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Utilization of Polypropylene (PP) Plastic Waste as a Substitute for Fine Aggregate on Indirect Tensile Strength Performance in AC-WC Asphalt Mixtures

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Abstract: *The increasing amount of polypropylene (PP) plastik waste and the growing demand for natural aggregates in road construction have encouraged the use of sustainable alternative materials. This study investigated the effect of polypropylene waste as a partial replacement for fine aggregate on the Indirect Tensile Strength (ITS) of Asphalt Concrete-Wearing Course (AC-WC) mixtures and determined the optimum PP content. Laboratory experiments were conducted using the dry process with PP contents of 0%, 10%, 20%, 30%, 40%, and 50%. The Optimum Asphalt Content was determined using the Marshall method followed by ITS testing using the optimum asphalt content determined for each mixture. The results showed that mixtures containing up to 40% PP satisfied the Marshall specification, whereas the 50% PP mixture did not. The ITS value increased from 2.55 kg/cm2 to 3.85 kg/cm2 at 30% PP before decreasing to 3.24 kg/cm2 at 40%, indicating the optimum tensile performance.*

Keywords: AC-WC, waste plastik, polypropylene, fine aggregate replacement, indirect tensile strenght.

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I. INTRODUCTION

Plastic waste accumulation has become one of the most pressing environmental challenges worldwide due to the continuous increase in plastic production and consumption. Each year, more than 280 million tonnes of short-lived plastic products reach the end of their service life and become waste. According to (UNEP, 2023), approximately 46% of global plastic waste is disposed of in landfills, while around 22% is inadequately managed, thereby increasing the risk of environmental pollution. Owing to its lightweight nature, durability, and ease of processing, plastic has become an essential raw material for a wide range of industrial products and daily consumer goods (Boll, 2019). Unlike organic materials, plastics do not undergo natural biodegradation; instead, they gradually fragment into smaller particles that persist in the environment for hundreds or even thousands of years (Environmental investigation agency, 2021).

Plastic waste management has also become a major concern in Palu City, Indonesia.(Putri, N et al 2025) reported that approximately 70,000 tonnes of municipal solid waste were generated in 2024, of which around 7.7 tonnes consisted of plastic waste. In response to this issue, various types of waste materials and industrial by-products have been investigated as alternative materials for asphalt pavement construction, including their use as aggregate substitutes, mineral fillers, and asphalt modifiers, thereby reducing dependence on natural resources (Pasetto et al., 2022) The rapid expansion of road infrastructure in Palu has further increased the demand for natural aggregates, which are primarily obtained from riverbeds and surrounding mountainous areas. Continuous extraction of these materials may result in adverse environmental impacts, including erosion, landscape degradation, and depletion of natural aggregate resources. Therefore, the development of alternative construction materials is essential not only to reduce plastic waste accumulation but also to minimize excessive exploitation of natural aggregates, thereby supporting more sustainable road infrastructure development.

Globally, the recycling rate of plastic waste remains relatively low, at approximately 9%, indicating that the majority of plastic waste is not effectively recycled or reused (Environmental investigation agency, 2022). One promising approach in asphalt pavement engineering is the incorporation of recycled polypropylene waste as a partial replacement for fine aggregate using the dry process. In this method, recycled plastic particles are blended with heated aggregates prior to asphalt addition, allowing the plastic to function both as a partial aggregate substitute and as a modifier of the asphalt mixture (Movilla-Quesada et al., 2019). This approach has been recognized as an effective strategy for reducing dependence on natural aggregates while simultaneously improving the sustainability of pavement construction materials (Kamaruddin et al., 2017). Although numerous studies have investigated the incorporation of waste plastics into asphalt mixtures, most have focused primarily on their role as asphalt modifiers and on the evaluation of Marshall properties. (Susanto et al, 2021) reported that research on polypropylene waste has largely concentrated on Marshall performance, whereas investigations into the tensile properties of asphalt mixtures remain relatively limited.

Studies investigating the use of polypropylene waste as a partial replacement for fine aggregate in asphalt mixtures are still scarce, particularly those focusing on the Indirect Tensile Strength performance of Asphalt Concrete-Wearing Course (AC-WC) mixtures. The ITS test is widely used to evaluate the tensile resistance of asphalt mixtures, which is closely associated with their resistance to cracking under traffic loading. Therefore, this study aims to investigate the effect of polypropylene waste content as a partial replacement for fine aggregate on the indirect tensile strength of AC-WC mixtures. In addition, the study seeks to determine the optimum polypropylene content that satisfies the requirements of the 2025 Bina Marga General Specifications. The findings are expected to broaden the application of polypropylene waste as an alternative material in AC-WC mixtures while contributing to plastic waste reduction, conservation of natural aggregate resources, and the promotion of sustainable pavement construction practices.

