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A LITERATURE STUDY: BEHAVIORAL OBSERVATION OF THE COMBINATION OF RIGID AND FLEXIBLE PAVEMENTS

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ABSTRACT

The use of longitudinally laid composite pavement is currently massively used in Indonesia as part of the 272 national road standard program. This study systematically reviews and discusses the essential characteristics of semi-rigid flexible pavement widely implemented in Indonesia by comparing the bonding conditions between concrete overlays on flexible pavement; asphalt overlays on rigid pavement; longitudinal joints between flexible-flexible pavements, rigid-rigid pavements, rigid (roadway) pavements, and flexible (shoulder) pavements; and finds the potential similarity in characteristics for longitudinal joints between rigid (shoulder) pavements and flexible (roadway) pavements. The results reveal that the stiffness of the material significantly affects the remaining service life. Furthermore, high temperatures and water immersion cause stiffness of asphalt specimens loss, potentially leading to rutting and raveling. This indicates that damages due to water and temperature significantly affect the roadway, which is a structure formed with homogeneity.

Keyword: *semi-rigid flexural pavement, interface conditions, stiffness modulus, residual life prediction.*

1. INTRODUCTION

Based on their binding materials, pavements commonly used in Indonesia, consist of three types: flexible pavements, rigid pavements, and composite pavements [1]. The use of each type of pavement is adjusted according to the expected service life based on traffic volume and growth predictions [2]. Flexible pavements are used to serve light to moderate traffic, such as urban roads, roads with utility systems located beneath the pavement, shoulders, and phased construction pavements [3]. Meanwhile, rigid pavements are utilized for traffic volumes exceeding 30 million ESA_4 and serve heavy vehicles with low speeds, such as the roadway for highways, and may also be considered for urban and rural roads [2], [3]. Additionally, composite pavements are rigid pavements combined with flexible pavements and laid in layers (Figure 1). Chronologically, the laying of composite pavements can be conducted either from the initial planning stage or on existing rigid pavements, through overlay treatment with asphalt layers.

Source: Riyanto and Sunarjono, 2014[4]
Figure 1. Composite Pavement Laid in Layers

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However, the extensive use of longitudinally laid composite pavements also massively occurs in Indonesia. The composite pavement referred to is illustrated in Figure 2.

Source: Maulana, 2015 [5]

Figure 2. Longitudinally Laid Composite Pavement on Cipali Highway

Figure 2. shows rigid pavement used for the roadway and flexible pavement for the shoulders. Conversely, rigid pavement for the shoulders is also widely used in Indonesia as a part of the 272 national road standard program, which involves widening by 2 meters on both sides of national roads with a width of 7 meters, type 2/2 [6]. This handling program has been implemented gradually since 2013, where national roads with widths less than 7 meters and sharp curves are repaired and widened by 2 meters on each lane. The 2-meter widening is intended for motorcyclists to prevent them from queuing behind four-wheeled vehicles.

Source: googlemaps.com

Figure 3. Gadobangkong Road, Cimahi, West Java

Source: googlemaps.com

Figure 3 illustrates an example of the location where rigid pavement is used for the shoulders, and flexible pavement for the roadway. The use of rigid pavement to widen existing roads with flexible pavement (hereinafter referred to as semi-rigid flexible pavement) has been widely implemented as a practical engineering effort in the field. Additionally, according to former Director of Technical Development at the Directorate General of Highways, Purnomo, asphalt prices are increasing while cement prices are more stable, resulting in higher construction costs for flexible pavements compared to rigid ones [7]. The locations of the semi-rigid flexible pavement referred to are scattered across Indonesia (Figure 4).

Figure 4. Location Distribution of Composite Pavements between Roadway and Shoulder[1]

Based on the findings from Figure 4, there are 11 locations scattered across several islands in Indonesia. There are 4 locations on Sumatera Island, 3 locations on Sulawesi Island, and 4 locations on Java Island.

[1] compiled from various sources [44], [45], [46], [47], [48], [49], [50], [51], [52]

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The widespread use of semi-rigid flexible pavement is not accompanied by adequate research due to the common occurrence of typical damages at each location.
Tie bars function to prevent rigid pavements from experiencing horizontal displacement [8]. Without tie bars, horizontal displacement along the road can occur, leading to frictional interaction between individual concrete panels. Meanwhile, lateral displacement across the road can occur, leading to cracks at longitudinal joints (linear cracking) or the breaking of concrete panels into several pieces (punch out) [9]. The deterioration of the longitudinal joint in asphalt pavement is a significant structural concern [10]. Compressive stress due to repeated traffic loading will further expand the pressure on the joint and reduction traffic performance [10]. Furthermore, the growth rate of such damage can also continue to increase due to weather conditions, water infiltration, material quality, and stiffness gradient [11].

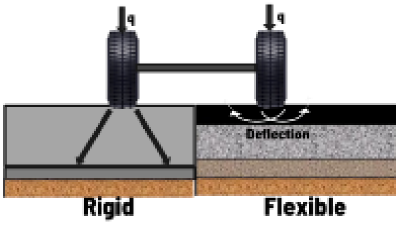

Figure 5. The load transfer direction in semi-rigid flexible pavement

The difference in load transfer concepts between rigid and flexible pavements is the main cause of typical damages. Figure 5 illustrates the example of single-axle vehicle track patterns that may occur in the field. The deflection that occurs in pavements is influenced by loading. The track patterns in Figure 5 indicate the direction of deflection in flexible pavements and the distribution of loading in rigid pavements. In the analysis of flexible pavements, traffic loads are responded to by the pavement involving the behavior of compressive stress, tensile strain, and deflection [12].

