 2070 statistics [1].

Due to rapid growth in various industries and population, there has been a noticeable surge in the generation of different types of waste materials. This has become a significant concern in both developed and developing countries, particularly when it comes to disposing of non-degradable waste materials. In 2015, the primary production of PET plastics in the world reached 68 million tonnes [2]. According to the Plastics Division of the American Chemistry Council and the Association of Plastic Recyclers, $2.782 x 10^6$t (1726 million pounds) of postconsumer PET bottles existed in 2017 in the United States; only 29.2% of them were recycled [3]. To address this issue, recycling waste materials into useful products is widely regarded as a highly sustainable solution. Consequently, there is extensive encouragement for research and exploration of innovative applications for waste materials. [4] applied shredded PET bottles, size: 0.425–1.18 mm to an asphalt mixture through the dry method and reported that the PET particles improved the fatigue behavior and stiffness of the asphalt mixture.

Hassani A., Ganjidoust H., Maghanaki AA., [5] replaced a 3.36–4.75 mm aggregate in an asphalt mixture with waste PET granules (~3 mm) and reported that the PET-modified mixture provided a similar Marshall stability and lower Marshall flow compared to those of the control mixture without PET. When PET-derived additives were added, the rubberized bitumen could maintain its original deformation resistance at 64°C and high stress of 3.2 kPa [6]. These studies explore various aspects such as performance, suitability, environmental considerations, and feasibility of utilizing each material. Their objective is to find a balanced combination that ensures both safe and cost-effective disposal of waste materials, while also improving the quality and affordability of construction materials. The cost saved in road construction by using waste plastic in the composition of about 11% by weight is $670 per km [7]. The use of plastic that is 5–10% of bitumen improves the Marshall stability, strength, fatigue life, and other required properties that go a long way to increase the lifespan of the road whereas some bitumen is saved too [8]. Plastics, predominantly consisting of High-Density Polyethylene (HDPE), Polyethylene Terephthalate (PET), and Polypropylene (PP), are extensively used in packaging. Several studies have been conducted to explore the potential utilization of waste plastic bags and plastics in general for asphalt mixtures. Depending on their chemical composition and physical properties, these materials have been employed as modifiers for binders or as coatings for aggregates. The results have been promising, demonstrating an improvement in the performance of the modified asphalt mixes.

The reuse of plastic waste has also been practiced in Nepal. Plastic wrappers from noodles, biscuits, milk packets, and tobacco products were used to blacktop a 100-meter plastic road in Annapurna Marga, Pokhara, Nepal in 2018 A.D.

1.2 Objectives

The basic intention behind this research is to utilize the waste plastic efficiently for construction purposes such that it proves to be useful to society.

The main objectives are:

- To utilize the waste plastic in road construction that end up in a landfill.
- To study the effects of adding different percentage of waste plastic as an aggregate cover on the properties of asphalt mix comparing it with conventional mix properties.
- To identify the optimum percent of waste plastic to be added to the hot mix asphalt.

1.3 Limitations

The results of this study depended on a set of limitations that were taken into account during the work. These limitations include:

- High-density polyethylene (HDPE), Polyethylene-Terephthalate (PET), and Polypropylene (PP) were studied for Dry Process.

- HDPE and PP are only studied for Wet Process.
- Waste plastics are added as an aggregate coat in the asphalt mix.
- Percentages of waste plastics are utilized in asphalt mix within the range of 8 – 14% with 2% incremental by weight.
- The carbon dioxide emission rate and quantity are not measured.

2. METHODOLOGY

2.1 Material

Bitumen: The bitumen with a penetration grade of 60/80 was used in this experiment. To evaluate mix properties number of laboratory tests have been performed such as specific gravity, ductility, softening point, and penetration.

Aggregate: Different sizes of aggregate were used for the preparation of our test specimen with the help of different sizes of sieves. The aggregate of sizes 12.5 mm as coarse, 4.5 mm size as fine, and 2 mm size as filler material (Fig.4) were used. They were separated with the help of a sieve shaker.

Plastic: Plastic waste was collected from various sources such as roads, garbage trucks, dumping sites, rag pickers, recycling centers, waste management facilities, and community initiatives. The collected plastic waste was thoroughly cleaned to remove any impurities or residues. After cleaning, the plastic waste was shredded into smaller pieces of 2-5mm size. Shredding increases the surface area of the plastic, making it easier to mix and incorporate into the road materials.

2.2 Wet Process

HDPE and PP are powdered and added to the bitumen with 8-14% of the total weight with 2% increment at 155˚C-165˚C [9]. The melting point of HDPE and PP are around 160˚C so, they become a key plastic type to be used in this process. Various tests like Penetration Test, Softening Point Test, and Ductility Test that were originally developed to test bituminous material are carried out on the specimen prepared by wet process.