II. EXPERIMENTAL PROCEDURE

2.1. Polypropylene.

Polypropylene (PP) is a thermoplastic polymer produced through the polymerization of propylene monomers. Owing to its low density, excellent mechanical properties, chemical resistance, and melting temperature of approximately 160–165°C, polypropylene is widely used in packaging materials and household products. These characteristics enable polypropylene to remain stable under asphalt mixing temperatures, making it a promising alternative material for asphalt pavement construction (Ma et al., 2021) (Pan et al., 2025).

2.2. Plastic Waste and Its Application in Asphalt Mixtures

Plastic waste has become one of the most critical environmental issues due to increasing plastic consumption, its resistance to natural biodegradation, and the relatively low recycling rate, all of which contribute to long-term environmental accumulation (Geyer et al., 2017). This situation has encouraged the development of various approaches for utilizing plastic waste as a construction material, thereby reducing environmental pollution while enhancing the economic value of waste materials (Pangestika et al., 2023) (Shah et al., 2025).

Previous studies have investigated the incorporation of several types of waste plastics into construction materials, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and polyethylene (PE) (Kamaruddin et al., 2017). . In asphalt pavement engineering, waste plastics are generally incorporated using two techniques: the wet process and the dry process. In the wet process, plastic is blended with asphalt binder to modify its properties before mixing with aggregates. In contrast, the dry process involves mixing recycled plastic with heated aggregates before the addition of asphalt binder, allowing the plastic to function both as a partial aggregate replacement and as a mixture modifier. The resulting performance of asphalt mixtures depends on both the type of plastic and the mixing technique employed (Latif and Setiawan, 2023) (Shah et al., 2025).

Among various plastic materials, polypropylene has attracted considerable attention because of its excellent mechanical strength, high chemical resistance, low density, and ease of processing. These characteristics make polypropylene a promising modifier for composite materials, including asphalt mixtures (Hossain et al., 2024). Although numerous studies have demonstrated that waste plastics can improve the physical and mechanical performance of asphalt mixtures, comprehensive environmental assessments remain essential to ensure that their application genuinely supports sustainable pavement construction (Wu et al., 2025).

2.3. Indirect Tensile Strength

The Indirect Tensile Strength (ITS) test is one of the most widely used methods for evaluating the tensile resistance of asphalt mixtures, which is closely associated with their resistance to cracking under traffic loading (Al-mosawy and Al-obaedi, 2023). Under vehicle loading, the upper layer of pavement is subjected to compressive stresses, whereas the lower layer experiences tensile stresses induced by pavement deflection. When the tensile stress exceeds the tensile capacity of the asphalt mixture, cracks generally initiate at the bottom of the pavement layer and gradually propagate toward the surface.

The Indirect Tensile Strength test is conducted by applying a diametral compressive load to a cylindrical asphalt specimen until failure occurs. The indirect tensile strength is calculated from the maximum applied load and is used to evaluate the tensile resistance of asphalt mixtures (Polytechnic et al., 2025). Consequently, the ITS value is widely accepted as an indicator of cracking resistance under repeated traffic loading and temperature variations. A higher ITS value indicates greater tensile resistance and, consequently, better pavement performance.

2.4. Research Location

This study was conducted at the UPT Laboratory of Public Works (Bina Marga), located on Jl. Towua No. 85, Palu City, Central Sulawesi, Indonesia.

2.5. Research Design

This study employed an experimental laboratory approach to evaluate the effect of recycled polypropylene waste as a partial replacement for fine aggregate on the indirect tensile strength of Asphalt Concrete-Wearing Course (AC-WC) mixtures. Different polypropylene contents were used as the experimental variable to investigate their influence on the tensile performance of the asphalt mixtures.

2.6. Materials

Aggregates

The aggregates were obtained from the Watusampu quarry, Palu City, through the production area of PT Sapta Unggul UD Maju. Aggregate samples were collected randomly from three different stockpile locations for the 3/4-inch crushed stone, 3/8-inch crushed stone, and stone dust fractions.