Meanwhile, in rigid pavements, traffic loads are responded to as uniformly distributed loads, resulting in less pronounced behavior compared to flexible pavements. However, the value remains observable. The deflection and stress resulting from traffic loads are instantaneous, occurring when the traffic is on the pavement. If these instantaneous strains exceed the limit strains, they will become permanent strains [13]. The nature of rigid pavement, which distributes the load, should be well received in the adjacent lanes with the use of tie bars. However, the fact that the flexible pavement lane is laid first makes it difficult to install tie bars, so the implementation is rarely done in the field.

Therefore, the authors are interested in conducting empirical studies on the characteristics of semi-rigid flexible pavements that have been widely implemented in Indonesia. This research aims to compare the bonding conditions between concrete overlays on flexible pavement; asphalt overlays on rigid pavement; longitudinal joints between flexible-flexible pavements, rigid-rigid pavements, rigid (roadway) pavements, and flexible (shoulder) pavements; and finds the potential similarity in characteristics for longitudinal joints between rigid (shoulder) pavements and flexible (roadway) pavements.

The hypothesis of this research is summarized as follows.

1. Widening asphalt pavements using rigid pavement as shoulders is an applicable alternative solution in the field, with performance characteristic differences that can be addressed with various modern technologies in the future.
2. The prediction of damage in longitudinal joints of semi-rigid asphalt pavements can be achieved by examining the stiffness modulus through analysis with Finite Element Method (FEM).

2. RESEARCH METHOD

Descriptive analysis is used as the method in this research. The research presents the findings of an exploration of semi-rigid flexible pavements, focusing on planning, implementation, and evaluation aspects. The initial hypothesis for the cause of damage in composite pavements was the different stiffness modulus between the two types of materials. Composite and joint types were varied for exploration and discussion (Figure 6). The findings are limited by the following criteria that journal data is obtained from several websites, such as Science Direct, Research Gate, Google Scholar, and official campus journals.

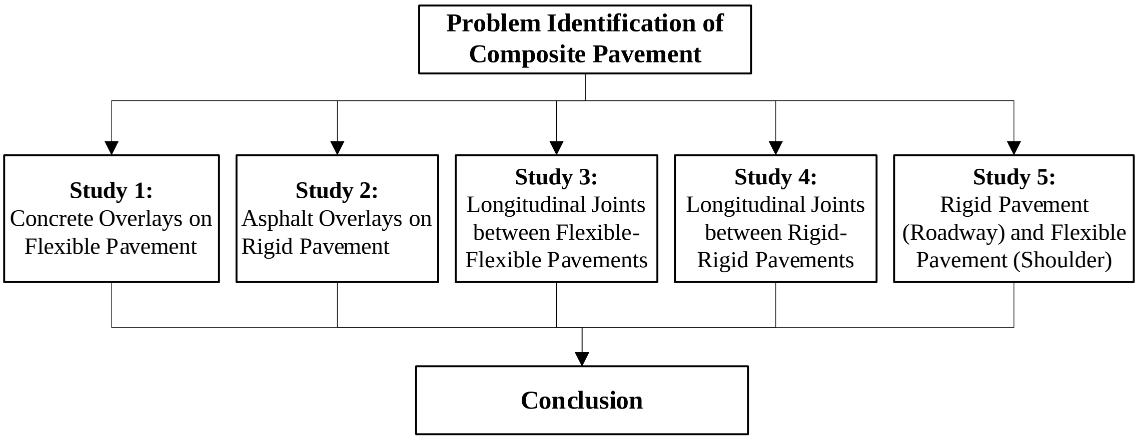

Figure 6. Research Scope

3. ANALYSIS AND RESULT

3.1. Study 1: Concrete Overlays on Flexible Pavement

The concrete overlay on flexible pavement is one of the rehabilitation treatment alternatives that has several limitations in its application to the field. This treatment term is referred to as whitetopping [14]. There are three types: white topping, thin-white topping, and ultra-thin white topping (UTW) [15]. According to the Sub directorate of Geometry, Pavement, and Drainage, Directorate of Road Development in Indonesia, the condition where concrete overlay on flexible pavement is considered unsuitable is because:

1. the level and quantity of pavement damage is minimal, allowing the use of more economical alternatives;
2. the bridge’s clearance height is no longer sufficient due to the concrete overlay’s thickness;
3. the existing pavement is prone to settlement [16].

According to Cantillo in 2021, there are several shortcomings of concrete overlay treatment on asphalt surfaces, including:

1. low adherence, meaning that the asphalt is not well-suited as a base for concrete overlay because it contains oily tar that reduces the concrete’s bonding strength;
2. poor longevity, meaning that it has a shorter lifespan because the subbase layer, which is asphalt, is prone to fatigue cracking over time, worsening the concrete’s performance;
3. costly in the long run, meaning that in the long term, it leads to an increase in maintenance costs, even though it may save costs in the short term [17], [18].

The results differ when whitetopping is planned to be laid using advanced technology. Research in India revealed that the low adherence characteristic can be minimized by grinding or milling to roughen the asphalt surface. This is done in accordance with the whitetopping design as per Indian Road Congress (IRC): 76-2015.

Table 1. Whitetopping specifications in the research in India

No	Aspects	Specifications
1	Concrete Layer’s	Concrete quality of fc'4.5 MPa with a thickness of 200 mm is laid on top:

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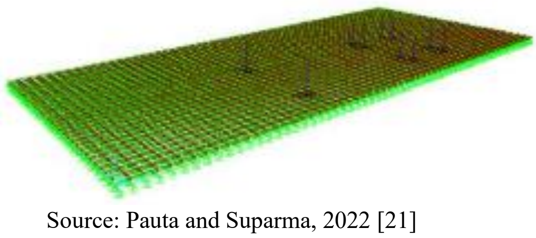
No	Aspects	Specifications
	Thickness and Quality	a. Asphalt layer with a rough surface b. Overlay thickness pf 25-30 mm so that the final thickness of the pavement is 180mm - 200 mm c. Polypropylene fibres are added to the concrete to reduce shrinkage cracks
2	Concrete Slabs	1000 mm x 1000 mm Transverse Joints Distance = 1000mm Longitudinal Joints Distance = 1250 mm Joint cutting is done within 14-16 hours after concrete casting
3	Dowel Bars	Diameter 32 mm, length 500 mm at a spacing of 250 mm c/c at the mid-depth of the slab only at construction joints
4	Tie Bars	Diameter 12 mm, length 650 mm at a spacing of 600 mm c/c at the mid-depth of the slab, and 140 mm from the top of the slab

