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Influence of Tensile Load on Bonding Strength of Asphalt Concrete Containing Modified Buton Asphalt and Polyethylene Terephthalate Waste: A Case Study of Indonesian Roads

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ABSTRACT

The natural bitumen coalesced with the sediment in Buton Island, Indonesia, is known as Buton rock asphalt (BRA). Modified Buton Asphalt (MBA) is one of the latest bitumen processing that extracted bitumen from BRA and furtherly mixed with petroleum bitumen. In Indonesia drinking bottle is made by used extensively the polyethylene terephthalate (PET) for domestic consumption. This research used PET waste of 0.5% to 2.5% of the total weight of aggregates and filler, while MBA was the main binder to produce AC-WC mixture. One mixture without PET waste and five mixtures containing PET waste of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% were produced to determine the compatibility of PET with MBA related to the bonding strength of the AC-WC mixture. Indirect tensile strength test equipped with deformation measurement devices was carried out with the aim to understand the bonding strength related to the vertical stress-strain relationship, peak tensile stress, Modulus of elasticity in tension and toughness index of each mixture. The test results showed that MBA was compatible with blending with PET waste in producing compacted specimens. The results of quantitative observations showed that the presence of PET waste made the mixtures better than the mixture without PET in terms of stiffness and elastic region. The peak tensile stress of mixture increased by 45.2% to 96.8% with PET waste compared to the mixture without PET. The mixture containing PET waste was 56.09% to 157.18% higher than the mixture without PET in terms of Et. Toughness index (TI) increased with the use of PET waste up to 2.0%, but was smaller at 2.5% PET waste compared to the mixture without PET waste.

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NOMENCLATURE

SNI	Standard National Indonesia	ASTM	American Standard Testing and Material
BRA	Buton Rock Asphalt	kPa	kilo Pascal
MBA	Modified Buton Asphalt	N	Newton
PET	Polyethylene Therepthalate	AC-WC	Asphalt Concrete Wearing Course
TI	Toughness Index	Et	Modulus of elasticity in tension
ITS	Indirect Tensile Strength	LVDT	Linear Variable Displacement Transducer

1. INTRODUCTION

In recent decades, the population growth has made the urban areas with transportation infrastructures increase in size. The sprawl in the size of transportation networks is a crucial factor in economic development of urban areas. Development of transportation networks supported by rigid pavement, flexural pavement, and others paved road provides efficient movement of people between different areas and improves supply chain and goods distribution. In addition, an increase in vehicle volume is accompanied by the increase in vehicle axle loads.

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Related to the conditions mentioned above, it is necessary to develop reliable road networks with paved roads to improve safety and comfort when driving.

A reliable transportation network needs to be supported by a road layer that can bear heavy vehicle axle loads. In this regards, highway engineers continuously develop innovations to use materials at affordable prices to improve the performance of asphalt mixtures. Intensive efforts to improve the performance of asphalt mixtures for flexible roads using polymers have been reported in technical and scientific papers [1-4]. However, there is an additional cost when using virgin polymer in asphalt modification.

Today, as in many big cities in the world, people in many cities of Indonesia use plastics, including PET plastic, increasing from year to year. Plastic is a material that is difficult to decompose hence it will be stored for long time in the landfills. The lack of infrastructure to recycle plastic waste has resulted in a lot of plastic waste dumping, including PET waste being disposed in the landfills, frequently dumped into drainage or rivers that further pollute the surrounding environment.

One of the effective efforts to reduce the environmental impact caused by plastic waste, inclusive of PET waste is the utilization of PET waste as a building material, including as an additive for asphalt mixtures. PET can be categorized as one of the polymer types [4]. The potential use of PET waste as an additive material has been studied, where the test results showed the use of PET waste could improve the performance of asphalt mixtures such as stone mastic asphalt mixture [5, 6].

