Sustainability & Environment

Development and Evaluation of Pavement Materials utilizing Renewable Resources deriving from Plants

Toshiaki Hirato[1], Hui Qu[1], Fumihiro Kato[2], Shigeki Takahashi[3]
[1]TOA ROAD CORPORATION, [2]East Nippon Expressway Company limited, [3]Nippon Expressway Research Institute Company Limited

Abstract

Long-life pavement is in high demand as a part of reducing expenses for public works and maintenance costs. In Japan, Asphalt concrete mixture is widely used for over 90% of road pavements and expressways because it is easy to construct and repair. Meanwhile, cement concrete pavement, which is more durable than asphalt pavement, is limited to some constructions due to issues such as recyclability and constraint on regulation time at repair. In recent years, despite the fact that sustainable materials are being promoted in various industries, asphalt, which is derived from petroleum, is used as the main material for road pavements. In order to solve the above problems, the authors have studied the materials used for pavement materials to develop alternative materials for asphalt mixtures. As a result, the authors have reached the development of sustainable materials from plants. The developed material can be easily constructed like asphalt pavement, and its strength does not depend on temperature like an asphalt mixture and it has strength close to that of cement concrete in the service temperature range. Since the developed material shows thermos-plasticity, unlike cement concrete, it can be recycled like asphalt pavements. In addition, plants as raw materials are widely available and can be easily procured. Although some plant-derived materials may be less resistant to water, but the developed material has a markedly higher resistance to water and oil than asphalt and binds very strongly to the aggregate. In this paper, the selecting process of the substance and the evaluating result of the characteristics of the developed materials by the various laboratory tests are shown. Furthermore, an inspection result of the performance of the developed mixtures obtained from trial and actual construction is shown.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

In Japan, road pavements are surfaced in either asphalt concrete or cement concrete and 95 % of the pavement is asphalt. Asphalt is highly versatile and has extended crack resistance and appropriate weather and water resistance properties, which are indispensable for pavement materials. Moreover, it is easy to repair and has excellent recycling performance. In contrast, although cement concrete paving has high durability and is more cost effective, the need for initial curing and maintenance limits its use.

In Japan, the rate of recycling of asphalt paving is about 99 % but repeated reuse makes it hard and less viscous. Therefore, an improvement in the recycling method is required recently. In the context of the societal demand for the movement away from petroleum, other industries have already attempted to switch to various alternative sustainable materials, which are needed in the pavement industry as well because bitumen is an exhaustible resource. From this perspective, authors examined the practical application of biomass paving based on plant-derived materials instead of fossil fuels. Hence, a biomass mixture was developed in this study, which is processable just like asphalt, and has an equivalent loading capacity (flexural strength).

The biomass mixture contains a plant-based binder (Bio binder) with a biomass rate of 80% or higher. The remaining components are composed of chemical substances. Plant-based binder strongly bonds with aggregates, resulting in the formation of a mixture with extremely high rigidity. Using biomass mixture on heavy-traffic roads and intersections extends the period for which repairs are not needed, which reduced the road constructions for repairs. Moreover, such mixture is suitable for use in areas with large-sized vehicles, such as parking areas, as well as for pavements on which containers and freight cargoes are parked. The binder in biomass mixtures is thermoplastic; thus, it is advantageous for recycling, similar to asphalt pavement.

The developed Bio binder has lower stress relaxation properties than asphalt and releases stress from the change in volume with temperature change, thereby necessitating construction joints after every 5–10 m, similar to cement concrete pavement. Based on previous studies, a hybrid binder containing 20 % plant-based resin and 80 % bitumen was developed. This asphalt using the hybrid binder does not require construction joints, enabling it to be processed in the same way as asphalt, and has high resistance to plastic deformation. It has been more than 10 years since its development, and its practicality has been verified in heavy-traffic roads and roads in harbor facilities [1]. Moreover, as asphalt for reinforcing steel decks, high rigidity asphalt pavement in which the blend ratio of plant-based resin is increased to 45 % is studied for practical use [2].

In this study, the selection method for using plant-based resin in paving materials, the properties of the biomass mixture, and the results of using it for a service area along a highway are explained. The use of hybrid binders with asphalt is also covered.

2. MATERIAL SELECTION FLOW

Asphalt has indispensable characteristics as a paving material, such as no cracking occurs even if the support base is deformed, or constructed pavement over a long distance. Such characteristics are considered to be due to the bitumen exhibiting viscoelasticity.

Figure 1 shows the fracture mode of the pavement and materials design strategy. Based on this diagram, a few plant-based resins suitable for use in paving were selected, and a Bio binder suitable for use in paving materials was developed through trial and error.