Source: Chintawar and Pawar, 2021 [19]

Single, tandem, and tridem axle loading is applied to the pavement and overlay layer, which has a Modulus of Rupture for the pavement of 4.413 MPa with a Poisson's ratio of 0.15, indicating it is relatively stiff and dense [20]. The result is a total stress (maximum lad stress + curling stress) of 34.3 kg/cm^2. This value is considered safe because the maximum limit is 45 kg/cm^2 [19].

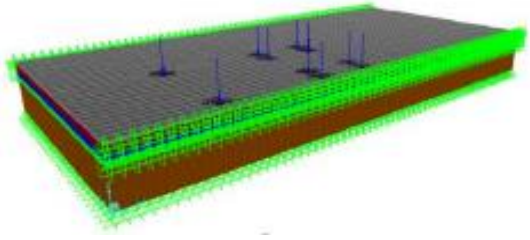
3.2. Study 2: Asphalt Overlays on Rigid Pavement

The plate analysis with an elastic foundation model utilizes specifications such as a 5 cm thick Hot Rolled Sheet (HRS) layer modeled as a solid element, tie bar reinforcement using constraint functions with a spacing of 75 cm, and foundation layer modeled as a compression-only element, as shown in Figure 7 [21]. Meanwhile for the three-dimensional solid model, the road pavement is modeled in 5 layers with a total thickness of 1.55 meters, as shown in Figure 8.



Source: Pauta and Suparma, 2022 [21]

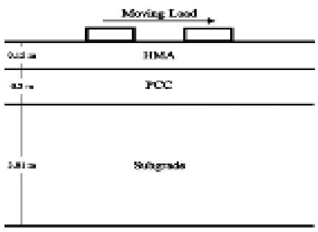
Figure 7. Elastic Foundation Model



Source: Pauta and Suparma, 2022 [21]

Figure 8. Three-dimensional Solid Model

By using the plate model on the elastic foundation and the three-dimensional solid model in SAP2000, or a subgrade soil with a CBR of 6%, the maximum tensile stress in the concrete slab reaches 2.081 MPa under the elastic foundation model and 2.51 MPa in the three-dimensional solid model [21]. Firstly, conduct the fatigue life analysis of the pavement. Zarei and Shafabakhshy in 2018, in their research that employed the finite element method (FEM) on composite pavement with a design as shown in Figure 9.



Source: Zarei and Shafabakhsh, 2018 [22]
Figure 9. Composite Pavement Layers in the Research

Research findings indicate that the elastic modulus of asphalt and concrete plays a crucial role in extending the fatigue life of composite pavements, exerting a greater influence than the thickness of the concrete layer [22]. Additionally, the tensile strain of the concrete layer is an important factor that needs to be considered to control fatigue failure and improve longevity.

Another research in China by Shuming Li and Kangda Xu in 2018 revealed that an interlayer is needed before asphalt overlay on concrete pavement using AC-5 substrate, which more refined aggregates, an enhanced mineral powder ratio, greater asphalt binder content, and decreased air void presence [23]. The purpose of using this substrate is to enhance the interface bond between concrete and asphalt. As a result, the AC-5 interlayer can decrease the strength and stiffness of the shear bond by 38.8% and 62.9%, respectively [23].

3.3. Study 3: Longitudinal Joints between Flexible-Flexible Pavements

According to the National Road Research Alliance (NRRA), in the construction, Hot Mix Asphalt (HMA) for longitudinal joints are still required. States within the NRRA such as California, Illinois, Michigan, Minnesota, Missouri, and Wisconsin have stipulated that these joints require a tack coat layer to be applied along the longitudinal joint surface before laying the new hot mix asphalt mixture [24].


Source: Korzilius, and Omer, 2018 [24]
Figure 10. Longitudinal Joint with Tack Coat in Minnesota


Source: Federal Highway Administration, 2020 [25]
Figure 11. Example of Longitudinal Joint Failure

Early longitudinal joint failures like those in Figure 11 are typically caused by a combination of low density, high permeability, segregation, improper overlapping of mixtures, and insufficient adhesion occurring at the asphalt binder, resulting in surface cracking [25], [26]. If the joint's density is

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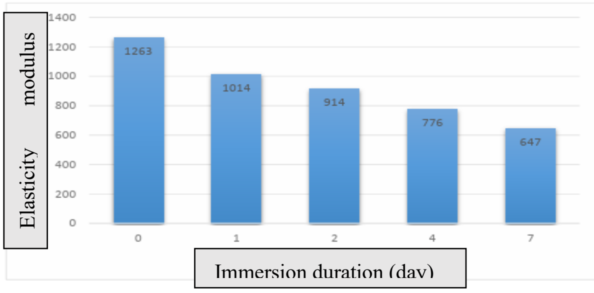
significantly lower than that of the existing mixture, the permeability of the mixture around the joint will be higher. This will allow a greater water flow into the pavement at the joint, accelerating the deterioration rate [25].

Studies on the effect of water on flexible pavement damage have been extensively conducted. The most influential characteristic is the decrease in asphalt stiffness modulus. Based on Figure 12, Adiman stated that the longer the immersion duration of the asphalt mixture specimens, the lower the elastic modulus value. The initial elastic modulus value of 1263 MPa without immersion decreased to 1.014 MPa after 1 day of immersion and continued to decline to 647 MPa on the seventh day [27]. This occurs due to the oxidation process by water, which weakens the bond between the asphalt and aggregates [28].



