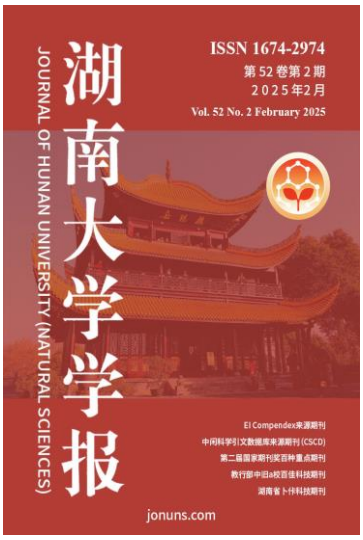

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The Effect of Coconut Fiber in Improving the Deformation Resistance of Asphalt Concrete Mixtures

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Abstract: Flexible pavement experiences permanent deformation known as rutting and shearing. This deformation is usually in the form of longitudinal deflections that occur in the vehicle wheel tracks and is an accumulation of deformation caused by increased loads. Because the road surface is no longer waterproof, damage can become more severe. To increase the strength of the asphalt concrete mixture in maintaining the performance of the mixture so that it does not experience deformation or rutting, efforts are made to add coconut fiber to the asphalt concrete mixture. This produces a strong asphalt mixture. The aim of this research was to determine the effect of adding coconut fiber in increasing the strength and resistance of the asphalt concrete mixture to permanent deformation. Wheel tracking testing is a simulation in which the wheel load moves back and forth across the test object. The deformation resistance of a predetermined test object can be measured by looking at the results obtained from the groove depth (Rut Depth) after passing a number of passes, or the Deformation Rate (RD) in mm/min. Apart from that, the Dynamic Stability (DS) value can also be measured, namely the number of passes required to form a

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groove 1 mm deep. The dynamic stability (DS) and Deformation Rate (RD) can be calculated using the Suherman formula. Based on the value of the optimum asphalt content (KAO) and the percentage and optimum length, testing was carried out using the Wheel Tracking test. The sample was compacted with a compactor 75 times, and the size was 30 cm x 30 cm x 5 cm. Tests were carried out at temperatures of 40ºC and 60ºC. Samples were placed in an oven at temperatures of 40ºC and 60ºC for 4 h before being tested. The rutting depth was recorded during testing. Dynamic stability (DS) and permanent deformation were used to evaluate the stability of the asphalt mixtures at high temperatures. The study demonstrated that the use of coconut fiber can increase the stability value of the asphalt concrete mixture. The relationship between the rutting behavior and the temperature of 40ºC resulted in a total deformation of 2.28 mm with a deformation rate of 0.0080 mm/min for a temperature of 0ºC, 2.42 mm with the rate of 0.0093 mm/min for a temperature of 40ºC and 2.48 mm with the rate of 0.0220 mm/min for a temperature of 60ºC.

Keywords: wheel tracking, temperature, asphalt concrete.

椰子纤维对沥青混凝土混合料抗变形性能的改善作用

摘要：柔性路面会发生永久变形，即车辙和剪切。这种变形通常表现为车辆车轮轨道的纵向偏转，是因负载增加而导致的变形累积。由于路面不再防水，损坏可能会变得更加严重。为了增加沥青混凝土混合料的强度，同时保持混合料的性能，使其不会发生变形或车辙，人们努力在沥青混凝土混合料中添加椰子纤维。这样可以产生坚固的沥青混合料。本研究的目的是确定添加椰子纤维对增加沥青混凝土混合料强度和抗永久变形能力的影响。车轮轨迹测试是一种模拟，其中车轮负载在测试对象上来回移动。可以通过查看经过多次通过后从凹槽深度（车辙深度）获得的结果或以毫米/分钟为单位的变形率（RD）来测量预定测试对象的抗变形能力。除此之外，还可以测量动态稳定性（DS）值，即形成 1 毫米深的凹槽所需的通过次数。可以使用 Suherman 公式计算动态稳定性（DS）和变形率（RD）。根据最佳沥青含量（KAO）的值以及百分比和最佳长度，使用车轮轨迹试验进行测试。用压实机将样品压实 75 次，尺寸为 30 厘米 x 30 厘米 x 5 厘米。测试在 40oC 和 60oC 的温度下进行。将样品放在 40oC 和 60oC 的烤箱中 4 小时后进行测试。在测试过程中记录车辙深度。动态稳定性（DS）和永久变形用于评估沥青混合料在高温下的稳定性。研究表明，使用椰子纤维可以提高沥青混凝土混合料的稳定性值。车辙行为与 40oC 温度之间的关系导致在 0oC 温度下总变形为 2.28 mm，变形速率为 0.0080 mm/min；在 40oC 温度下总变形为 2.42 mm，变形速率为 0.0093 mm/min；在 60oC 温度下总变形为 2.48 mm，变形速率为 0.0220 mm/min。