Bio binder, though plant-based, bond strongly with aggregates and shows high weather resistance. Compared with bitumen, Bio binder shows extremely high resistance to water and oil. The deformation temperature of Bio binder is designed to be around 80 °C, enabling processing at the same processing temperature as bitumen, and it has a high fluidity resistance at 80 °C or lower.

Table 1 shows a comparison of the material properties between Bio binder which does not involve any bitumen and bitumen, and **Photo 1** shows the overall appearance of the biomass mixture.

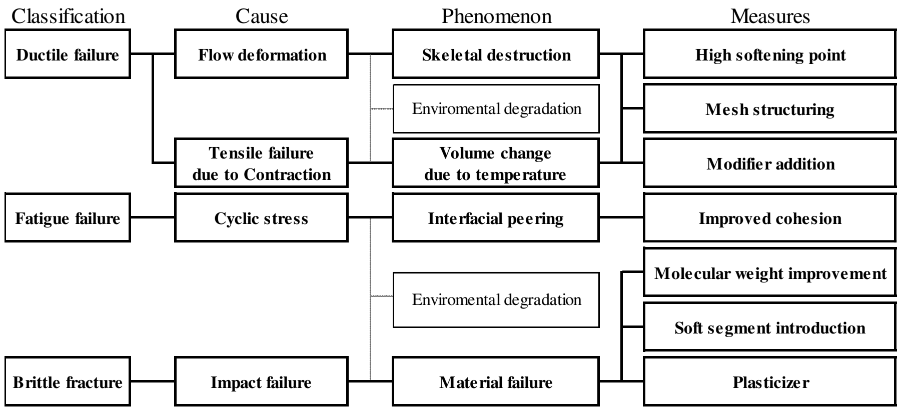


Figure 1. Material Design Method corresponding to Failure Mode of Pavement

Table 1. Comparison of material characteristics of Bio binder and Bitumen

Items	Bitumen	Bio Binder
Visco-elasticity	○	×
Strength	○	◎
Water resistance	○	○
Oil resistance	△	◎
Construction Joint	Not required	5～10 m

Phot 1. Appearance of Biomass mixture

3. DESCRIPTION FOR BIO BINDER

3.1. Physical properties of Bio binder

Bio binder has considerably different resin-like properties from asphalt. **Table 2** shows the standards of the two representative binders often used in Japan, so called “Polymer Modified Bitumen Type 2” (Type 2) and “Polymer Modified Bitumen Type H” (Type H) and the characteristics of Bio binder.

Type 2 is suitable for use in continuous grading, such as in dense-graded asphalt, and Type H is used in porous asphalt. The characteristics of Bio binder are equivalent to those of Type H, except for its penetration and ductility.

When a thin film of general plant resin is heated, its low molecular mass evaporates, and it hardens due to heat deterioration, causing a high mass change rate upon thin film heating and a low penetration residual factor. The developed Bio binder has equivalent thermal stability to bitumen, showing little changes in its characteristics, even when mixed with aggregates.

Moreover, Bio binder is flexible even at the test temperature of −20 °C and thus has a large bending work and low stiffness. Therefore, the developed binder is resistant to brittle fracture even at low temperatures, although it has low stretch characteristics.

In terms of high-temperature properties, the 180 °C viscosity of the Bio binder is close to Type 2, so the mixing and compaction temperature of the mixture is almost the same as Type 2.

Table 2. Comparison of properties of Bio binder and Polymer modified bitumen

Items		Bio Binder	Type2	Type H
Penetration (25 °C)	1/10 mm	11	Min 40	Min 40
Softening Point (R&B)	°C	84.0	Min 56	Min 80
Ductility (15 °C)	cm	1.0	Min 30	-
Thin film heating mass change rate	%	0.34	Max 0.6	Max 0.6
Thin film heating penetration change rate	%	84.6	Min 65	Min 65
Density (15°C)	g/cm^3	0.96	Report	Report
Flash Point	°C	294	Min 260	Min 260
Work load* (-20°C)	MPa	790	-	Min 100
Stiffness* (-20 °C)	MPa	314	-	Max 450
Viscosity（180 °C)	mPa･s	270	200	500

*A063 Bending test for Polymer Modified Bitumen

3.2. Stress relaxation performance of Bio binder

A thermal stress restrained specimen test (TSRST) was conducted to evaluate the stress relaxation characteristics of Bio binder. **Table 3** shows the test conditions and **Figure 2** shows the results of the temperature stress tests. The mixture used is the same as that mentioned in next Chapter 4.

Bio binder shows little stress relaxation alone; thus, stress occurs because of contraction as the temperature decreases. Therefore, a mixture with Bio binder requires construction joints, similar to that in cement concrete pavement, to release stress from the change in volume with temperature change.