In Indonesia, the sustainability of national transportation infrastructure has become a prominent issue in recent decades. The effort for sustainability has driven the reuse of waste material such as PET waste, thereby decreasing the PET waste dumping and the consumption of virgin polymer.

At the same time, there are several areas in the southern part of Buton Regency, Bau-Bau Island, Indonesia, containing natural asphalt in the form of rock. A large amount of bitumen has been fused with minerals to form Buton rock asphalt (BRA), where it is estimated that the mineral and bitumen amounts are 70 and 30 percents, respectively. The bitumen contained in BRA has physical properties similar to petroleum bitumen [7, 8]. Continuous efforts are being made to optimize the use of BRA. The use of BRA in a granular form known as Buton garnural aspgalt (BGA) has been widely reported to have favorable compatibility in improving the asphalt mixtures properties [9-11]. Currently, a number of BRA processing plants have succeeded in extracting bitumen from BRA. Modified Buton asphalt (MBA) is the latest product of BRA processing and development. MBA is made from bitumen extraction from BRA, which is then mixed with petroleum bitumen. The use of MBA to produce reliable hot asphalt mixtures has been widely reported [12, 13]. However, the compatibility of MBA with waste materials such as plastic waste needs to be studied more deeply in relation to the development of eco-asphalt mixtures that support sustainable technology.

In order to obtain a reliable asphalt mixture at an affordable price, a design process is needed, which includes carrying out tests in the laboratory. Many studies promote indirect tensile strength (IDT) test as an appropriate laboratory cracking test for part of the mixture design and production control mechanism. The failure pattern of asphalt concrete specimens, the behavior of asphalt concrete under load as degeneration of the material and the limit of elasticity, can be reflected by the tensile stress-strain relationship of asphalt concrete in tensile [14-16].

One of Indonesia's most widely used road surface layers is Asphalt Concrete Wearing Course (AC-WC). This study used one of the local resources that have been developed in the form of MBA with PET waste as materials for making AC-WC. In order to understand the compatibility of PET waste with MBA concerning the bonding strength of the AC-WC mixture, one mixture without PET waste and mixtures containing PET waste from 0.5% to 2.5% by total weight of aggregates and filler (with 0.5% increments) were considered. Furthermore, this present study carried out ITS test, which was equipped with a set of LVDTs to quantify the bonding strength of AC-WC mixtures. The report presented in the present study focused on bonding strength in terms of the relationship of tensile stress-strain, tensile strength, modulus of elasticity in tension (Et) and toughness index. The present experimental investigation based on the ITS test was conducted to comprehend the influence of MBA and PET waste concurrently in the hot mixture asphalt production (AC-WC).

2. MATERIALS AND METHODS

2. 1. Modified Buton Asphalt MBA that was obtained from a national refinery was used to fabricate asphalt concrete specimens. MBA is fairly recent production in which bitumen extracted from BRA was mixed with petroleum bitumen, and it was introduced in several national road pavement constructions in recent years.

The physical properties of the reference MBA are presented in Table 1 and fulfill by Indonesia requirement for road construction.

2. 2. PET Waste Figure 1 (a) displays the used PET bottle as a source of PET in this study. PET bottles were cut into small pieces to facilitate mixing with other materials when producing hot mixture asphalt. Figure 1 (b) shows the small sheets of PET waste obtained from

TABLE 1. Physical properties of the MBA

Property	Test Value
Penetration before loss (mm)	53.00
Softening point (°C)	53.60
Ductility at 25°C, 5cm/minute (cm)	128.50
Flash point (°C)	286.00
Specific gravity	1.11
Penetration after loss (mm)	95.80
Weight loss (TFOT)	0.20

(a) Used PET bottle (b) Small sheets of PET waste

Figure 1. PET waste

the used bottle. The natural state, glass transition temperature and softening point of PET were a semi-crystalline resin [17-19] about 70°C and 260°C, respectively [20-22]. The average size of small pieces which are cutted by 5-10 mm.