关键词：车辙、温度、沥青混凝土

1. Introduction

Basically, the main function of fibers is as reinforcing materials that provide additional tensile strength resulting from the incorporation of material elements, which can increase the amount of strain energy that can be absorbed during fatigue in the mixing process [1, 2]. Some fibers have high tensile strength in asphalt mixes, so fibers can increase the cohesive and tensile strength of asphalt mixes. Fiber amendment may provide physical changes to asphalt mixes [3]. It is believed that the addition of fibers to the asphalt can improve the strength and fatigue properties of the material while increasing ductility due to the inherent compatibility of the fibers with the asphalt and their excellent mechanical properties [4]. Fiber reinforcement is used as a void barrier rather than a reinforcing element to carry the tensile load and prevent crack initiation and propagation [5]. Finely divided fibers also provide a high surface area per unit weight and behave like a filler material. The fibers also tend to blend with the asphalt, strengthening the bond between the aggregates during construction. In terms of efficiency, the mixtures with fibers showed a slight increase in the optimum asphalt content.

Coconut fiber consists of two parts: fiber cells and

non-fiber cells or dust, commonly referred to as pith. As an additive to the Laston (AC) wearing course mix, the dust must first be separated from the fibers. Coconut fiber is very durable under normal weather conditions [6].

Figure 1. Coconut fiber (authors' photos)

Permanent deformation is one of the most important parameters for pavement design and is expected to result from increased traffic loads [7]. Permanent deformation is the permanent settlement of the pavement structure. To estimate the depth of the tire marks, a parameter is needed to determine the permanent deformation of the material for each layer [8].

The strength and durability of the asphaltic concrete mixtures in the pavement layers are related to their ability to resist damage due to the temperature and loading effects. During their service life, pavements often suffer damage in the form of rutting, corrugation and wash boarding caused by the accumulation of permanent deformation due to repeated traffic loads [9]. Repeated loading results in stresses and strains in the pavement structure, coupled with thermal stresses due to temperature, causing the asphalt concrete mix to deform and degrade in performance, ranging from fine cracking to rutting. The sensitivity to temperature changes is the basis for the differences in the service life of asphalt before final cracking and hardening (aging) [10].

Permanent deformation in flexible pavements, commonly referred to as rutting and shearing, usually consists of longitudinal deflections that occur in the path of vehicle wheels and are accumulations of small amounts of deformation caused by increased loads. Damage can develop further because the pavement is no longer impervious and water can weaken the bond between the rock and asphalt [11].

The purpose of this study was to analyze the effect of adding coconut fiber to the asphalt concrete mix on the permanent deformation.

2. Research Methods

2.1 Research Tools and Materials

Asphalt inspection test equipment (penetration, soft point, viscosity, flash point and burn point, ductility, specific gravity), aggregate inspection test equipment (sieve analysis, bulk density, specific gravity, soundness test, aggregate adhesion to asphalt), asphalt mixture characteristics test equipment (Marshall test), and deformation test equipment (wheel tracking) testing using tools available at the Highway and Transportation Laboratory of the Civil Engineering Study Program, Faculty of Engineering, Muslim University of Indonesia.

The materials used in this research include:

1) The natural aggregate consists of coarse aggregate (retained on sieve no. #4) and fine aggregate (passing sieve no. #4 and retained on no. #200), which is obtained from the stone crusher process of PT. Lompulle Soppeng Regency with aggregate types 1-2, 0.5-1 and Abu Bartu.

2) The asphalt used in this study is 60/70 penetration asphalt. The asphalt (60/70) was obtained from Public Works Department of Soppeng Regency.

3) Coconut Fiber was collected from the public market Soppeng Central Market.