The addition of fiber reinforcement and modifiers or bitumen to Bio binder can improve its stress relaxation properties, which, like asphalt pavements, can provide long pavements that do not require joints. Chapter 6 details the use of pavement mixtures containing asphalt.

Table 3. Test Condition

Items	Conditions
Test method	Thermal Stress Restrained Specimen Test (EN 12697-46)
Mixture type	Dense graded Asphalt (13)
Loading method	Start at 20 °C*
Specimen dimension	50 mm × 50 mm × 250 mm
Cooling rate	10 °C/h

* Since the temperature stress of the Bio binder generated at a high temperature, the TSRST test started from 30 °C only for the bio binder.

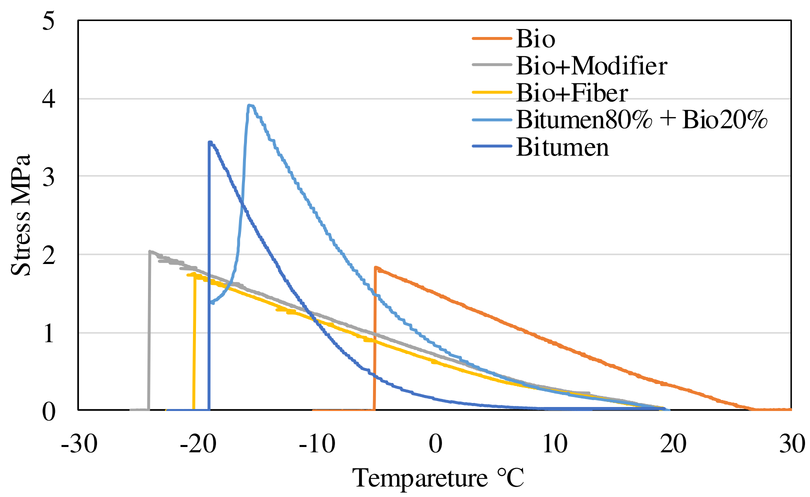


Figure 2. Result of TSRST

4. MIXTURE PERFORMANCE OF BIOMASS MIXTURE

4.1. Mixture design

Similar to the asphalt, the mixture design of Bio binder can be determined by Marshall test. **Table 4** shows the aggregate mixture used in the design and **Table 5** shows the Marshall properties. Herein, in the tests to evaluate the mixture characteristics, this specimen was used to conduct each test.

Table 4. Gradation

Sieves (mm)	26.5	19.0	13.2	4.75	2.36	0.6	0.3	0.15	0.075
Gradation	100.0	100.0	98.7	65.6	44.2	26.5	16.1	8.9	6.0
Passing of sieve %	100.0	100.0	95.0～100.0	55.0～70.0	35.0～50.0	18.0～30.0	10.0～21.0	6.0～16.0	4.0～8.0

Table 5. Marshall properties

Items	Binder content %	Density g/cm^3	Theoretical density g/cm^3	Air void %	Saturation %	Marshall stability kN	Flow 1/100cm
Dense-graded Asphalt	5.1	2.373	2.461	3.6	77.3	18.8	34
	-	-	-	3 - 6	70 - 85	Min 4.9	20-40

4.2. Evaluation of Flow Resistance

Biomass mixture has high resistance to plastic deformation, and in regular wheel tracking (WT) tests, its dynamic stability reaches its maximum. Authors conducted a wheel tracking tests under strict conditions (hereinafter refer to as low speed and heavy load WT test) to evaluate the resistance of the biomass mixture to plastic deformation. **Table 6** shows the test conditions and **Figure 3** shows the results. Dynamic stability is the number of passes required to deform a material by 1 mm, which is calculated based on the deformation 45 min after testing and the deformation after making 630 passes after that. The dynamic stability formulas are shown in Equations (1) and (2).

As the result of the low speed and heavy load WT tests, the dynamic stability of the biomass mixture was found to be as high as 7000 passes/mm, which shows over 2.5 times that of the semi-flexible mixture.

Table 6. Wheel Tracking Test condition

Items		Condition	
Test Method		B003 Wheel Tracking Test [3]	
		Conventional Condition	Low speed & Heavy load
Load	MPa	0.63	0.90
Velocity	Passes/min.	42	10.5
Test Temperature	°C	60	
Tire type		Rubber Tire	

$$\text{Conventional dynamic stability} = \frac{42\times15}{d_{60}-d_{45}} \quad \cdot\cdot\cdot (1)$$

$$\text{Low speed \& Heavy load dynamic stability} = \frac{10.5\times60}{d_{105}-d_{45}} \quad \cdot\cdot\cdot (2)$$