2.3 Dry Process

For the flexible pavement, hot stone aggregate (170°C) is mixed with hot bitumen (160°C), and the mix is used for road laying. The aggregate is chosen on the basis of its strength, porosity, and moisture absorption capacity. The bitumen is chosen on the basis of its binding property, penetration value, and viscous-elastic property. In this process, the plastics are chopped finely and then poured over the heated aggregates (Fig.5), thereby, forming plastic-coated aggregates which are then mixed with hot bitumen to form a plastic-coated aggregate bitumen mixture (Fig.6) for laying roads. The coating of plastic decreases the porosity and helps to improve the quality of the aggregate and its performance in the flexible pavement. The dry process usually consumes 15% of plastic waste and is frequently used due to low energy investment [10, 11]. Marshall Stability Test is carried out on the specimen prepared by dry process.

3. RESULTS AND DISCUSSION

3.1 Specific Gravity Test for Bitumen

The Specific Gravity test of bitumen is a valuable method to determine its density and assess its quality for construction purposes. By measuring the relative density, this test offers insights into the suitability of bitumen for different applications. Additionally, it can detect mineral impurities within the bitumen specimen, as a higher specific gravity indicates a larger quantity of such impurities. This information is particularly useful for extracting impurities from bitumen, ensuring a higher purity level. Overall, the specific gravity test plays a significant role in evaluating and optimizing the performance of bitumen in construction projects.

The test result was obtained at 27℃ and was found to be 1.01 gm/cm^3 which is the expected result as the range of specific gravity of pure bitumen is (0.97 to 1.02) gm/cm^3 [12].

3.2 Penetration Test

The Penetration Test of the specimen prepared by wet process involves measuring the consistency and hardness by penetrating it with a steel needle carrying a 100g load for 5 seconds at a temperature of 25°C. The penetration value, measured in 1/10 mm, helps determine the hardness, softness, and consistency [12]. This test is essential for assessing the suitability of the plastic-bitumen mix for construction purposes and ensuring its appropriate composition for safe use.

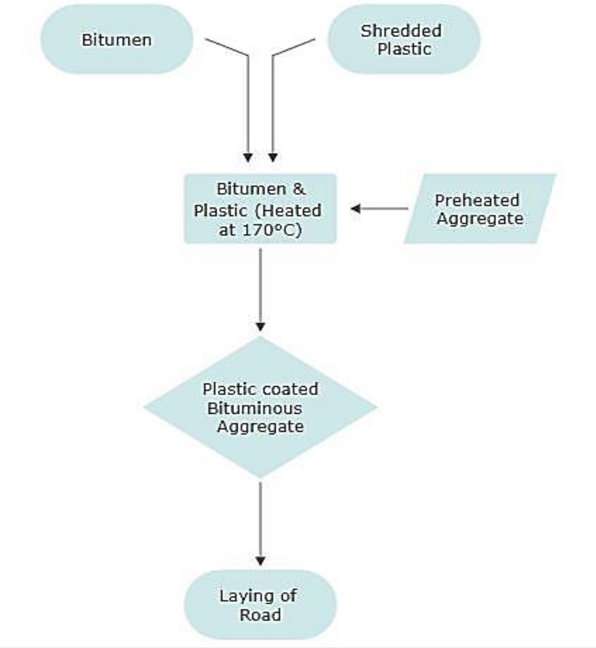

Fig. 1. Wet Process

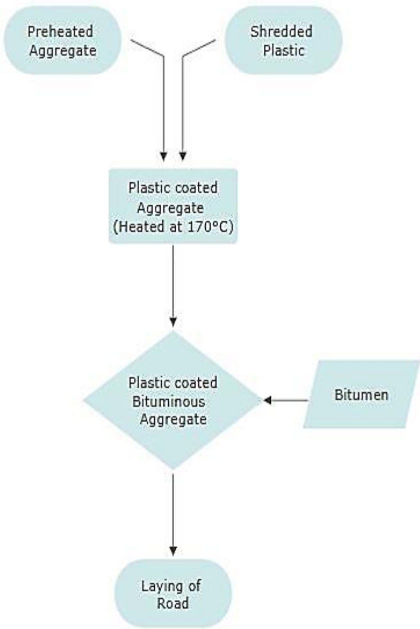

Fig. 2. Dry Process

Fig. 3. Bitumen-Plastic sample

Fig. 4. Aggregate sample

Fig. 5. Plastic Coating of Aggregate

Fig. 6. Sample Mix

Fig. 7.8%,10%,12%, and 14% plastic mixes samples (from left)