Asphalt Binder

The asphalt binder used in this study was 60/70 penetration grade asphalt manufactured by PT Pertamina, supplied by the UPT Laboratory and Material Testing Unit, Department of Highways and Spatial Planning, Central Sulawesi Province.

Polypropylene Waste

The polypropylene used in this study consisted of recycled polypropylene pellets obtained from PT Rajawali Plastik Indojaya, located in the Pantoloan Special Economic Zone, Central Sulawesi, Indonesia. The recycled polypropylene was used as a partial replacement for the fine aggregate fraction passing the No. 4 sieve and retained on the No. 8 sieve using the dry process.

Figure 1 Recycled polypropylene pellet

III. RESULTS AND DISCUSSIONS

3.1. Material Characteristics

The material characterization results indicated that both the aggregates and asphalt binder satisfied the requirements of the 2025 Bina Marga General Specifications, confirming their suitability for use in Asphalt Concrete-Wearing Course (AC-WC) mixtures. The characterization of recycled polypropylene showed a specific gravity of 0.909 and a melting temperature of approximately 160°C, indicating that the material possesses suitable physical properties for use as a partial replacement for fine aggregate in AC-WC mixtures.

3.2. Marshall Test

The Marshall test results demonstrated that the incorporation of polypropylene waste affected the characteristics of the AC-WC mixtures. Based on the Marshall analysis, the Optimum Asphalt Content (OAC) was determined for each polypropylene content using the mixture properties that satisfied the AC-WC specification requirements.

Table 1 Optimum Asphalt Content

PP Content (%)	OAC (%)	Specification
0	6,25	Satisfied
10	6,10	Satisfied
20	6,00	Satisfied
30	5,97	Satisfied
40	5,95	Satisfied
50	-	Not Satisfied

Mixtures containing 0–40% polypropylene satisfied all Marshall specification requirements, allowing the determination of the optimum asphalt content for each mixture. However, the mixture containing 50% polypropylene failed to satisfy the Marshall criteria specified in the 2025 Bina Marga General Specifications; therefore, no optimum asphalt content could be established for this mixture. These findings are consistent with those reported by (Tambunan and Putri, 2021), who observed that increasing polypropylene content improves Marshall characteristics only up to a certain limit, after which the performance deteriorates with further increases in polypropylene content.

3.2 Preparation of Modified AC-WC Specimens Using the Optimum Asphalt Content.

The modified AC-WC specimens were prepared using the optimum asphalt content determined from the Marshall test for each polypropylene content. All specimens used in the Indirect Tensile Strength (ITS) test were produced using the corresponding optimum asphalt content. This procedure ensured that the influence of polypropylene content on the tensile performance of AC-WC mixtures was evaluated under the optimum asphalt condition for each mixture.

3.3 Indirect Tensile Strength.

The Indirect Tensile Strength (ITS) increased progressively with increasing polypropylene content up to 30%, after which a reduction was observed at higher polypropylene contents.

Table 2 Indirect Tensile Strength Test Results

No	Specimen	PP Content	OAC	Specimen Thickness (t)	Specimen Diameter (D)	Maximum Load (Pmaks)	Indirect Tensile Strength
		(%)	(%)	cm	cm	kgf	Kg/cm^2
1	A	0	6,25	6,0	10,13	243,51	2,55
	B			6,0	10,15	229,73	2,40
	C			6,0	10,14	257,29	2,69
		Average		**6,0**	**10,14**	**243,51**	**2,55**
2	A	10	6,10	6,0	10,15	248,10	2,60
	B			6,0	10,12	261,89	2,75
	C			6,0	10,11	252,70	2,65
		Average		**6,0**	**10,13**	**254,23**	**2,66**
3	A	20	6,00	6,0	10,11	266,48	2,80
	B			6,0	10,14	261,89	2,74
	C			6,0	10,14	271,08	2,84
		Average		**6,0**	**10,13**	**266,48**	**2,79**
4	A	30	5,97	6,0	10,11	372,16	3,91
	B			6,0	10,15	362,97	3,80
	C			6,0	10,14	367,56	3,85
		Average		**6,0**	**10,13**	**367,56**	**3,85**
5	A	40	5,95	6,0	10,15	298,64	3,12
	B			6,0	10,12	307,83	3,23
	C			6,0	10,13	321,62	3,37
		Average		**6,0**	**10,13**	**309,36**	**3,24**