Source: Adiman, 2012 [27].

Figure 12. The reduction elastic properties of the asphalt mixture test specimen based on the immersion duration

Table 2. Decrease in Resilient Modulus Value from UMATTA Test

Mixture type	Resilient Modulus (MPa)		Decrease (%)
	25°C	45°C	
60-40	2251	222	90.14
50-50	2683	269	89.97
0-100	2798	275	90.17

Source: Adtihya, Kosasih, and Hendarto, 2016 [29]

In addition to water, temperature also affects the decrease in asphalt stiffness modulus [29], [30], [31], [32]. As an example, based on Table 2, out of the three variation of asphalt mixtures by Aditya, the average decrease in resilience modulus due to a temperature of 45°C reached 90.093%. This indicates that if damage can occur to other than pavement joints as shown in Figure 11 due to water and temperature, then damage to the joints between asphalt pavements is even more prone to occur.

Standardized tests can be conducted in analyzing fractures in asphalt pavement; however, these tests are limited because the results are unreliable due to difficult procedures and inadequate stress values obtained [33], [34]. However, efforts to observe fractures in the longitudinal joints of flexible pavements continue. Research in Mexico analyzed mode I fracture, which is a type of fracture in flexible pavements caused by thermal cyclic loading or traffic, using three synthetic geometry test specimens at temperatures of 10, 20, and 30 °C, with shapes as depicted in Figure 13.

Source: Pérez-Landeros, 2022[35]

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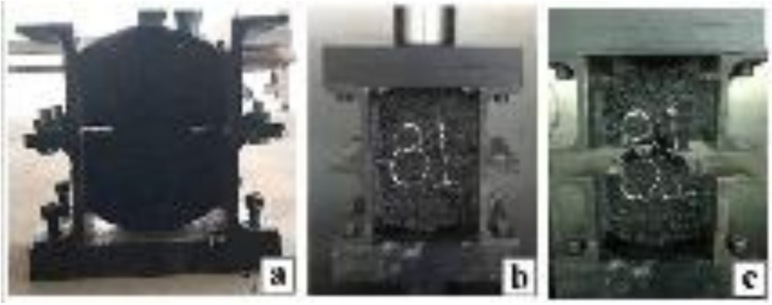
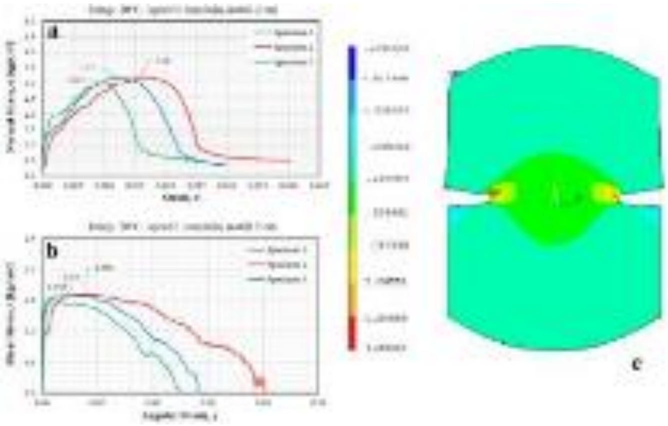
Figure 13. Test specimens (a); Cut and notch on test specimen (b); Size of cut and notch (c)



Source: Pérez-Landeros, 2022[35]

Figure 14. Test specimens ready for use (a); Direct tension test clamping system on the GCTS machine (b); Specimen fracture produced in the direct tension test (c) [35]

A specimen maintained at 20°C was deemed the most representative for evaluating test stress, given its incorporation of both elastic and viscous material properties. This assessment was based on a tensile strength of 143 kg/cm², a notch length of 2 cm, a specimen thickness of 5 cm, and a load application rate of 1 mm/min. [35], [36]. The finite element model (FEM) within the ANSYS framework was utilized to simulate the cracking behavior of asphalt mixtures.



Source: Pérez-Landeros, 2022[35]

Figure 15. Normal Stress and Shear Stress from Tensile Test (a, b); ANSYS Simulation (c)

Referring to Figure 14 and Figure 15, specimens with 2 cm notches, tested at 10 °C under different load application speeds, exhibit the elastic properties of asphalt, displaying increased stiffness due to the elevated stress levels, which leads to brittle failure. In contrast, specimens tested at 30°C reveal the material's viscous behavior, attributed to the lower normal stress, resulting in permanent deformations. Consequently, these conditions are not representative and were excluded. Meanwhile, specimens tested at 20°C under varying load application speeds display both elastic and plastic characteristics of asphalt, demonstrating a quasi-brittle response. This behavior closely resembles real pavement conditions, making it the most suitable scenario for assessing crack development. [35].
The findings from the ANSYS simulation reveal that the discrepancy in cracking behavior between asphalt test specimens in direct tensile testing and the proposed model simulation ranges from 30% to 35%. This variation suggests that the FEM model is reliable for approximating and forecasting asphalt mixture cracking behavior, as its results align well with observed experimental trends. [35].

3.4. Study 4: Longitudinal Joints between Rigid-Rigid Pavements

Cracks in longitudinal joints can be subjected to preventive maintenance before the cracks become larger and repair costs escalate, by cross-stitching. cross-stitching is a maintenance method to maintain the

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strength of rigid pavement, both for longitudinal cracks and as a binder for longitudinal joints experiencing separation [37].