2. 3. Aggregates and Filler Two fractions of crushed river stone were used as coarse aggregate, viz coarse aggregate with diameter 5-10 mm and with diameter 10-20 mm, respectively. (coarse aggregate pass sieve No. ½" and retained on sieve No. 4). Coarse aggregate with diameter of 10 – 20 mm had water absorption of 2.04%, saturated surface dry density of 2.67 and abrasion of 24.26%, respectively. Coarse aggregate with a 5 – 10 mm diameter had a water absorption of 2.03%, saturated surface dry density of 2.66 and abrasion of 25.32%, respectively. The stone dust obtained from the river rock crushing process was used as fine aggregate and filler, respectively. Stone dust (fine aggregate pass sieve No. 8 and retained on sieve No. 200 (0.075 mm) that used as fine aggregate in this study had a water absorption of 2.18%, saturated surface dry density of 2.63 and sand equivalent of 89.63%, respectively. Stone dust used as filler (pass sieve no. 200) in this study had water absorption of 2.28% and saturated surface dry density of 2.65, respectively.

2. 4. Material Preparation Preliminary research based on Marshall properties resulted the optimum level of MBA in the mixture without PET was 6.25% by weight of the mixture. MBA content of 6.25% by weight of the mixture was maintained for all mixtures in this experimental study. Table 2 shows the combination of aggregates, filler and PET waste. The use of PET waste was from 0.5 to 2.5% of the total weight of the aggregates and filler. The use of PET waste was taken into account to adjust the combined composition of aggregates, filler,

TABLE 2. The combination of aggregate, filler and PET waste

Aggregate, filler and MBA	PET Waste content (g)					
	Without PET	0.5% (5.63 g)	1.0% (11.25 g)	1.5% (16.88 g)	2.0% (22.50 g)	2.5% (28.13 g)
3/4"	-	-	-	-	-	
1/2"	45.03	44.47	43.91	43.34	42.78	42.22
3/8"	102.03	101.47	100.91	100.35	99.78	99.22
No. 4	259.04	258.48	257.91	257.35	256.79	256.23
No. 8	228.79	228.23	227.67	227.11	226.54	225.98
No. 16	168.10	167.53	166.97	166.41	165.85	165.28
No. 30	88.50	87.94	87.38	88.82	86.25	85.69
No. 50	58.05	57.48	56.92	56.36	55.80	55.23
No. 100	54.02	53.45	52.89	52.33	51.77	51.20
No. 200	26.65	26.09	25.52	24.96	24.40	23.84
Filler	94.79	94.23	93.67	93.10	92.54	91.98
MBA	75.00 g					
Total (Aggregate, filler, MBA and PET waste)	1,200 g					

and PET waste. The combined composition of aggregates and filler changes according to the amount of PET waste content in the mixtures, but overall it does not change the composition of AC-WC mixture.

MBA, PET waste, aggregates and filler were mixed with the dry method. The mixing method in this study follows previous research and can be found elsewhere [5]. The asphalt mixtures without and with PET waste were prepared and compacted in the laboratory for indirect tensile testing. Marshall hammer was used with seventy-five blows on each side of top and bottom to produce a compacted specimen with a diameter of 101.5 mm and height of approximately 65 mm [22]. In general, three IDT specimens were tested to characterize the bond strength of each mixture design. Prior to testing, all specimens were immersed in water at room temperature for 24 hours, weighed, and subsequently immersed in water at 60°C for 30 minutes.