2.2 Sample Test Item

The test specimens were produced after the constituents of the bituminous concrete were tested and qualified in accordance with the regulations. The first step was to weigh the aggregate according to the mix design, heat the aggregate at a temperature of (110 ± 5ºC), heat the asphalt until it reaches a certain viscosity, and mix the asphalt and aggregate until the aggregate is evenly covered at a temperature of (± 130ºC), Then the mixture is placed in the mold under hot conditions (100-150ºC), the mixture is placed in the mold and compacted as much as 2 x 75 tumbles with a size of 30 cm x 30 cm x 5 cm, the test piece is removed and left for 24 hours [12]. Tests were conducted at 40°C and 60ºC. The test wheel stroke is 21 cm. The specimens were placed in the oven at 40°C and 60°C for 4 h before testing. After the oven reached the time, it was removed and the mix was tested with the Wheel Tracking Tool to determine the deformation that occurred in the mix. To measure the average depth and volume of the material displacement due to the tire pressure and deflection area. This is considered to be the easiest way to study the permanent deformation characteristics. The rut depth and permanent deformation recorded during the dynamic stability (DS) test were used to evaluate the stability of the asphalt mixtures at elevated temperatures.

Table 1. Sample test piece with coconut fiber (compiled by the authors)

Optimum Fiber Percentage (%)	Optimum Fiber Length (cm)	Wheel Tracking Test Temperature		
		0°C	40°C	60°C
0.75%	1.5	1	1	1
Total Sample			3	

After being pounded, the samples were tested with several parameters. The sample testing method follows the Indonesian National Standard (ISN), the American Association of State Highway and Transportation Officials (AASHTO) or the American Society for Testing and Materials (ASTM) as follows: Specification for designing SMA. American Association of State Highways Transportation Officials [13], Standard test

method for determination of drain down characteristics in un-compacted asphalt mixtures. American Association of State Highways Transportation Officials. (AASHTO T- 305; 2008) [14], Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Coated Samples. ASTM International and American Society for Testing and Materials (ASTM), 2000 Standard Test Methods [15].

2.3 Data Analysis

Illustration of the permanent deformation model as shown in Figures 1 and 2, where the deformation on the pavement surface does not return to the initial position (unrecoverable) after loading. Permanent deformation (in the form of rutting) occurs mostly in the path of vehicle wheel treads. To evaluate the rutting resistance of the asphalt concrete mixes. There are two main causes of rutting:

a) Rutting caused by excessive repetitive stress/loading resulting in subgrade damage (due to poor subgrade). Illustration as shown in Figure 2.

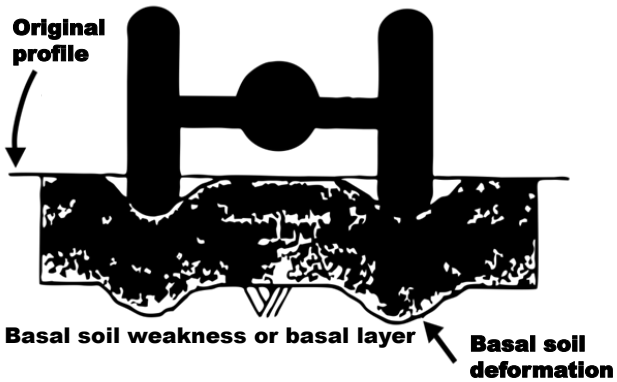

Figure 2. Illustration of the permanent deformation (Modified source Asphalt Institute, SP-2, 1996 [16]

b) Rutting caused by excessive pressure/repeated loading, which has an effect on the damage to the top layer (pavement structure), as shown in Figure 3.

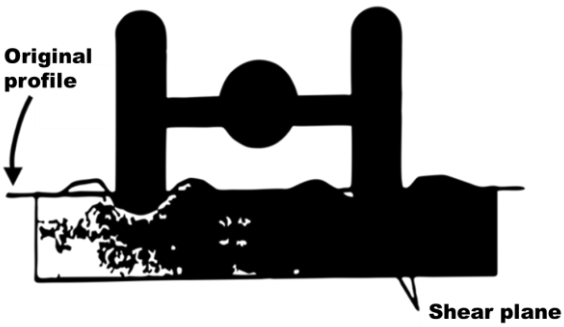

Figure 3. Illustration of the permanent deformation [16]

The wheel tracking test is a simulation in which the wheel load moves back and forth across the specimen. The deformation resistance of the specimen can be measured by looking at the results of the rut depth after several passes or the deformation rate (RD) in mm/min. It is also possible to measure the Dynamic Stability (DS) value, which is the number of passes required to form a 1-mm-deep rut. The dynamic stability (DS) and the rate of deformation (RD) can be calculated using the formula [16]:

$$DS = 21 \times 2 \times + \frac{(t_2 - t_1)}{(d_2 - d_1)} \times c_1 \times c_2 \ldots\ldots\ldots 1$$

$$RD = 1 + \frac{(d_2 - d_1)}{(t_2 - t_1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where:

DS = Dynamic Stability (passes/mm)
RD = Deformation rate (mm/min)
d_1 = Deformation at the 45 min test (mm)
d_2 = Deformation at 60 min test (mm)
c_1 = Equipment correction factor is 1.0
c_2 = Specimen correction factor is 1.0
t_1 = 45 min
t_2 = 60 min

c) The permanent deformation behavior of the asphalt concrete pavement with low temperature variations due to the rough asphalt surface causes water to be trapped in the tire ruts, resulting in reduced skid resistance, increased hydroplaning potential, and water spray that reduces visibility. The development of ruts leads to cracking and eventual disintegration or failure. The problem of rutting is a crucial part of maintenance activities and costs on both arterial and secondary roads [17].

Figure 4. Rutting testing (authors' photos)

3. Results and Discussion

3.1 Aggregate Testing Results

The aim of aggregate testing is to determine the quality of the aggregate with several aggregate tests, both for the coarse aggregate, fine aggregate and filler. The average specific gravity of the aggregate is above 2.5, which exceeds the minimum limit according to the general specification of Bina Marga 2018 Revision 2. The results of the aggregate tests are presented in Table 2.

Table 2. Aggregate testing results (compiled by the authors)

No	Description	Results	Specifications

1	Coarse Aggregate		
	SG Bulk	2.57	Min 2.5
	Obvious SG (%)	2.73	
	Absorption (%)	2.31	Max. 3%
2	Fine Aggregate		
	SG Bulk	2.35	Min 2.5
	Obvious SG (%)	2.41	
	Absorption (%)	2.67	Max. 3%
3	Aggregate Adhesion to Asphalt	96.45	Min 90%

In Table 2, the test results show that overall, the aggregates used in the asphalt mix are qualified for use as the AC-WC asphalt mix. Coarse and fine aggregates have specific gravity greater than 2.5. The absorption or absorption of aggregates tends to be large, so it affects the absorption of the asphalt content.

3.2 Asphalt Testing Results

The purpose of the asphalt testing is to determine the quality of the asphalt used, and the results of the asphalt testing are shown in Table 3. Asphalt testing showed that Pen 60/70 asphalt was suitable for use as a binder in asphalt concrete mixes.

Table 3. Physical properties of the Pen 60/70 Asphalt (compiled by the authors)

Testing	Testing Results	Specifications
Penetration at 225°C (0,1 mm)	61	59-70
Softening Point (°C)	52	48-56
Ductility at 25°C (cm)	146	> 100
Flash Point (°C)	245	> 200
Burn Point (°C)	275	> 200
Specific gravity	1,030	1,0-1,16

Table 4. Aggregate merger (compiled by the authors)

AGGREGATE COMBINING AGGREGATE ANALYSIS TRIAL AND ERROR METHOD											
No. Sieve	% Passed BP 1	2 % Passed BP 0.5-1	% Passed Stone Ash	BP 1-2	BP 0.5-1	Stone ash	Total Aggregate	Specification Ideal			Specification
				17%	31%	52%					
19.1 (3/4")	100	100	100	17	31	52	100	100	-	100	100
12.7 (1/2")	59.27	100	100	10.08	31	52	93.08	90	-	100	95
9.52 (3/8")	17.98	83.10	100	3.06	25.76	52	80.82	77	-	90	83.5
No. 4	0.90	19.98	100	0.15	6.07	52	58.22	53	-	69	61
No. 8	0	1.20	84.24	0	0.37	43.80	44.18	33	-	53	43
No. 16	0	0	61.97	0	0	32.22	32.22	21	-	40	30.5
No. 30	0	0	38.22	0	0	19.87	19.87	14	-	30	22
No. 50	0	0	26.38	0	0	13.72	13.72	9	-	22	15.5
No. 100	0	0	17.13	0	0	8.91	8.91	6	-	15	10.5
No. 200	0	0	10.35	0	0	5.38	5.38	4	-	9	6.5