Where,

Dynamic Stability (passes/mm)

d_{105}(mm): Amount of deformation at 105 minutes

d_{60}(mm): Amount of deformation at 60 minutes

d_{45}(mm): Amount of deformation at 45 minutes

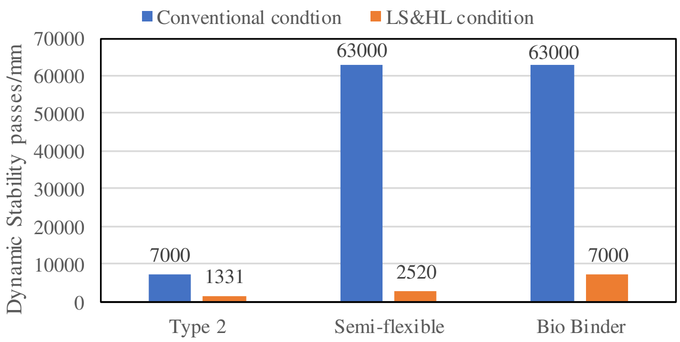


Figure 3. Test result of Flow resistance

4.3. Evaluation of Complex Modulus

The complex modulus was measured to understand the rigidity of the biomass mixture at operational temperatures. Among the several methods that can be used to evaluate complex modulus of asphalt, the repeated 4-point bending test was selected. The complex modulus was calculated on the interval during which the stress stabilizes after repeated loading. **Table 7** shows the test conditions and **Figure 4** shows the relation between the test temperature and complex modulus. Comparison of dense graded asphalt (13) (annotated as Type 2 in the figure) using Type 2 and fiber-reinforced cement concrete (SFRC) can be seen in the figure.

Compared to SFRC, the complex modulus of biomass mixture decreases as the temperature increases. However, compared to asphalt, the complex modulus of biomass mixture at 60 °C and that of the asphalt at 20 °C are almost equivalent.

Table 7. Test condition for Complex modulus

Items	Conditions
Test method	B018T Flexural Fatigue Test for Asphalt [3]
Loading method	Sin wave, 5 Hz
Strain	400 μ
Specimen dimension	400 mm × 40 mm × 40 mm
Temperature	5 to 60 °C

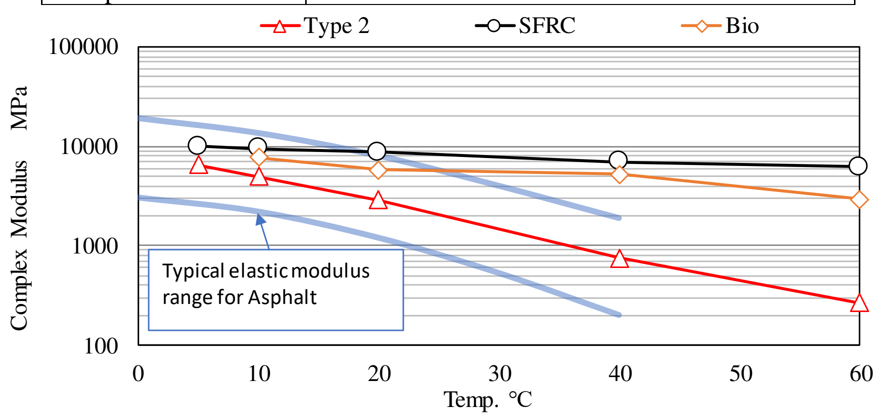


Figure 4. Relationship between temperature and Complex modulus

4.4. Evaluation of Bending Characteristics

Bending testing at a different temperature was conducted to evaluate the flexibility of the biomass mixture.

Table 8 shows the test conditions, **Figure 5** shows the relation between the test temperature and flexural strength, and **Figure 6** shows the relation between the temperature and flexural breaking strain. As a comparison, asphalt using Type 2 and a specimen cut from a cement concrete plate was used.

The flexural testing revealed that the flexural strength of biomass mixture is high in the range from −10 to 60 °C. Biomass mixture shows similar temperature dependence to the asphalt, with decreasing flexural strength above 20 °C, and its flexural strength is lower than that of cement concrete above 40 °C. However, like the complex modulus, the flexural strength of biomass mixture at 60 °C is equivalent to that of the asphalt using Type 2 at 20 °C.

The strain of the asphalt using Type 2 increased as the temperature increased, but biomass mixture did not show any changes in strain due to a change in temperature, similar to cement concrete.