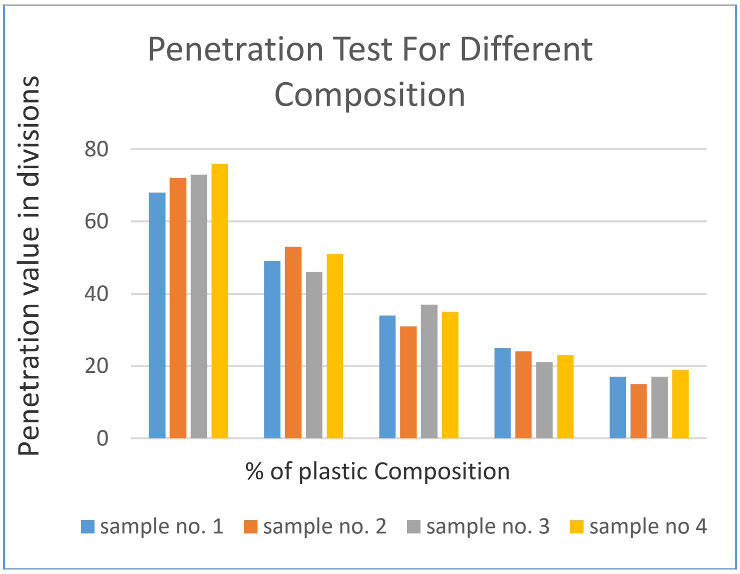

Fig. 8. Penetration value for different samples of the mix

From the above test, The bituminous specimen with plastic content 0, 8, 10, 12, and 14 percent of the weight of the bitumen shows penetration value in the range of 30 to 80 mm. For pure bitumen, the penetration value should lie between 60 to 80 mm [12] but in the case of plastic-used bitumen, 30 to 80 mm is acceptable.

3.3 Softening Point Test

The Softening Point of the specimen is the temperature at which it reaches a soft, flowable state under a specific load or deformation. This property is crucial in determining the suitable temperature range for various road applications. The softening point is typically determined using the Ring and Ball method, where a sample is heated in a brass ring with a steel ball placed on top. As the temperature increases, the specimen softens and starts to flow. The point at which the ball sinks a prescribed distance is recorded as the softening point [12]. This test provides essential information about the plastic-bitumen mix behavior under different temperature conditions, aiding in the selection and application in road construction.

From the above test performed, we found that the softening value of all sample mixes is above 45℃ which is acceptable since the required minimum value should be in the range between (45-55) ℃ [12].

3.4 Ductility Test

Ductility refers to the property of the specimen that allows it to deform or elongate without breaking. It is measured by the distance, in centimeters, that a standard specimen can stretch before it fractures when pulled at a specified speed and temperature. Ductility plays a vital role in applications where flexibility and elongation are critical, such as road construction and pavement materials. This property indicates the ability to withstand tensile stresses and deformations without failure, making it important for ensuring the durability and performance of infrastructure [12]. Ductility testing also serves as a quality control measure during construction process and assists in selecting the suitable composition for specific climatic and traffic conditions.

A good bituminous sample should have a minimum ductility value of 45 cm for its use in the construction of roads [12]. So, from the above test, the specimen with up to 10% of the plastic percentage by weight of the bitumen is accepted.

3.5 Marshall Stability Test

The Marshall Stability test is a fundamental method for assessing the load-bearing capacity and resistance to deformation of asphalt mixtures. This test involves shaping cylindrical specimens from the mixture, conditioning them, and applying compressive loads to determine their maximum load-bearing capacity without deformation or failure [13]. By conducting this test, valuable insights into the strength, stability, and flow characteristics of the asphalt mixture can be obtained. This information is essential for evaluating the suitability of the mixture for road construction and assessing its performance under varying traffic loads. Widely used in the asphalt industry, the Marshall Stability test plays a crucial role in optimizing mix design, ensuring quality control, and driving research and development efforts related to asphalt materials and technologies.