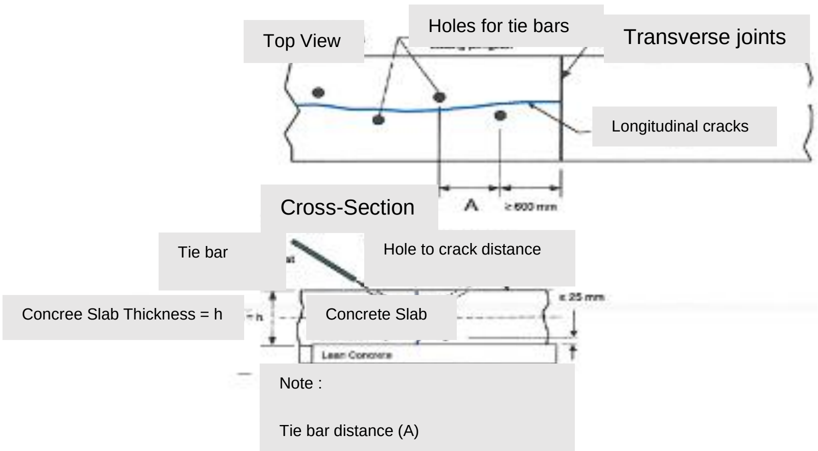

Figure 16. Scheme of Tie Bar Installation Location

With the drilling, tying of bars, and filling of gaps with epoxy adhesive material in Figure 16, this treatment is considered effective if it can distribute the load of rigid pavement experiencing cracks/longitudinal joints, thus delaying more severe damage [38].

3.5. Study 5: Rigid Pavement (Roadway) and Flexible Pavement (Shoulder)

Road shoulder construction using asphalt pavement needs to consider the number of compactors passes for each layer so that the final height of the road shoulder is the same as the existing surface and has sufficient slope to drain rainwater into the drainage channel. There are excavation space sides that are unreachable by the roller when using compactors weighing 4-8 tons [39]. Compaction for such narrow spaces must be performed gradually using three types of compactors: light compactors, horse tamper compactors, and compactors with a capacity of more than 25 tons [40]. Therefore, its implementation in the field is quite impractical.

Concrete pavement requires some spacing between its panels for expansion and contraction space, thus relying on joints for load transfer. The stiffness on rigid pavement, characterized by high elasticity modulus, plays a significant role in enhancing the structural capacity to distribute loads [41]. Rigid pavement with low elasticity modulus can lead to early damage characterized by the appearance of corner cracks and panel separation [9].

Meanwhile, asphalt pavement tends to experience vertical deflection (depression) when subjected to a load [9], [42]. Often, it fails to return to its original shape if the load exceeds the design, resulting in rutting and shoving [9], [42]. The permanent deformation occurs due to the continuous decrease in asphalt's resilient modulus as temperature and weather conditions change, as explained in point C.

In this case, researchers in China observed polyurethane grouting material for engineering repairs of longitudinal joint damage in this semi-rigid asphalt base pavement. Splitting Tensile Test (Figure 17) was conducted on two types of cubic specimens, namely asphalt mixture and cement stabilized macadam, which were injected with polyurethane as shown in Figure 18.

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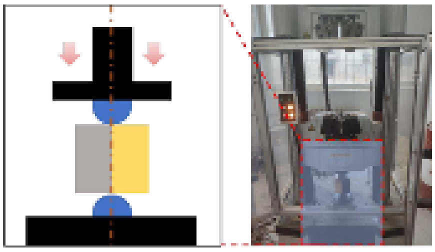
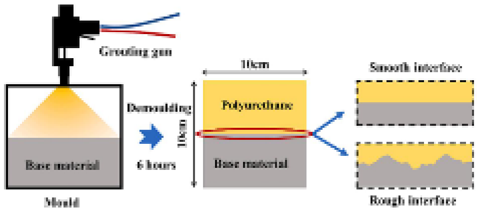


Source: Zhong, et al, 2023[10]

Figure 17. Splitting Tensile Test

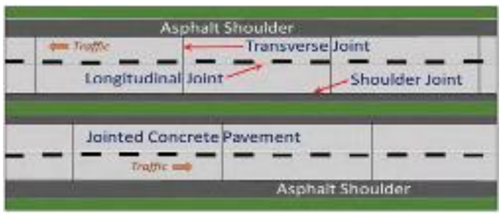


Source: Zhong, et al, 2023[10]

Figure 18. Test Specimen Fabrication Scheme

When in contact with the base material interface, a solid polyurethane film layer is formed. This film demonstrates strong adhesion properties and has the ability to penetrate the pores of the base material. Experimental results from the interface shear strength and splitting tensile strength models reveal a roughness index varying between 2.0 and 15.7. The tested specimen densities fall within the typical range used in engineering applications, approximately 0.25 g/cm³ to 0.55 g/cm³. These findings confirm that polyurethane is a viable option for grouting applications and optimizing polymer grouting techniques to address longitudinal joint pressure issues in semi-rigid base asphalt pavements [10].

Meanwhile, longitudinal joints in rigid and flexible pavement as shown in Figure 19 have been researched since 2010 in Arizona and Minnesota, United States.



Source: Galehouse and Scofield, 2022 [43]

Figure 19. Configuration of Rigid-Flexible Pavement Joints

Typical damage on such rigid-flexible pavement includes linear cracking to expanding holes if not promptly addressed. According to long-term research, the damage to the pavement joints is caused by imperfect bonding between the new mixture and the pavement or lower joint density, increasing air voids. This makes the joints vulnerable to water (permeable) and accelerates damage [43].

Source: Galehouse and Scofield, 2022 [43]

Figure 20. Example of Damage on Interstate 494, United States

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The research was conducted in Interstate 494 expressway (Figure 20). Closure was done with a microsurface mixture with the Type II gradation specified by the International Slurry Surfacing Association incorporates granite sourced from the St. Cloud quarry [43]. The laying was done on two longitudinal joints and shoulder joints, each with a total length of 28000 ft.

The results prove that compared to regular patching and joint sealant, micro surface mixture is a cost-effective and durable maintenance solution that works well with high traffic volumes [43].