Table 8. Evaluation Condition of Bending Characteristics

Items	Conditions
Test method	B005 Bending Test for Asphalt, Central load, 2-point Support [3]
Loading speed	50 mm/min.
Test Temperature	-10 to 60 °C
Specimen dimension	300 mm × 100 mm × 50 mm
Span length	200 mm

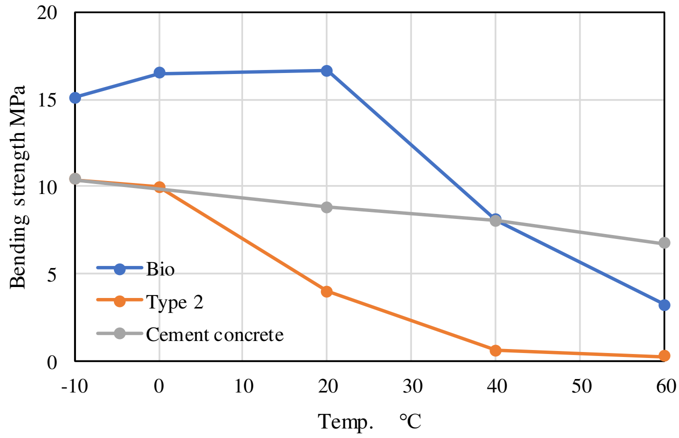


Figure 5. Relationship between Temperature and Bending Strength

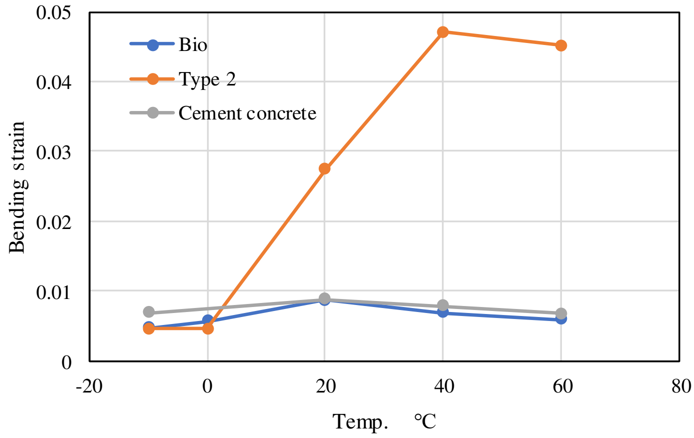


Figure 6. Relationship between Temperature and Bending Strain

4.5. Evaluation of Water Resistance

A water immersed wheel tracking test was conducted to evaluate the water resistance of biomass mixture. The water immersion wheel tracking test is a test in which the wheel is traveled for 6 hours on the specimen immersed warm water at 60 °C. After that, breaking the specimen into four parts manually. The stripping area ratio was calculated by dividing the area of exposed aggregate by the total cross-sectional area. **Table 9** shows the test conditions, **Photo 2** shows the test conditions, and **Photo 3** shows the stripping conditions after this test.

In the left-hand side of Photo 3, the aggregate is exposed, this asphalt indicates low water resistance. Biomass mixture shows high adhesion even at 60 °C, and manual partitioning into four parts was not possible. Some aggregates broke when a compressor was used to forcefully partition it into two parts. There was no observation of stripped binder from the aggregate in the biomass mixture after the water immersed WT test.

Table 9. Test condition for water resistance

Items	Conditions
Test Method	B004 Immersed Wheel Tracking Test [3]
Test temperature	60 °C
Test time	6 h
Tracking velocity	42 passes/min.
Traverse velocity	10 cm/min.
Specimen dimension	300 mm × 300 mm × 50 mm
Valuation method	Stripping area ratio

Phot 2. Immersed Wheel Tracking Test

Asphalt with Low water resistance

Biomass mixture

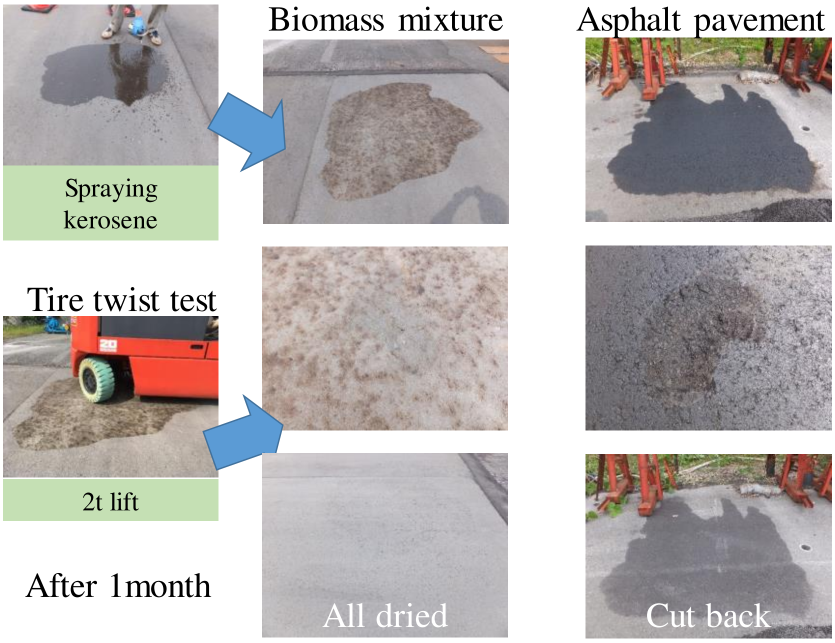
Phot 3. The result of Immersed wheel tracking test

4.6. Evaluation of Oil Resistance

2 L of kerosene was sprayed onto biomass pavement and conventional asphalt pavement and two round trips of tire twisting by a fork lift were conducted immediately afterwards to evaluate the oil resistance. **Photo 4** shows the test conditions.