2. 5. Indirect Tensile Strength Test The ITS test was carried out by applying an increasing monotonic load at a rate of 50 mm/min, which acts along the diameter of the specimen. A load cell was used to measure the load applied to the specimen. Displacements was measured using two LVDTs mounted vertically on the specimen. Load and displacements were monitored and recorded continuously using a computer-connected data logger. ITS (σ) was determined using Equation (1). Strain was obtained using Equation (2). The stress-strain relationship was obtained by using widely available software in the market. Figure 2 shows ITS test equipment. Vertical strain were derived via two linear variable differential transducers (LVDTs) measuring platen to platen displacement. The recording equipment consists of digital interface unit (data logger) connected to a computer that utilized to monitor and record data from the load actuator and LVDTs.

$$C = \frac{2P}{\pi\, d\, t} \tag{1}$$

where :

σ = Maximum stress component in the x direction on the vertical line (kPa)

P = Applied vertical load (N)

d = Diameter of the specimen (mm)

t = Thickness of the specimen (mm)

$$\varepsilon_V = \frac{\left(\frac{\Delta 1 + \Delta 2}{2}\right)}{d} \tag{2}$$

where :

ε_v = Vertical strain (mm/mm)

Δ1 = Displacement of the right part of the specimen (mm)

Δ2 = Displacement of the left part of the specimen (mm)

d = Diameter of the specimen (mm)

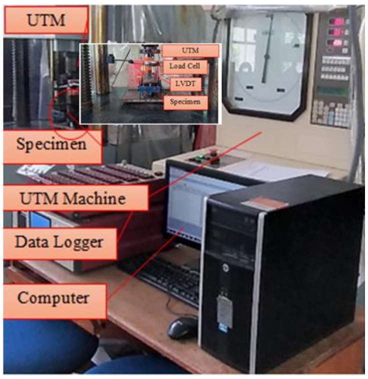

Figure 2. Indirect tensile strength test equipment

2. 6. Toughness Index (TI) Research conducted by others [13-16] used the results of the ITS test to determine the toughness index (TI) to characterize the fatigue resistance of asphalt mixtures. TI is determined using the Equation (3).

The TI values can be used to describe the behavior of the material post-peak stress until it reaches complete failure.The amount of stress-strain energy required to accomplish the failure of the material is denoted by TI.

There is no post-peak load if the TI value is zero, and represents a brittle material. The TI was calculated using the following Equation (3) from a typical stress–strain diagram as shown in Figure 3 where, TI = toughness index, Ae = area under the stress– strain curve up to strain (ε, Ap = area under the stress–strain curve up to strain εp, εp = horizontal strain corresponding to the peak stress, and ε = horizontal strain at the point of interest. For this study, most of the specimens pointed a maximum of 3% strain rate therefore, a strain level was selected at point of interest for calculating the TI.

$$\text{TI} = \frac{A\varepsilon - Ap}{\varepsilon - \varepsilon p} \tag{3}$$

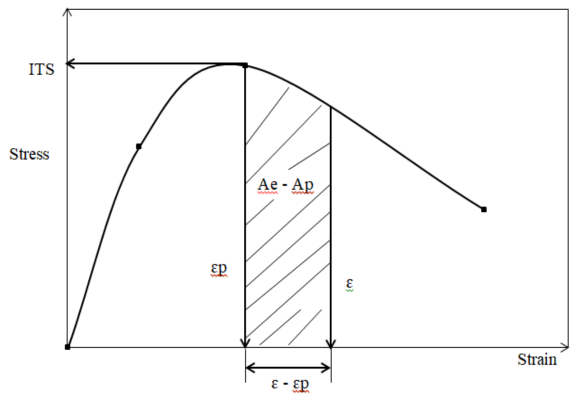

Figure 3. Toughness index

3. RESULTS AND DISCUSSION

3. 1. External Appearances of Compacted Specimen As mentioned earlier, that the melting temperatures of MAB and PET are very different, it is very important to evaluate the compatibility between the two materials early. In this study, the initial stage of evaluating the compatibility between PET waste and MBA was visual observation during mixing. It can be observed that even mixing occured hence the aggregates can be covered with MAB in the mixture without PET waste, as well as even mixing can be achieved in all mixtures containing PET waste, where there were no visible lumps of PET waste moreover without bleeding and segregation.