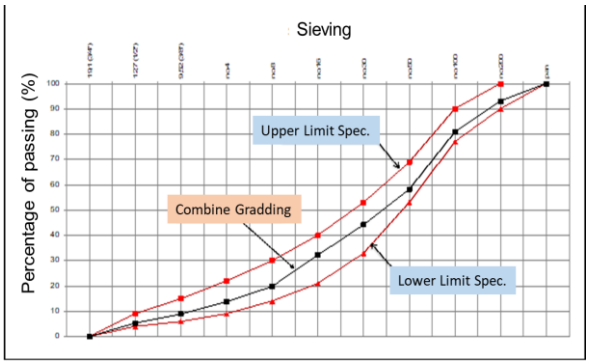

Figure 5. Combine grading mixed aggregate asphalt (AC-WC) (developed by the authors)

3.3 Deformation Test Results for the Use of Coconut Fiber

Figure 5 shows that the distribution pattern of coconut fiber in the mixture in the mixture is able to increase the density value and stability of the mixture due to increased traffic load with increased adhesion and cohesion properties, so that the percentage of air voids in the mixture remains within the required range, with the risk of shear forces that can affect the shifting between the aggregate surface planes in the mixture due to traffic load can be reduced, where the condition of the asphalt as a binder undergoes changes in viscoelastic properties or softening point, which has an impact on reducing the binding force in the mixture.

Increased temperature and traffic loads and volumes cause rutting in the surface layer of the flexible pavement structures. Rutting indicates the presence of deflection or settlement caused by vehicle wheel tracks and occurs when the permanent deformation of each layer in the pavement structure accumulates due to repeated increases in vehicle loads [18]. In general, the two modes or conditions of rutting in the pavement layers are compaction and the plastic properties of the mixture [17, 19].

The results of the relationship between deformation and trajectory at temperatures of 0°C, 40°C and 60°C with the optimum percentage and length can be seen that the deformation value increases as the temperature increases. The longer the loading time and the number of repeated passes of the mixture, the greater the deformation. The deformation value obtained was 2.28 mm with a deformation rate of 0.0080 mm/min and a track stability of 2650 passes/mm at a temperature of 0°C, while at a temperature of 40°C, the deformation value obtained was 2.42 mm with a deformation rate of 0.0093 mm/min and a track stability of 2250 passes/mm, and at a temperature of 60°C, the deformation value obtained was 2.48 mm with a deformation rate of 0.0220 mm/min and a track stability of 1045.45 passes/mm.

Table 5. Results with wheel tracking at temperatures 0ºC, 40ºC, 60ºC

Temperature		0ºC	40ºC	60ºC
Time (minute)	Number of cycles	Deformation (mm) Percentage of Optimum fiber 0.75% / 1.5 cm		
0	0	0.00	0.00	0.00
1	21	0.84	0.94	0.99
5	105	1.45	1.55	1.62
10	210	1.99	2.09	2.13
15	315	2.42	2.52	2.59
30	630	2.85	2.95	3.00
45	945	3.14	3.39	3.40
60	1260	3.26	3.53	3.70
Total deformation		2.28	2.42	2.49
Dynamic stability (trajectories/mm)		2625.00	2250.00	1045.45
Deformation rate (mm/min)		0.0080	0.0093	0.0201

The test results show that the mixture with fiber at two different temperatures of 40ºC and 60ºC has a lower stability value against rutting resistance than the asphalt concrete mixture at 0ºC. The ability of coconut fiber in reducing the occurrence of rutting on the surface layer of asphalt concrete mixes is due to two factors: 1) fibers have the ability to stabilize and increase the adhesion of asphalt on the surface plane between the aggregate and asphalt against changes in the viscosity properties of asphalt due to increased temperature, 2) fibers can form a network pattern and a strong bonding structure in asphalt concrete mixtures [20].

3.4 Effect of Temperature on Deformation

Temperature has a significant effect on deformation, and the measurement results of the pavement layers with rutting increased with temperature (Figure 6). Thus, the higher the deformation value produced in a mixture, the greater the change in the shape of the mixture, and vice versa, the lower the deformation value, the smaller or less the change in the shape of the mixture. What is meant by a change in the shape of the mixture is a change in the shape of the mixture due to loading, such that rutting occurs.