The conventional asphalt was dissolved by kerosene, and the aggregate was peeled off and spread when the twist shear load was applied by the fork lift; however, biomass pavement was not dissolved by kerosene, was caused no damage.

A month after testing, the cut back by kerosene continued on the conventional asphalt pavement, and the asphalt pavement had weakened. Conversely, the kerosene had evaporated from biomass mixture, and the surface had not been weakened.



Phot 4. Evaluation for oil resistance

5. TRIAL CONSTRUCTION IN SERVICE AREA OF EXPRESSWAY

5.1. Overview of Construction

A plant-based Bio binder was implemented in parking lots for large vehicles on an expressway to evaluate its long-term durability.

The existing pavement was semi-flexible (open graded asphalt filled by cement mortar), with many cracks reaching its base. Evaluated on bearing capacity tests by FWD (Falling Weight Deflectometer), it was determined that bearing capacity was sufficient since the average deflection of the existing pavement was within 0.35 mm. Therefor repair method adopted a cutting overlay of 5 cm one layer.

Table 10 shows the construction summary, and **Figure 7** shows a view of the upper surface of the biomass pavement.

Table 10. Construction summary

Items	Contents
Date	2019.3.1
Place	Expressway Service area Heavy vehicle
Mixture type	Biomass mixture
Gradation	Dense-graded
Maximum particle size	13 mm
Content of Binder	5.2 wt%
Dimension	11.48 m×2.75 m×5cm×2 Lane

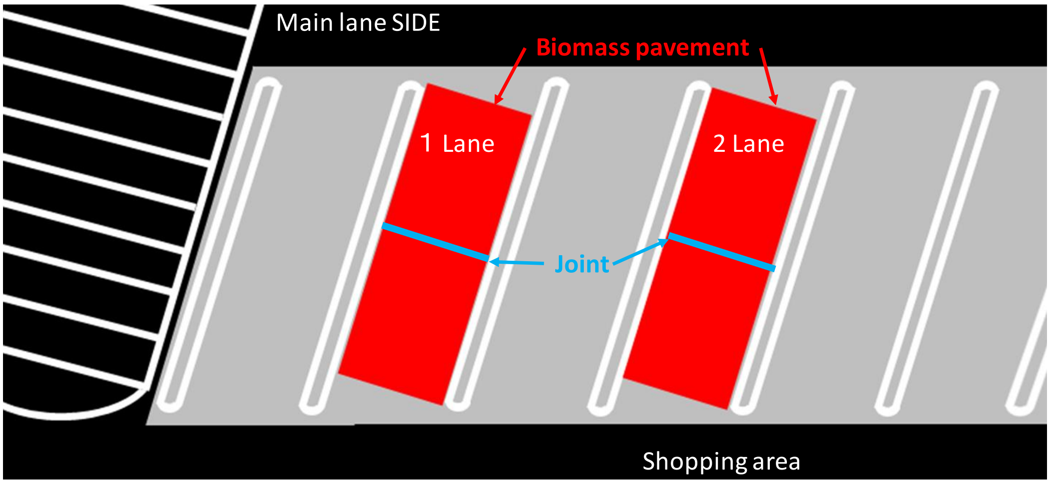


Figure 7. View of upper surface

5.2. Construction method

The construction was conducted on two of the large vehicle parking lots. Due to the possibility of cracks occurring in sharp areas, the repair shape was designed to be rectangular.

The difference in the contraction/expansion behavior of the biomass mixture and the asphalt pavement at the base might lead to cracks. Since the construction length exceeded 10-m, a cutting joint was installed in the center of the construction direction and at a right angle.

A fabric sheet was placed below the cutting joint to control reflective crack. A molding joint material was also placed at the joint between the existing pavement and construction end. The construction machines were used similar to those used in the construction of conventional asphalt.

After the temperature of the pavement surface falls below 50 °C, a 2-mm wide and 40-mm deep cut joint was installed at the center of the length direction of the construction. **Figure 8** shows each cross section of the joint. A joint material was filled into the cutting joint a day after construction.