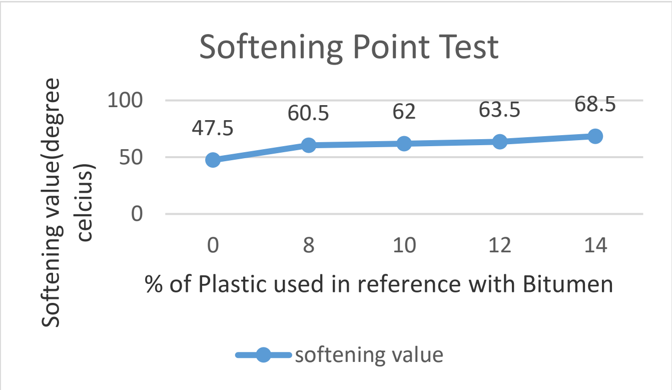

Fig. 9. Softening value for different samples of the mix

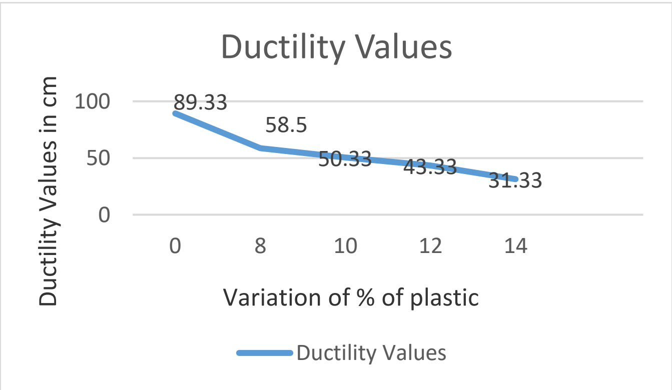

Fig. 10. Ductility value for different samples of the mix

3.5.1 Marshall stability load test

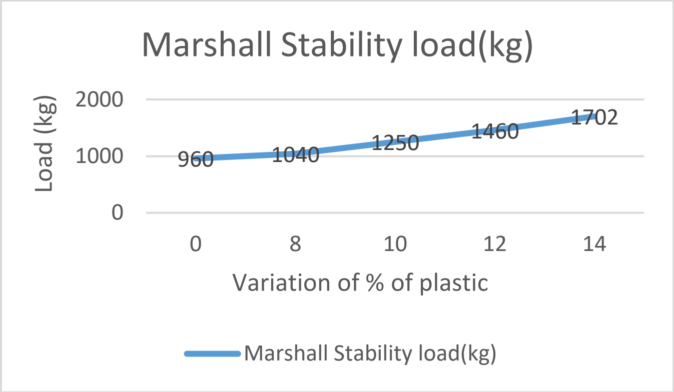

Fig. 11. Marshall stability load for different samples of the mix

For the above test performed, the chart indicates that specimens of all the compositions of plastic are suitable for bearing heavier loads, as they exceed the desired Marshall stability value of 900kg traffic load [13]. Therefore, a range of compositions can be considered suitable for the intended construction project.

3.5.2 Flow Value

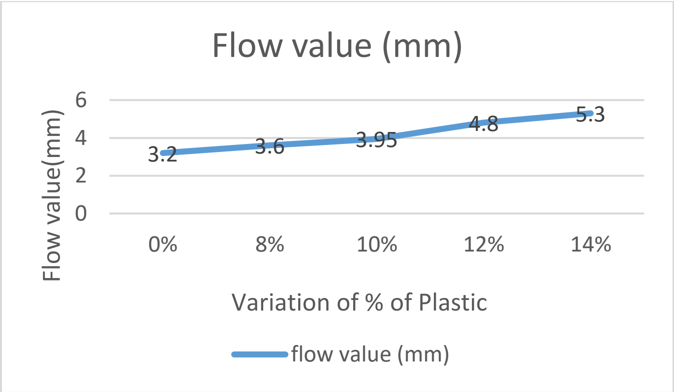

Fig.12. Flow value for different samples of the mix

Mixes with very high Marshall stability values and low Flow values are not desirable as the pavements constructed with such mixes are likely to develop cracks due to heavy moving loads if the pavement components permit relatively high deflection values.

The flow value should be in the range of 2-4mm [13]. The chart indicates that compositions with 8% and 10% plastic are more suitable.

Table 1. Stability test result

Test	Pure bitumen (0%)	8% Plastic	10% Plastic	12% Plastic	14% Plastic	Standard Value
3.2	72.25	49.75	34.25	23.25	17	30-80mm
3.3	47.5	60.5	62	63.5	68.5	>45ºC
3.4	89.33	58.5	50.33	43.33	31.33	>45cm
3.5.1	960	1040	1250	1460	1702	>900kg
3.5.2	3.2	3.6	3.95	4.8	5.3	2-4mm

The mix-up to 10% by weight of bitumen shows adequate results in Marshall Stability, Penetration, Softening, and Ductility tests. As the bitumen content is reduced and locally available plastic waste is utilized, it helps in cost reduction.

4. CONCLUSION

The generation of waste plastics is increasing day by day. The major polymers namely polyethylene, polypropylene, and polystyrene show adhesion properties in their molten state. Plastic will increase the melting point of the bitumen. The waste plastic bitumen mix up to 10% by weight of bitumen forms better material for pavement construction as the mix shows an adequate result in Marshall Stability, Penetration, Softening, and Ductility tests. The cost reduction is also achieved. Hence the use of waste plastics for pavement is one of the methods for easy disposal of waste plastics. Plastic roads would be a boon for Nepal's hot and humid climate, where temperatures frequently cross 35℃ and torrential rains create havoc, leaving most of the roads with big potholes. Further studies can be carried out on performance criteria such as rutting and aging. Replacing a certain part of bitumen with plastic in asphalt mixes for pavement construction, studying the rate of carbon dioxide (CO_2) and other harmful gas production can be a relevant and important area of research.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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