4. CONCLUSION

Based on existing research findings, there are different characteristics between the application of rigid-flexible pavement when laying in layers and laying longitudinally/transversely. When laying common composite pavement in layers, interlayer shear stress should be minimized to withstand the shear forces from vehicle wheels. Meanwhile, the application of rigid-flexible pavement in the longitudinal/transverse direction should be sufficiently dense. Research in Arizona and Minnesota has proven that the composite pavements can be accomplished with the careful planning of joint maintenance using micro surface mixtures, as successfully implemented on Interstate 494.

The stiffness modulus of the material significantly affects the remaining service life. Furthermore, high temperatures and water immersion cause stiffness of asphalt specimens loss, potentially leading to rutting and raveling. This indicates that if damage can occur to other than pavement joints due to water and temperature, then damage to the joints between asphalt pavements is even more prone to occur. Meanwhile, the low elasticity modulus in concrete leads to corner cracking and panel separation. Predicting damage to longitudinal joints in the flexible-rigid pavement can also be done in more detail by observing mechanical properties, considering that significant changes in joint conditions on Interstate 494 have occurred visually. By considering the stiffness modulus of each material, the prediction of damage and remaining service life can be conducted using the finite element method by examining the residual stresses that occur.

In the future, further studies are needed on FEM analysis of longitudinal joints in semi-rigid asphalt pavements to predict cracks, similar to the research on asphalt pavements in Mexico by Pérez-Landeros et al. (2022) and to complement the study on rigid-flexible pavement joints by Galehouse.

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REFERENCES

[1] Dinas Pekerjaan Umum Perumahan dan Kawasan Pemukiman Kabupaten Kulon Progo, "Perkerasan Jalan Raya." Accessed: Feb. 13, 2024. [Online]. Available: https://dpu.kulonprogokab.go.id/detil/55/perkerasan-jalan-raya
[2] Kementerian Pekerjaan Umum dan Perumahan Rakyat, *Manual Desain Perkerasan Jalan*, Edisi kedu., no. 02. Jakarta, 2017.
[3] Sukirman, *Perencanaan Tebal Struktur Perkerasan Lentur*, vol. 53, no. 9. 2010.
[4] S. Sunarjono and A. Riyanto, "Bahan Perkerasan." Accessed: Feb. 06, 2024. [Online]. Available: https://www.slideserve.com/debra/bahan-perkerasan-semester-5-2-sks
[5] A. Maulana, "Jalan Tol Cipali, Ada yang Dilapisi Aspal, Ada Juga Beton," *Detik Oto,* Jakarta, p. 1, 2015. [Online]. Available: https://oto.detik.com/berita/d-2957293/jalan-tol-cipali-ada-yang-dilapisi-aspal-ada-juga-beton
[6] F. Selly, "Jalur lintas Nakau-Lubuklinggau diberlakukan program 272," *AntaraNews*, Bengkulu, 2013. [Online]. Available: https://sumsel.antaranews.com/berita/275146/jalur-lintas-nakau-

P-ISSN : 2598-1277
E-ISSN : 2621-3966

lubuklinggau-diberlakukan-program-272

[7] A. S. A. Maharani and H. B. Alexander, "Ini Kelebihan dan Kekurangan Tol yang Dilapisi Aspal dan Beton," *kompas.com*, Cilacap, Apr. 15, 2023. [Online]. Available: https://www.kompas.com/properti/read/2023/04/15/100651421/ini-kelebihan-dan-kekurangan-tol-yang-dilapisi-aspal-dan-beton

[8] Badan Pengembangan Sumber Daya Manusia (BPSDM) Kementerian PUPR, "Jenis Perkerasan Kaku (Rigid Pavement)." [Online]. Available: http://ptb.sipil.ft.unp.ac.id/jenis-perkerasan-kaku-rigid-pavement/

[9] Kementerian Pekerjaan Umum dan Perumahan Rakyat, "Penentuan Indeks Kondisi Perkerasan (IKP)," *SE Menteri PUPR*, pp. i–79, 2016.

[10] Y. Zhong, S. Xu, J. Chi, B. Zhang, G. Shen, and Z. Yang, "Experimental study on the interface bonding characteristic of polyurethane and pavement materials," *Constr. Build. Mater.*, vol. 397, no. March, p. 132390, 2023, doi: 10.1016/j.conbuildmat.2023.132390.

[11] M. T. Bevacqua, T. Isernia, F. G. Praticò, and S. Zumbo, "A Method for Bottom-Up Cracks Healing via Selective and Deep Microwave Heating," *Autom. Constr.*, vol. 121, 2021, doi: https://doi.org/10.1016/j.autcon.2020.103426.

[12] A. S. Hidayat and C. A. Prastyanto, "Analisa Hubungan Antara Nilai Lendutan Dengan Modulus Elastisitas Perkerasan Lentur Akibat Beban Berlebih Dengan Metode Boussinesq," vol. 17, pp. 59–68, 2019.

[13] A. D. Widodo, "Evaluasi Kondisi Perkerasan dan Prediksi Sisa Umur Perkerasan Lentur dengan Metode Pavement Condition Index, Bina Marga, dan Metode Mekanistik-Empirik dengan Studi kasus Ruas Jalan Magelang – Yogyakarta Sta 11±000 – Sta 12±000) Program Kenpave," Universitas Islam Indonesia, 2018.

[14] Chaney Enterprises, "Whitetopping." Accessed: Feb. 13, 2024. [Online]. Available: https://www.chaneyenterprises.com/Whitetopping

[15] J. Kamalanathan and S. N. Subbarao, "Experimental investigation of interface treatment technique on interface shear bond fatigue behavior of Ultra-Thin Whitetopping," *Constr. Build. Mater.*, vol. 161, pp. 489–500, 2018, doi: https://doi.org/10.1016/j.conbuildmat.2017.11.057.

