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**Karakteristik Mekanis Campuran AC-WC dengan Substitusi Bio-Binder Cangkang Pala Berdasarkan Uji
Ketahanan Deformasi Alur dan Kerusakan Akibat Kelembapan**
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INTISARI

Permintaan aspal sebagai bahan konstruksi perkerasan terus meningkat, menimbulkan kekhawatiran akan kelangkaan dan kenaikan harga aspal minyak bumi, sehingga dibutuhkan bahan alternatif seperti bio-binder. Limbah cangkang pala berpotensi diolah melalui proses pirolisis menjadi bio-oil yang dapat disubstitusikan pada aspal penetrasi 60/70 dalam campuran *Asphalt Concrete-Wearing Course* (AC-WC), yang selama ini rentan terhadap kerusakan berupa deformasi alur *(rutting)* dan kerusakan akibat kelembapan (moisture damage). Penelitian ini bertujuan untuk merancang Kadar Aspal Optimum (KAO) pada campuran AC-WC dengan substitusi bio-oil cangkang pala (BOCP) pada kadar 0%, 10%, dan 20%, serta mengevaluasi pengaruhnya terhadap ketahanan rutting, kerusakan akibat kelembapan, dan menentukan kadar BOCP optimum yang memberikan kinerja terbaik.

Penelitian dilakukan secara eksperimental di Laboratorium Transportasi dan Jalan, Departemen Teknik Sipil dan Lingkungan, Universitas Gadjah Mada. Karakteristik fisis aspal dan agregat diuji sesuai Spesifikasi Umum Bina Marga 2018 Revisi 2. Kadar Aspal Optimum ditentukan melalui pengujian Marshall pada lima variasi kadar aspal untuk setiap kadar BOCP, dengan parameter stabilitas, flow, density, VIM, VMA, dan VFA. Selanjutnya, dilakukan pengujian perendaman Marshall (*immersion test*), *Indirect Tensile Strength* (ITS) dan *Tensile Strength Ratio* (TSR), serta pengujian *Wheel Tracking Machine* (WTM) pada suhu 60°C mengacu pada Japan Road Association (JRA 1980) untuk mengevaluasi ketahanan terhadap *rutting* dan kelembapan pada kadar BOCP 0% dan 10%.

Hasil penelitian menunjukkan bahwa kadar BOCP 20% tidak memenuhi spesifikasi penetrasi aspal 60/70 sehingga tidak dilanjutkan pada pengujian durabilitas. Nilai KAO yang diperoleh adalah 5,6% (0% BOCP), 6,0% (10% BOCP), dan 6,4% (20% BOCP). Substitusi BOCP 10% meningkatkan *Index of Retained Strength* dari 94,02% menjadi 95,12% dan meningkatkan nilai ITS *unconditioned* maupun *conditioned* secara proporsional, meskipun nilai TSR sedikit menurun dari 85,29% menjadi 84,79%, namun masih memenuhi syarat minimum 80%. Pada pengujian *Wheel Tracking*, substitusi BOCP 10% menurunkan laju deformasi dari 0,029 mm/menit menjadi 0,023 mm/menit dan meningkatkan Stabilitas Dinamis dari 1471,71 menjadi 2896,84 lintasan/mm dengan syarat minimum 2500 lintasan/mm. Dengan demikian, substitusi *bio-oil* cangkang pala pada kadar 10% terbukti memberikan kinerja terbaik dalam meningkatkan ketahanan campuran AC-WC terhadap rutting dan kerusakan akibat kelembapan.

Kata kunci: *bio-binder*, cangkang pala, AC-WC, *rutting*, *moisture damage*

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ABSTRACT

The demand for asphalt as a pavement construction material continues to increase, raising concerns about the scarcity and rising prices of petroleum-based asphalt in the coming years, thereby requiring alternative materials such as bio-binder. Nutmeg shell waste has the potential to be processed through pyrolysis into bio-oil, which can partially substitute penetration grade 60/70 asphalt in Asphalt Concrete-Wearing Course (AC-WC) mixtures, a layer that is generally susceptible to rutting and moisture damage. This research aims to design the Optimum Asphalt Content (OAC) of AC-WC mixtures with nutmeg shell bio-oil (BOCP) substitution at contents of 0%, 10%, and 20%, and to evaluate its influence on rutting resistance and moisture damage, as well as to determine the optimum BOCP content that provides the best performance.

The research was conducted experimentally at the Transportation and Highway Laboratory, Department of Civil and Environmental Engineering, Universitas Gadjah Mada. The physical characteristics of the asphalt and aggregates were tested in accordance with the 2018 General Specification of Bina Marga (Revision 2). The Optimum Asphalt Content was determined through Marshall testing at five asphalt content variations for each BOCP content, evaluating stability, flow, density, VIM, VMA, and VFA parameters. Subsequently, Marshall immersion testing, Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) testing, and Wheel Tracking Machine (WTM) testing at 60°C referring to the Japan Road Association (JRA 1980) were carried out to evaluate rutting and moisture resistance at 0% and 10% BOCP contents.

The results showed that the 20% BOCP content did not meet the 60/70 penetration specification and was therefore excluded from further durability testing. The Optimum Asphalt Content values obtained were 5.6% (0% BOCP), 6.0% (10% BOCP), and 6.4% (20% BOCP). The 10% BOCP substitution increased the Index of Retained Strength from 94.02% to 95.12% and proportionally increased both unconditioned and conditioned ITS values, although the TSR value slightly decreased from 85.29% to 84.79%, still meeting the minimum requirement of 80%. In the Wheel Tracking test, the 10% BOCP substitution reduced the rate of deformation from 0.029 mm/minute to 0.023 mm/minute and increased the Dynamic Stability from 1471.71 to 2896.84 passes/mm. Thus, the substitution of nutmeg shell bio-oil at 10% content was proven to provide the best performance in enhancing the resistance of AC-WC mixtures against rutting and moisture damage.

Keywords: bio-binder, nutmeg shell, AC-WC, rutting, moisture damage