Photo 5 shows an external view of the completed pavement.

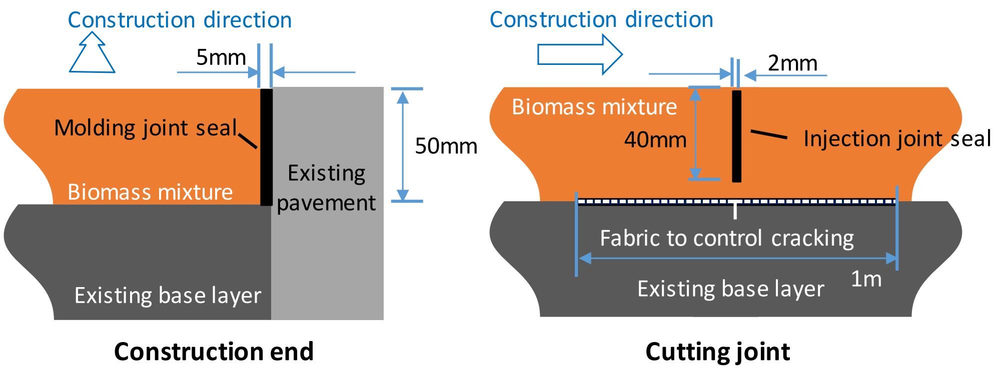
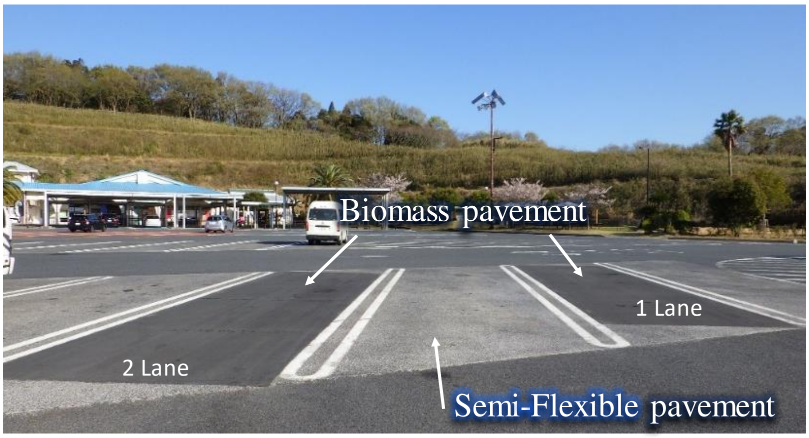


Figure 8. Joint Construction Method

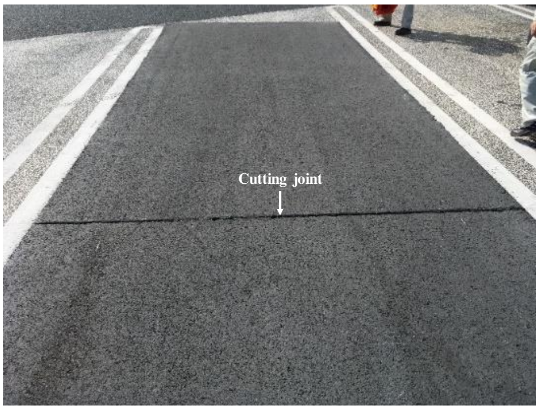


Phot 5. Appearance after Construction

5.3. Follow-up survey

Rutting and cracking on the biomass pavement, or contraction/expansion conditions of the pavement join were assessed after four months post construction, there was no major damage observed other than an expansion of the joint material. This phenomenon implies the necessity for a joint material, which has high adhesiveness as well as the ability to adapt to any changes in the volume.

Photo 6 shows a view of the operation and surface conditions of the biomass mixture.



Phot 6. Biomass pavement for in-service

6. Other Use of Renewable Resources

In the following projects, the asphalt, which is a combination of the developed plant-based resin and polymer-modified bitumen, is discussed.

6.1. High Stability Asphalt with hybrid binder

The plant-based resin and polymer-modified bitumen were mixed in a 1:4 ratio and developed as a high-stability asphalt, which can be used just like conventional asphalt. It has equivalent fluidity resistance as a semi-flexible pavement or epoxy asphalt pavement. The longest period for such a material operation is ten years, which shows that the developed plant-based binder does not degrade in the environment or undergo biodegradation.

High-stability asphalt, compared to asphalt, has high resistance to fluid deformation. It can be used as a material for paving large vehicle parking spaces, bus stops, distribution centers, and container yards where there are heavy loads. **Photo 7** shows the situation of each application place.