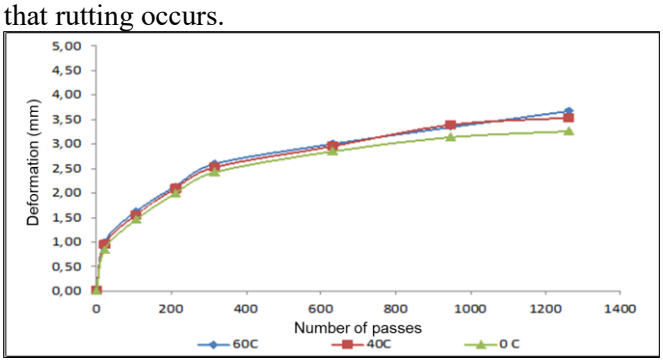

Figure 6. Relationship between deformation and the number of temperature passes (developed by the authors)

The higher the temperature of a solid object, the more ductile its nature and the less its strength. For example, a glass pipe cannot be bent at normal air temperature, if forced it will break because it is vegas (brittle), once heated it is easy to bend. The same is true of the rock. At the surface, it is solid and brittle, but deep below the surface, where the temperature is high, it is ductile.

Temperature is a factor that greatly affects the toughness of a material where the lower the temperature of the material, the lower the toughness starting from brittle. very low temperatures where the grains of the material will be so tight that there is no room for elastic deformation and the absorption of energy is very small, on the contrary, the increasing temperature of the material grains will stretch and increase the occurrence of deformation and the absorbed energy is also getting bigger. The results of testing the mixture at a temperature of 0°C with coconut fiber reinforcement has a better performance than the mixture at temperature 40°C and 60°C.

4 Conclusion

Several series of tests on the properties and characteristics of asphalt concrete wearing course (AC-WC) mixtures with coconut fiber reinforcement that have resistance to deformation (rutting) have been discussed in this paper. The conclusions that can be drawn from this study are as follows:

The mix with coconut fiber reinforcement has a deformation value at 0ºC with a total deformation of 2.28 mm with a deformation rate of 0.0080 mm/min and for a temperature of 40ºC, and 2.42 mm with a deformation rate of 0.0093 mm/min and 2.49 mm with a deformation rate of 0.00201 mm/min for a temperature of 60ºC. Mixtures with coconut fiber reinforcement at 0ºC have better performance compared to those at 40°C and 60ºC. The effect of temperature in the mix has an effect on increasing deformation so that the level of the mix decreases and has the potential for permanent deformation.

Coconut fiber with a random distribution pattern in the mixture has the ability to accept and absorb stresses due to traffic loads with a uniform stress distribution pattern to the pavement structure layer with a higher level of mixture flexibility. Coconut fiber can improve the adhesion and cohesion properties of the asphalt concrete mixtures. The fiber-reinforced mixtures contribute to the mixing of the deformation values so that the asphalt concrete mixture is able to maintain its strength until no deformation occurs.

Declarations

Author Contributions

Conceptualization, H.A. and A.S.W.; methodology, H.A. and A.S.W; software, S., and W.; validation, H.A.;

formal analysis, S., and W.; investigation, H.A. and A.S.W.; resources, H.A.; data curation, H.A.; writing—original draft preparation, H.A. and A.S.W.; writing—review and editing, H.A.; visualization, S., and W.; supervision, H.A.; project administration, H.A. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Funding information is not available.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies, have been completely observed by the authors.

References

[1] FORTEA-VERDEJO M., BUMBARIS E., BURGSTALLER C., BISMARCK A., & LEE K. Y. Plant fibre-reinforced polymers: where do we stand in terms of tensile properties? *International Materials Reviews*, 2017, 62(8): 441-464. https://doi.org/10.1080/09506608.2016.1271089

[2] KU H., WANG H., PATTARACHAIYAKOOP N., & TRADA M. A review on the tensile properties of natural fiber reinforced polymer composites. *Composites Part B: Engineering*, 2011, 42(4): 856-873. https://doi.org/10.1016/j.compositesb.2011.01.010

[3] ZHANG M., ZHANG J., LYU L., LI Y., TAN X., LI Z., & PEI J. Durable and environmental asphalt pavement with plant fiber: a state-of-the-art review. *Journal of Materials in Civil Engineering*, 2024, 36(3): 03123003. https://doi.org/10.1061/JMCEE7.MTENG-17074

[4] ASGHAR M. F., & KHATTAK M. J. Fracture and fatigue characteristics of high performing novel hot mix asphalt composites. *Construction and Building Materials*, 2023, 383, 131217. https://doi.org/10.1016/j.conbuildmat.2023.131217

[5] SHAFEI B., KAZEMIAN M., DOPKO M., & NAJIMI M. State-of-the-art review of capabilities and limitations of polymer and glass fibers used for fiber-reinforced concrete. *Materials*, 2021, 14(2): 409. https://doi.org/10.3390/ma14020409