[16] Subdirektorat Geometrik Perkerasan dan Drainase PUPR, "Overlay Perkerasan Kaku Di Atas," 2019, *Sugih Sujana, Jakarta*. [Online]. Available: https://subdirektoratgpd.files.wordpress.com/2019/08/3-paparan-desain-overlay-perkerasan-kaku-di-atas-perkerasan-lentur.pdf

[17] R. Cantillo, "Why Paving Concrete Over Asphalt is Only a Temporary Solution," Empire Parking Lot Services. Accessed: Feb. 13, 2024. [Online]. Available: https://www.empirepls.com/blog/paving-concrete-over-asphalt-temporary

[18] A. U. Qureshi, "Experimental Analysis of White Topping and Bitumen Roads in Sagar," NIT Kurukshetra, 2020. [Online]. Available: https://www.researchgate.net/publication/339723449_Experimental_Analysis_Of_White_Topping_Bitumen_Roads_In_Sagar

[19] S. B. Chintawar and K. Pawar, "White Topping or Concrete Overlay for Highways," *Int. J. Creat. Res. Thoughts*, vol. 9, no. 7, pp. 80–86, 2021, [Online]. Available: https://ijcrt.org/papers/IJCRT2107654.pdf

[20] "What is Poisson's Ratio?," Matmatch. Accessed: Feb. 13, 2024. [Online]. Available: https://matmatch.com/learn/property/poissons-ratio

[21] B. K. Pauta, B. Suhendro, and L. B. Suparma, "Respons Struktur Perkerasan Jalan Komposit Akibat Beban Lalu Lintas Dengan Metode Elemen Hingga Di Kabupaten Merauke," *J. Transp.*, vol. 22, no. 3, pp. 237–248, 2022, [Online]. Available: https://journal.unpar.ac.id/index.php/journaltransportasi/article/view/6352%0Ahttps://journal.unpar.ac.id/index.php/journaltransportasi/article/view/6352/3926

[22] B. Zarei and G. Ali Shafabakhsh, "Dynamic Analysis of Composite Pavement using Finite Element Method and Prediction of Fatigue Life," *Comput. Res. Prog. Appl. Sci. Eng. CRPASE*, vol. 04, no. 02, pp. 33–37, 2018.

[23] S. Li and K. Xu, "Interface bond condition of cement concrete pavement with an asphaltic interlayer," vol. 4, no. 4, pp. 186–190, 2018, doi: 10.15406/mojce.2018.04.00118.

[24] SRF Consulting Group Inc, J. Korzilius, and M. Omer, *Longitudinal Joint Construction*, no.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

September. California, Illinois, Michigan, Minnesota, Missouri, and Wisconsin: NRRA, 2018. [Online]. Available: https://www.dot.state.mn.us/mnroad/nrra/newsletter/documents/Longitudinal Joints.pdf
[25] Federal Highway Administration, "Tech Brief: Improving Longitudinal Joint Performance," no. 5, pp. 1–16, 2020, [Online]. Available: https://www.fhwa.dot.gov/pavement/asphalt/pubs/hif21023.pdf
[26] J. Chen *et al.*, "New Innovations in Pavement Materials and Engineering: A Review on Pavement Engineering Research 2021," *J. Traffic Transp. Eng. (English Ed.*, vol. 8, no. 6, pp. 815–999, 2021, doi: https://doi.org/10.1016/j.jtte.2021.10.001.
[27] E. Y. Adiman, "Pengaruh Durasi Rendaman Air Banjir Terhadap Nilai Modulus Elastisitas Campuran Aspal Modifikasi," no. 2012, pp. 171–180, 2022, [Online]. Available: https://osf.io/7z9m6/download
[28] R. G. Hicks, *Moisture Damage in Asphalt Concrete*, vol. 175. 1991.
[29] A. P. Adtihya, B. S, D. Kosasih, and S. Hendarto, "Evaluasi Karakteristik Modulus Resilien dan Deformasi Permanen Campuran Beton Beraspal (AC-Binder Course) Menggunakan Campuran Agregat Berabrasi Tinggi," *J. Civ. Eng.*, vol. 23, no. 2, pp. 223–232, 2016.
[30] I. Susanto and N. Suaryana, "Evaluasi Kinerja Campuran Beraspal Lapis Aus (AC-WC) dengan Bahan Tambah Limbah Plastik Kresek," *J. Apl. Tek. Sipil*, vol. 17, no. 2, p. 27, 2019, doi: 10.12962/j2579-891x.v17i2.4980.
[31] A. Iman Adiwidodo, H. Rahman, and N. Zain, "Analisis Kinerja Modulus Resilien dan Ketahanan Fatigue Campuran AC-WC dengan Asbuton Murni, BNA Blend, dan Aspal Pen 60/70," *J. Tek. Sipil*, vol. 30, no. 3, pp. 481–490, 2023, doi: 10.5614/jts.2023.30.3.16.
[32] Suherman, "Kinerja Modulus Resilien dan Deformasi Permanen Dari Campuran Lapis Antara (AC-BC) yang Menggunakan Material Hasil Daur Ulang (Rap) Ac Lapis Antara (AC-Binder Course , AC- BC) dan AC Lapis Pondasi (AC-Base). Perencanaan Campuran Beton Aspal Lapis," *Sains, Teknol. dan Ind.*, vol. 10, no. 1, pp. 51–58, 2012, [Online]. Available: http://ejournal.uin-suska.ac.id/index.php/sitekin/article/download/575/547
[33] J. Bonnot, "Asphalt Aggregate Mixtures," *Transp. Res. Rec. 1096*, 1986, [Online]. Available: https://onlinepubs.trb.org/Onlinepubs/trr/1986/1096/1096-005.pdf
[34] J. Hu, P. Liu, D. Wang, M. Oeser, and Y. Tan, "Investigation on Fatigue Damage of Asphalt Mixture with Different Air-Voids Using Microstructural Analysis," *Constr. Build. Mater.*, vol. 125, pp. 936–945, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.08.138.
[35] J. F. Pérez-Landeros, P. Limón-Covarrubias, J. R. Galaviz-González, D. Avalos-Cueva, M. de la L. Pérez-Rea, and M. Zamora-Palacios, "Evaluation of Mode-I Fracture Toughness of Asphalt Mixtures with Symmetric Geometry Specimen at Intermediate Temperature," *MDPI Mater.*, vol. 15, no. 14, 2022, doi: https://doi.org/10.3390/ma15144977.
[36] M. R. Eghbali, M. F. Tafti, M. R. M. Aliha, and H. Motamedi, "The effect of ENDB specimen geometry on mode I fracture toughness and fracture energy of HMA and SMA mixtures at low temperatures," *Eng. Fract. Mech.*, vol. 216, 2019, doi: https://doi.org/10.1016/j.engfracmech.2019.106496.
[37] Kementerian Pekerjaan Umum dan Perumahan Rakyat, *Spesifikasi Khusus Interim Pemeliharaan Preventif Penjahitan Melintang pada Pemeliharaan Perkerasan Kaku Cross Stitching*. Jakarta, 2017. [Online]. Available: https://depobeta.com/spesifikasi-khusus-interim-pemeliharaan-preventif-penjahitan-melintang-pada-pemeliharaan-perkerasan-kaku-cross-stitching.html
[38] Kementerian Pekerjaan Umum dan Perumahan Rakyat, *Penjahitan Melintang pada Pemeliharaan Perkerasan Kaku*. Jakarta, 2016. [Online]. Available: https://desadonorojo.files.wordpress.com/2021/11/pedoman-penjahitan-melintang-cross-stiching-pada-pemeliharaan-perkerasan-kaku.pdf
[39] PUPR, "Spesifikasi Umum 2018," *Edaran Dirjen Bina Marga Nomor 02/SE/Db/2018*, no. Revisi 2, pp. 6.1-6.104, 2018.
[40] J. Purwanto *et al.*, "Penanganan Pelebaran Perkerasan Jalan Pada Ruas-Ruas Jalan Dengan Lahan Terbatas," vol. 6, no. 2, pp. 119–128, 2020.
[41] H. Pasaribu and M. T. Simanullang, "Hubungan Kekuatan Tanah Dasar dengan Perkerasan Kaku (Rigid Pavement)," *J. Tek. Sipil*, vol. 1, no. 1, pp. 1–10, 2021.