After compaction process and removed from the mold, the external appearances of specimens were observed to evaluate the compaction result. It can be observed that all specimens containing PET waste and without PET waste were successfully compacted without bleeding, as well as no visible segregation in the form of lumps of fine aggregate at specific points. Coarse aggregate skeletal with mastic containing MBA, PET waste, fine aggregate and filler was well bonded through the compaction process which was indicated by the absence of peeling of coarse aggregate or fine aggregate and no cracks due to compaction. After being removed from the immersion bath, the specimens were visually checked for external appearances to evaluate the compaction results and the effects of immersion for 24 hours at room temperature of 25 °C, followed by immersion at water with at temperature of 60 °C for 30 minutes.

3. 2. Stress-Strain Relationship under Tensile Figure 4 shows the stress-strain relationship of mixtures used MBA as the main binder and containing PET waste and without PET waste due to tensile loads. All mixture containing PET waste from 0.5% to 2.5% have steeper slope than the mixture without PET waste. This finding shows that the stiffness of the mixture becomes better with the presence of PET waste in the mixture compared with that without PET waste.

At the relationship between tensile stress and vertical strain of mixture without PET, it can be seen that the upward path formed concave part which indicates the settling of the specimen when responding the load, where no appearance of the concave upward path of the mixtures containing PET waste. This explains that mastic asphalt made of MBA and PET waste provided better stiffness compared to mixture made only of MBA.

The relationship between stress and strain due to tensile load in mixture containing PET waste of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% formed straight line up to

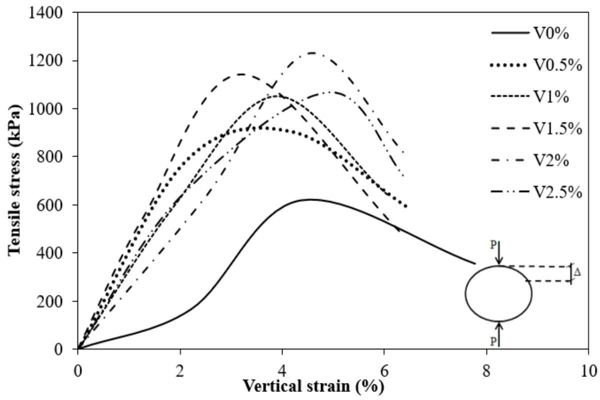

Figure 4. Tensile stress and vertical strain relationship

55%, 58%, 60%, 62% and 55% of the peak tensile stress, respectively. The elastic area is reflected by the linear portion of the tensile stress-strain curve. The presence of PET waste from 0.5 to 2.0% resulted tend to increase the linear area and then decline at 2.5% of PET.

3. 3. Peak Indirect Tensile Stress (Indirect Tensile Strength) Figure 5 compares the average indirect tensile values of the mixtures without PET waste and containing PET waste considered in the present experimental program. The error bars presented represent one standard deviation for each mixture. The value of the indirect tensile strength of mixture without PET waste was 620 kPa while for mixture containing PET waste of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% was higher about 45,8%, 69.52%, 84.03%, 98.06% and 71.93%, respectively. In addition, after the inclusion of PET from 0.5% to 2.0%, the indirect tensile strength value rises until it attains the peak point, after which it begins to decline at 2.5% of PET waste.

As the above figure depicts, after the inclusion of PET from 0.5% to 2.0%, the indirect tensile strength value

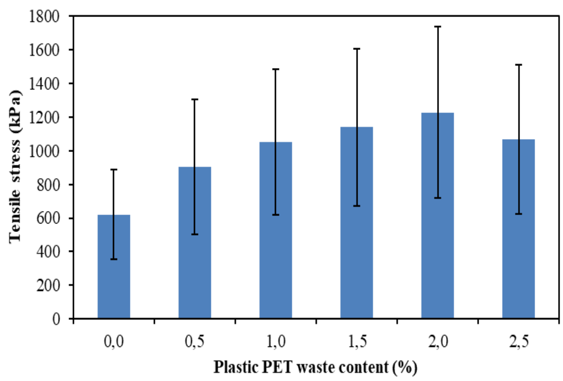

Figure 5. Peak indirect tensile stress

rises until it attains the peak point, after which it begins to decline at 2.5% of PET waste. The decrease in tensile strength at the 2.5% PET content may be attributed to the excessive PET waste enlarge the surface area that needs to be covered with MBA-based mastic, which further reduces the thickness of MBA-based mastic that bonds the aggregates.