[6] RAMLI M., KWAN W. H., & ABAS N. F. Strength and durability of coconut-fiber-reinforced concrete in aggressive environments. *Construction and Building Materials*, 2013, 38: 554-566. https://doi.org/10.1016/j.conbuildmat.2012.09.002

[7] LEIVA-VILLACORTA F., VARGAS-NORDCBECK A., & AGUIAR-MOYA J. P. Permanent deformation and deflection relationship from pavement condition assessment. *International Journal of Pavement Research and Technology*, 2017, 10(4): 352-359. https://doi.org/10.1016/j.ijprt.2017.03.005

[8] XU T., WANG H., LI Z., & ZHAO Y. Evaluation of permanent deformation of asphalt mixtures using different laboratory performance tests. *Construction and Building Materials*, 2014, 53: 561-567. https://doi.org/10.1016/j.conbuildmat.2013.12.015

[9] PEDDINTI P. R., PUPPALA H., & KIM B. Pavement monitoring using unmanned aerial vehicles: an overview. *Journal of Transportation Engineering, Part B: Pavements*, 2023, 149(3): 03123002. https://doi.org/10.1061/JPEODX.PVENG-1291

[10] MIRÓ R., MARTÍNEZ A. H., MORENO-NAVARRO F., & DEL CARMEN RUBIO-GÁMEZ M. Effect of ageing and temperature on the fatigue behaviour of bitumens. *Materials & Design*, 2015, 86: 129-137. https://doi.org/10.1016/j.matdes.2015.07.076

[11] NING Z., SUN Z., LIU Y., DONG J., MENG X., WANG Q., & WEI Y. Evaluating the impervious performance of hydraulic asphalt concrete in embankment dams: A study of crack evolution at different temperatures. *Construction and Building Materials*, 2024, 440: 137247. https://doi.org/10.1016/j.conbuildmat.2024.137247

[12] ASPHALT INSTITUTE. *Mix Design Methods for Asphalt Concrete and Other Hot Mix Types*, Manual Series No.2 (MS-2) Seventh Edition, 2014.

[13] AASHTO. M.8-01. Standard specification for designing stone matrix asphalt (SMA). American Association of State Highway and Transportation Officials. USA, 2005.

[14] AASHTO. T-305. Standard test method for determination of draindown characteristics in uncompacted asphalt mixtures. American Association of State Highway and Transportation Officials. USA, 2014.

[15] ASTM: D1188-07e1. *Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Coated Samples*. ASTM International, 2007. http://dx.doi.org/10.1520/D1188-07E01

[16] SUHERMAN S. Kinerja Modulus Resilien dan Deformasi Permanen dari Campuran Lapis antara (AC-BC) yang Menggunakan Material Hasil Daur Ulang (RAP). *SITEKIN: Jurnal Sains, Teknologi dan Industri*, 2012, 10(1): 51-58. http://dx.doi.org/10.24014/sitekin.v10i1.575

[17] GARBA R & HORVLI I. Prediction of Rutting Resistance of Asphalt Mixtures. In GOMES CORREIA A. *Bearing Capacity of Roads*, Volume 2. London, CRC Press, 2020. https://doi.org/10.1201/9781003078821-7

[18] TAYFUR S., OZEN H., & AKSOY A. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. *Construction and Building Materials*, 2007, 21(2): 328-337. https://doi.org/10.1016/j.conbuildmat.2005.08.014

[19] KIM W. J., LEE H. J., & PHAN H. T. Calibration and validation of a rutting model based on shear stress to strength ratio for asphalt pavements. *Construction and Building Materials*, 2017, 149: 327-337. https://doi.org/10.1016/j.conbuildmat.2017.05.053

[20] CHEN J.S., & LIN K.Y. Mechanism and behavior of bitumen strength reinforcement using fibers. *Journal of Materials Science*, 2015, 40: 87–95. https://doi.org/10.1007/s10853-005-5691-4

参考文：

[1] FORTEA-VERDEJO M.、BUMBARIS E.、

BURGSTALLER C.、BISMARCK A. 和 LEE K. Y. 植物纤维增强聚合物：其拉伸性能如何？国际材料评论，2017，62(8)：441-464。https://doi.org/10.1080/09506608.2016.1271089

[2] KU H.、WANG H.、PATTARACHAIYAKOOP N. 和 TRADA M. 天然纤维增强聚合物复合材料拉伸性能综述。复合材料 B 部分：工程，2011，42(4)：856-873。https://doi.org/10.1016/j.compositesb.2011.01.010