Phot 7. Application place

6.2. Steel Deck Reinforcement Method using High Rigid Asphalt Pavement

For asphalt pavement on steel plate deck in Japan, Guss-asphalt is commonly used for the base layer and dense graded asphalt is used in the surface layer. In hot seasons such as summer, the Guss-asphalt becomes soft and its load bearing properties decrease, leading to large strains on the steel plate deck. In fact, some of the steel decks are facing to have fatigue crack at the corner plate and ribs under heavy traffic loads.

To avoid such serious damage on the steel decks, steel fiber reinforcement concrete (SFRC) is attempted to introduce as the base layer of a pavement to reduce the strain occurring on the steel deck [4]. However, construction of SFRC involves pouring and curing of cement concrete, which requires an extended period of traffic restrictions (all-day continuous restrictions) [5]. Therefore, it is considered difficult to apply SFRC on heavy traffic roads.

Therefore, steel deck reinforcement method using high rigidity asphalt is making a study on [2][6]. This steel plate deck reinforcement method is characterized in that the asphalt with high rigidity is firmly adhered to the steel plate deck with a special adhesive to achieve integration. High rigidity asphalt contains 45 % of the plant-based resin based on the amount of bitumen. High rigidity asphalt does not need any cutting joint just like conventional asphalt as well.

Figure 9 shows the composition of the highly rigid asphalt pavement. The surface mixture will be selected depending on the required traveling performance, but the highly rigid asphalt can also be used for the surface layer. **Photo 8** shows an overall view of the highly rigid asphalt constructed as trial section in an actual bridge.

Based on the road temperature and traffic data, the cumulative damage was used to examine the reinforcement effects on the steel plate deck. As a result of analysis, the resistance of through crack on the deck plate in the highly rigid asphalt pavement has less effect than the SFRC, however its lifetime was estimated to be 3.1 times longer than the conventional method (Guss-asphalt) [2].

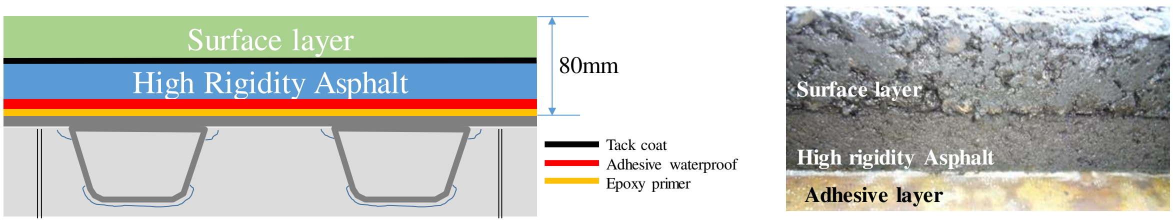


Figure 9. Composition of High Rigid Asphalt Pavement

Phot 8. Appearance after Construction

7. CONCLUSION

The following findings were observed in this study:

- The developed Bio binder has high adhesion to aggregate, high fluidity resistance and water resistance, and has an equivalent loading capacity (flexural strength) and oil resistance compared to that of cement concrete. Furthermore, it can be implemented by conventional machines and construction systems used for asphalt pavement.
- The binder has thermoplastic and can be repaired and recycled similar to asphalt pavement.
- After testing in parking lots on expressways, it was confirmed that construction by machines was well conducted, but there is a requirement for a better filling material to cutting joint.
- The developed binder has a low stress relaxation performance and thus requires cutting joints every 5-m to 10-m when used alone, similar to cement concrete. However, by blending it with asphalt, designing a highly durable material that does not require cutting joints is possible, as is the case in asphalt pavements.

REFERENCES

[1] T. HIRATO, M. MURAYAMA, et al, DEVELOPMENT OF HIGH STABILITY HOT MIX ASPHALT CONCRETE WITH HYBRID BINDER, ISAP2012 International Symposium, 2012, 12-115
[2] R. SASAKI, T. HIRATO, et al, Development of Steel Deck Reinforcement Method using High Rigid Asphalt Pavement, DOROKENSETSU, No.775, 2019, pp. 87-94 (Japanese)
[3] Japan Road Association：Pavement investigation and examination method handbook, 2019.3. (Japanese)
[4] C. MIKI, K. SUZUKI, et al: Preventive Works for Fatigue Damage in Orthotropic Steel Bridge Deck by SFRC Pavement and Long-Term Monitoring of The Composite Action, Journal of JSCE A1, Vol.62, No.4, 2005, pp.950-963(Japanese)
[5] East Nippon Expressway Co., Ltd, Kanto Office: Press release, https://www.e-nexco.co.jp/en/pressroom/press_release/kanto/h30/0418/
[6] Y. WADA. S. ONO, et al, Research on Steel Deck Reinforcement by New Material， 9th Proceeding of Symposium on Decks of Highway Bridges, 2016, pp.177-180(Japanese)