As clearly measured in Figure 5, an increase in the value of the indirect tensile strength of the mixture containing PET waste of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% toward the mixture without PET waste was 45.2%, 69.4%, 83.9%, 96.8% and 71%, respectively. The finding contributes insight that the incorporation of PET waste positively influenced the bonding strength of asphalt mixture related to indirect tensile strength.

3. 4. Tensile Modulus Elasticity (Et) Figure 6 shows the relationship between waste PET content and the average value of the modulus of elasticity in tension. It can be observed that the average value of the modulus of elasticity in the tension of mixture containing PET waste of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% was 56.09%, 92.22%, 149.06%, 157.18% and 53.66% higher than that of without PET waste. This can result from the higher bonding strength of the mixtures containing PET compared to that without PET waste.

3. 4. Toughness Index (TI) Figure 7 displays the TI index of each mixture that represents the residual bonding strength to carry tensile loads until fracture occurs at post-peak tensile stress. The TI value of the mixture containing 2.5% PET waste was less than that without PET, while the TI value of the mixtures containing 0.5% to 2.0% PET waste was increased between 0,77% - 9,3% than the mixture without PET waste. The result confirms that the bonding strength of mixtures containing waste PET provided higher cracking resistance than that without PET waste regarding the post peak tensile stress features.

It can be observed that the average of the peak indirect tensile stress, tensile modulus elasticity and toughness

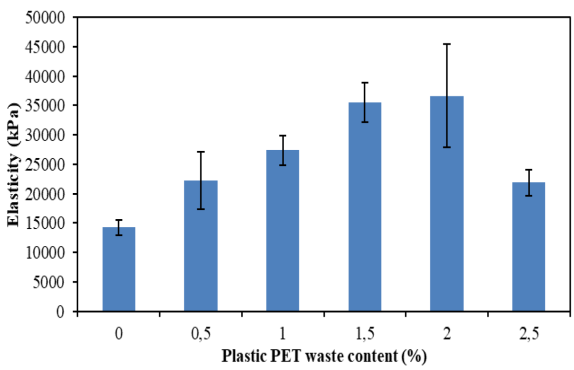

Figure 6. Tensile modulus elasticity

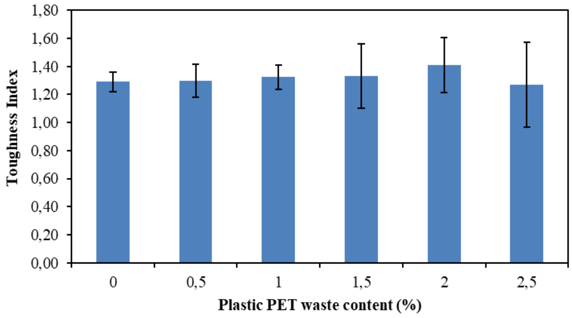

Figure 7. Toughness index

index of asphalt mixture increased until it raised the maximum value, which corresponds to 2% of the PET content, and then it decreased slightly at 2.5% of the PET.