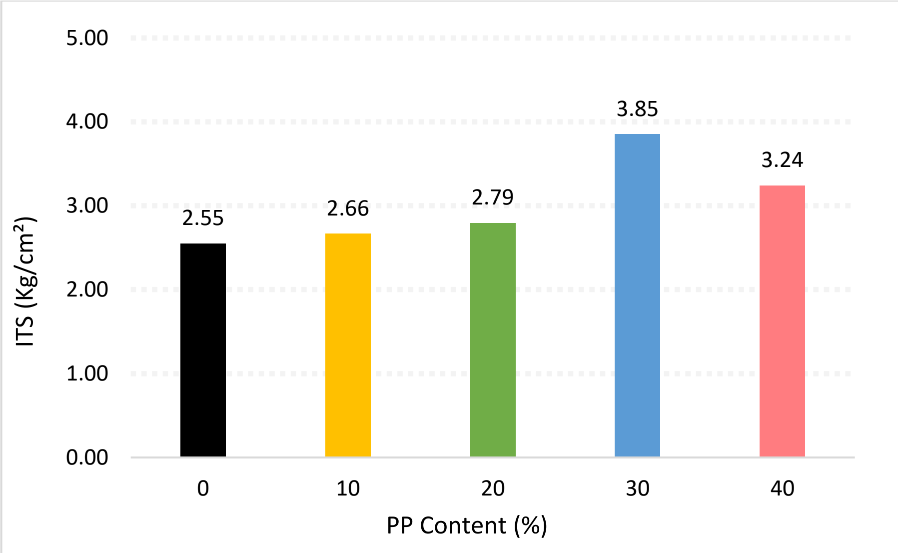


Figure 2 Relationship between Polypropylene Content and Indirect Tensile Strength

The test results indicate that the partial replacement of fine aggregate with recycled polypropylene significantly influenced the indirect tensile strength of the AC-WC mixtures. The average ITS increased from 2.55 kg/cm² for the control mixture (0% polypropylene) to 3.85 kg/cm² at a polypropylene content of 30%. This improvement demonstrates that the incorporation of polypropylene up to a certain level enhances the tensile resistance of the asphalt mixture.

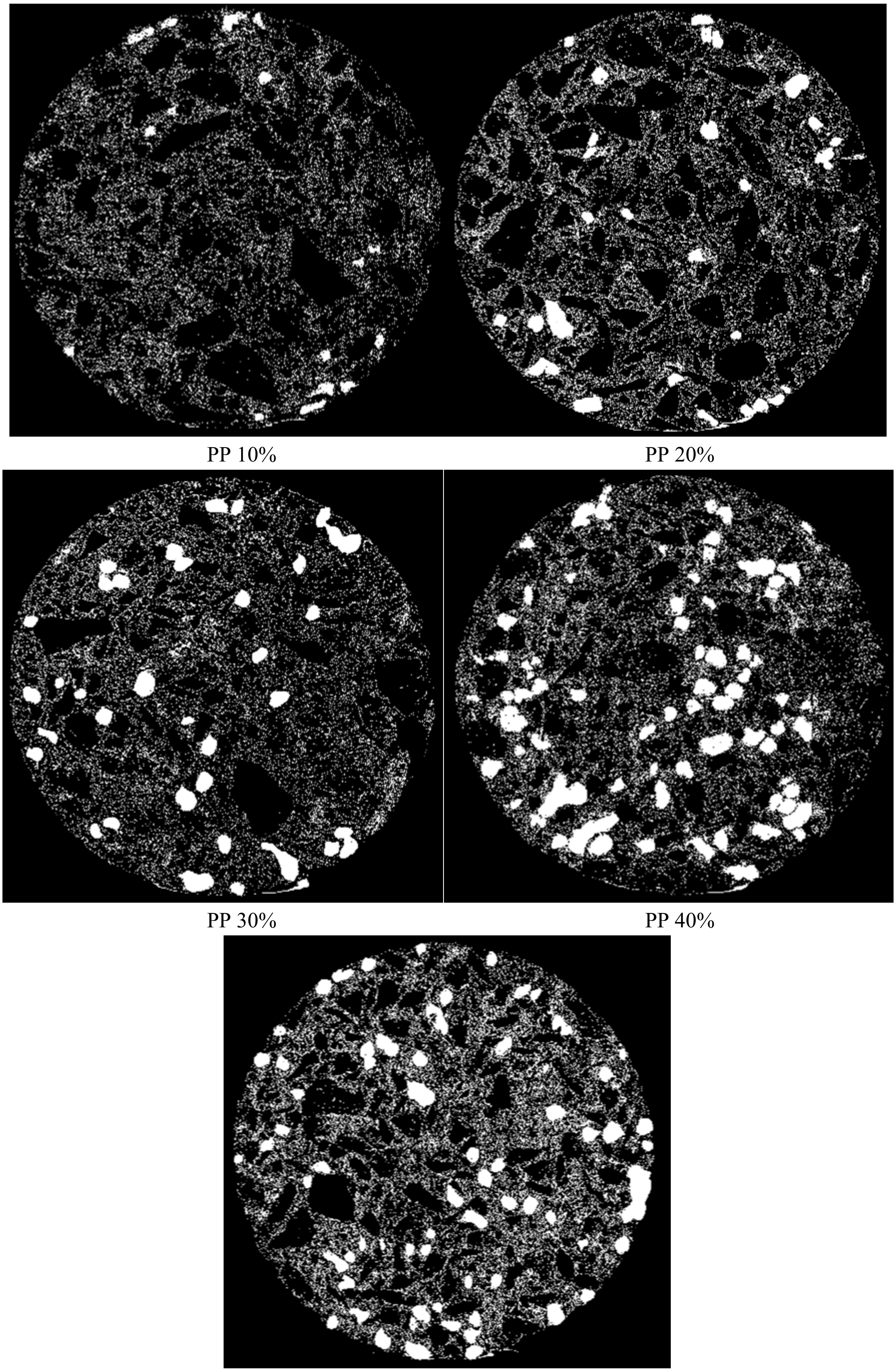
When the polypropylene content was increased to 40%, the ITS decreased to 3.24 kg/cm². Although this value was lower than that obtained at 30% polypropylene, it remained higher than those of the mixtures containing 0%, 10%, and 20% polypropylene. These results indicate that increasing the polypropylene content beyond 30% no longer provides additional improvement in tensile performance. Therefore, 30% polypropylene can be regarded as the optimum substitution level based on the ITS parameter.