[3] ZHANG M., ZHANG J., LYU L., LI Y., TAN X., LI Z., & PEI J. 耐用环保的植物纤维沥青路面：最新综述。土木工程材料杂志，2024，36(3): 03123003。https://doi.org/10.1061/JMCEE7.MTENG-17074

[4] ASGHAR M. F., & KHATTAK M. J. 高性能新型热拌沥青复合材料的断裂和疲劳特性。建筑与建筑材料，2023，383，131217。https://doi.org/10.1016/j.conbuildmat.2023.131217

[5] SHAFEI B.、KAZEMIAN M.、DOPKO M. 和 NAJIMI M. 对用于纤维增强混凝土的聚合物和玻璃纤维的能力和局限性的最新回顾。材料，2021，14(2)：409。https://doi.org/10.3390/ma14020409

[6] RAMLI M.、KWAN W. H. 和 ABAS N. F. 椰子纤维增强混凝土在恶劣环境下的强度和耐久性。建筑与建筑材料，2013，38：554-566。https://doi.org/10.1016/j.conbuildmat.2012.09.002

[7] LEIVA-VILLACORTA F.、VARGAS-NORDCBECK A. 和 AGUIAR-MOYA J. P. 路面状况评估中的永久变形和挠度关系。国际路面研究与技术杂志，2017，10(4)：352-359。https://doi.org/10.1016/j.ijprt.2017.03.005

[8] XU T.、WANG H.、LI Z. 和 ZHAO Y. 使用不同的实验室性能测试评估沥青混合料的永久变形。建筑与建筑材料，2014，53：561-567。https://doi.org/10.1016/j.conbuildmat.2013.12.015

[9] PEDDINTI P. R.、PUPPALA H. 和 KIM B. 使用无人机监测路面：概述。《交通工程杂志》，B 部分：路面，2023，149(3)：03123002。https://doi.org/10.1061/JPEODX.PVENG-1291

[10] MIRÓ R.、MARTÍNEZ A. H.、MORENO-NAVARRO F. 和 DEL CARMEN RUBIO-GÁMEZ M. 老化和温度对沥青疲劳行为的影响。《材料与设计》，2015，86：129-137。https://doi.org/10.1016/j.matdes.2015.07.076

[11] NING Z., SUN Z., LIU Y., DONG J., MENG X., WANG Q.，和 WEI Y. 评估土石坝中水力沥青混凝土的抗渗性能：不同温度下裂缝演变研究。建筑与建筑材料，2024，440：137247。https://doi.org/10.1016/j.conbuildmat.2024.137247

[12] ASPHALT INSTITUTE。沥青混凝土和其他热混合料类型的混合设计方法，手册系列第 2 号 (MS-2) 第七版，2014。

[13] AASHTO。M.8-01。石基沥青 (SMA) 设计标准规范。美国州际公路和运输官员协会。美国，2005。

[14] AASHTO。T-305。未压实沥青混合料排水特性测定的标准试验方法。美国州际公路和运输官员协会。美国，2014。

[15] ASTM：D1188-07e1。使用涂层样品测定压实沥青混合料容重和密度的标准试验方法。ASTM International，2007。http://dx.doi.org/10.1520/D1188-07E01

[16] SUHERMAN S. 混凝土与混凝土（RAP）材料之间的弹性模量和永久变形。 SITEKIN：科学、技术和工业杂志，2012，10(1)：51-58。http://dx.doi.org/10.24014/sitekin.v10i1.575

[17] GARBA R 和 HORVLI I. 沥青混合料抗车辙性能预测。在 GOMES CORREIA A.《道路承载力》第 2 卷中。伦敦，CRC出版社，2020。https://doi.org/10.1201/9781003078821-7

[18] TAYFUR S.、OZEN H. 和 AKSOY A. 含聚合物改性剂沥青混合料车辙性能调查。建筑与建筑材料，2007，21(2)：328-337。https://doi.org/10.1016/j.conbuildmat.2005.08.014

[19] KIM W. J.、LEE H. J. 和 PHAN H. T. 基于沥青路面剪切应力与强度比的车辙模型的校准和验证。建筑与建筑材料，2017，149：327-337。https://doi.org/10.1016/j.conbuildmat.2017.05.053

[20] CHEN J.S. 和 LIN K.Y. 使用纤维增强沥青强度的机理和行为。材料科学杂志，2015，40：87-95。https://doi.org/10.1007/s10853-005-5691-4

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