 P-ISSN : 2598-1277
E-ISSN : 2621-3966

[42] L. B. Suprama and D. Idwal, "Mending Jalan Aspal atau Beton?" [Online]. Available: https://pijak.id/page/19/

[43] L. Galehouse and L. Scofield, "Maintenance and Longevity of Longitudinal Joints," *TR News*, Arizona, pp. 15–19, 2022. [Online]. Available: https://onlinepubs.trb.org/onlinepubs/trnews/trnews339Maintenance.pdf

[44] Yudi, "Terjadi Diproyek Pemeliharaan Berkala Ruas Jalan Simpang Duku Ketaping Pariaman : Belum Lama Dilewati Kendaraan, Rigid Beton Bahu Jalan Mengalami Cacat Fisik ?" Accessed: Nov. 26, 2024. [Online]. Available: https://www.internewss.com/2021/11/terjadi-diproyek-pemeliharaan-berkala.html

[45] "Proyek Pekerjaan Bahu Jalan Keranjalembah Akses Padat Wilayah Kabupaten Sigi," radarnusantara. Accessed: Nov. 26, 2024. [Online]. Available: https://www.radarnusantara.com/2019/12/proyek-pekerjaan-bahu-jalan.html

[46] "Pekerjaan Rabat Beton Bahu Jalan Jalinsum Way Kanan Diduga dikerjakan Asal Asalan," Berani News. Accessed: Nov. 26, 2024. [Online]. Available: https://www.berani-news.com/2018/10/pekerjaan-rabat-beton-bahu-jalan.html

[47] "Penanganan Ruas Jalan Watumurah - Nogosari," Dinas Pekerjaan Umum Perumahan dan Kawasan Permukiman Kabupaten Kulon Progo. Accessed: Nov. 26, 2024. [Online]. Available: https://dpu.kulonprogokab.go.id/detil/996/penanganan-ruas-jalan-watumurah-nogosari

[48] Agus and Tommy, "Pengecoran Bahu Jalan yang Dikerjakan PT. Kaltim Tidak Sesuai RAB." Accessed: Nov. 26, 2024. [Online]. Available: https://pirnas.com/daerah/pengecoran-bahu-jalan-yang-dikerjakan-pt-kaltim-tidak-sesuai-rab/

[49] Rahmad and Danny, "DPUPR Rabat Beton Bahu Jalan Pinang Mas." Accessed: Nov. 26, 2024. [Online]. Available: https://dpupr.bengkulukota.go.id/dpupr-rabat-beton-bahu-jalan-pinang-mas/

[50] Abrar, "Pekerjaan Talud dan Bahu Jalan Di Wajo, Nyaris Hasilnya Amburadul," Pembela News. Accessed: Nov. 26, 2024. [Online]. Available: https://pembelanews.com/2023/09/pekerjaan-talud-dan-bahu-jalan-di-wajo-nyaris-hasilnya-amburadul/

[51] B. Setiyawan, "Ketua LBH Lambar Soroti Pengerjaan Proyek Bahu Jalan Nasional," Media Lampung. Accessed: Nov. 26, 2024. [Online]. Available: https://medialampung.disway.id/read/59868/ketua-lbh-lambar-soroti-pengerjaan-proyek-bahu-jalan-nasional

[52] M. Ikhsan, "Warga Cianjur Keluhkan Proyek Betonisasi Bahu Jalan Raya Bandung." Accessed: Nov. 26, 2024. [Online]. Available: https://www.ayobandung.com/umum/pr-791270654/warga-cianjur-keluhkan-proyek-betonisasi-bahu-jalan-raya-bandung