It can be stated that the optimum value of adding waste PET is up to 2.0% to increase the bonding strength of the asphalt mixture made with MBA. The decrease in bonding strength with the addition of PET to 2.5% is based on the fact that PET changes at a temperature of around 70°C and has a high melting point of about 250°C while the maximum temperature for producing hot mix asphalt is around 180°C hence the PET in the mixture is still maintained in the semi-crystalline resin nature with little deformation. So in this study, an increase in the surface area due to addition of PET up to 2.5% caused a decrease in the thickness of the layer covered by MBA which reduces the bonding strength between MBA based mastic and coarse and fine aggregates. The results obtained by the study indicate that the physical characteristics of MBA are similar to petroleum bitumen which has the strength to cover and bind waste PET with in turn to increase the adhesive or bonding strength between mastic and aggregates and this result in line with the research conducted by Ahmadinia et al. [5-6] that used PET to improve mechanical properties of petroleum bitumen based stone mastic asphalt (SMA) mixture.

4. CONCLUSIONS

This paper experimentally evaluated the influence of tensile load on bonding strength of asphalt concrete containing MBA and PET waste. From the test results some important finding is concluded as follows:

1. The relationship between tensile stress and strain in the vertical direction shows that PET waste produced the mixture better than the mixture without PET in terms of stiffness and elastic region. Peak tensile stress (tensile strength) is higher 45.2% to 96.8% with waste PET compared to the mixture without PET. The mixture containing PET was higher 52.9% to 151.9% than the mixture without PET in terms of tensile modulus of elasticity. TI increases with PET

waste up to 2.0%, but is smaller at 2.5% PET waste compared to a mixture without PET waste.

2. This condition that observed in the experimental results showed that PET waste contributed positively to an increase in indirect tensile strength value. Besides, increased indirect tensile strength also can occur due to the modified Buton asphalt integrated adequately with PET waste to improve bonding strength between aggregate and mastic.

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Persian Abstract

چکیده

قیر طبیعی ترکیب شده با رسوبات جزیره بوتون اندونزی به آسفالت سنگ بوتون (BRA) معروف است. آسفالت بوتون اصلاح شده (MBA)یکی از آخرین فرآوری های قیر است که قیر را از BRA استخراج کرده و سپس با قیر نفتی مخلوط می کند. در اندونزی بطری نوشیدنی با استفاده گسترده از پلی اتیلن ترفتالات (PET)برای مصرف داخلی ساخته می شود. در این تحقیق از ضایعات PET ۰/۵ تا ۲.۵ درصد از وزن کل سنگدانه ها و پرکننده استفاده شد، در حالی که MBA چسب اصلی برای تولید مخلوط AC-WC بود. یک مخلوط بدون ضایعات PET و پنج مخلوط حاوی ضایعات PET، ۰/۵٪، ۱/۰٪، ۱/۵٪، ۲/۰٪، ۲/۵٪ برای تعیین سازگاری PET با MBA مربوط به استحکام پیوند مخلوط AC-WC تولید شد. آزمایش مقاومت کششی غیرمستقیم مجهز به دستگاه های اندازه گیری تغییر شکل با هدف درک استحکام پیوند مربوط به رابطه تنش-کرنش عمودی، تنش کششی اوج، مدول الاستیسیته در کشش و شاخص چقرمگی هر مخلوط انجام شد. نتایج آزمایش نشان داد که MBA با اختلاط با ضایعات PET در تولید نمونه های فشرده سازگار است. نتایج مشاهدات کمی نشان داد که وجود ضایعات PET باعث می‌شود که مخلوط‌ها از نظر سفتی و ناحیه الاستیک بهتر از مخلوط بدون PET باشند. حداکثر تنش کششی مخلوط با ضایعات PET در مقایسه با مخلوط بدون PET ۴۵/۲ ٪به ۹۶/۸ ٪ افزایش یافت. مخلوط حاوی ضایعات PET ۵۶/۰۹٪ تا ۱۵۷/۱۸ ٪ بیشتر از مخلوط بدون PET از نظر Et بود. شاخص چقرمگی (TI) با استفاده از ضایعات PET تا ۲/۰ ٪ افزایش یافت، اما در ۲/۵ ٪ زباله PET در مقایسه با مخلوط بدون زباله PET کوچکتر بود.