Since the ITS test does not specify minimum or maximum acceptance criteria for asphalt mixtures, the evaluation was performed by comparing the ITS values among the different polypropylene contents. Based on the experimental results, the mixture containing 30% polypropylene exhibited the highest ITS value (3.85 kg/cm²), indicating superior tensile performance compared with the other mixtures. Accordingly, 30% polypropylene was identified as the optimum content with respect to the indirect tensile strength performance.

3.4 Visual Observation of AC-WC Mixtures.

Visual examination of the cross-sections of the Asphalt Concrete-Wearing Course (AC-WC) specimens revealed that the distribution of polypropylene particles increased with increasing substitution content. At a polypropylene content of 10%, only a small number of particles were visible. Their distribution became more apparent at 20%, while considerably greater particle dispersion was observed at 30% and 40%. The 50% polypropylene mixture exhibited the highest concentration of polypropylene particles among all mixtures.

The polypropylene particles generally retained their original pellet shape after the mixing process. This observation can be attributed to the melting temperature of polypropylene, which ranges from 160 to 170°C, whereas the mixing temperature of the AC-WC mixtures ranged between 155 and 165°C. Consequently, most polypropylene particles did not melt completely during mixing. Therefore, the visual observations primarily describe the distribution of polypropylene particles within the mixture and do not provide information regarding the microstructural interaction between polypropylene, aggregates, and asphalt binder.



PP 10% PP 20%

PP 30% PP 40%

PP 50%

Figure 3 Briquette Cross-Section Image Using ImageJ

IV. CONCLUSION

The incorporation of recycled polypropylene waste as a partial replacement for fine aggregate influenced the mechanical performance of Asphalt Concrete-Wearing Course (AC-WC) mixtures. The Marshall test results demonstrated that increasing the polypropylene content generally enhanced mixture stability while reducing the Optimum Asphalt Content (OAC), indicating an increase in mixture stiffness accompanied by a lower asphalt binder requirement.

The Indirect Tensile Strength (ITS) increased with increasing polypropylene content, reaching a maximum value of 3.85 kg/cm² at a 30% substitution level before decreasing at 40% polypropylene. These findings indicate that a polypropylene content of 30% provides the optimum tensile performance while simultaneously satisfying the Marshall specification requirements.

Overall, recycled polypropylene waste has considerable potential as a partial replacement for fine aggregate in AC-WC mixtures. In addition to improving the mechanical performance of asphalt mixtures up to an optimum substitution level, its utilization contributes to reducing the consumption of natural aggregates and promotes the development of more sustainable pavement construction materials.

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