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Natural/plant-based binder, Asphalt alternative, Recycled hot mix asphalt, Reduction of CO_2 emissions, Decarbonized society.

ABSTRACT:

Efforts to reduce carbon dioxide in the pavement field are also very important issue to realize decarbonate society. More than 40 million metric tons of hot mix asphalt (HMA) is annually produced in Japan. And about 75% of them are recycled HMA (RHMA).

It should be one of the measures to reduce its carbon footprint of HMA if using natural/plant-based binder (NPB), i.e., asphalt alternative. Some NPBs are commercially available. The authors produced RHMA using one of them. And that produced RHMA was evaluated through some laboratory tests, test pavement and so on.

Used NPB can be adjust penetration by changing two components from the laboratory tests. And this has similar rheological property as petroleum asphalt. When using this NPB with penetration of 90, produced RHMA shows as similar performance as a general RHMA and shows about twice as rutting resistant performance. This RHMA can be produced at a general asphalt plant and paved with general sets of paving machines. Paved surface is good condition.

On estimating the carbon footprint, reduction rate of materials is 38%, that of production is 2% and total reduction rate including hauling is 8% comparing to a general RHMA.

One of the biggest challenges is cost, which is estimated about 1.7 times of a general RHMA. This paper shows that such a NPB can be an alternative binder. The authors hope that asphalt alternative can be widely used resulting in lower costs and further this RHMA contributes decarbonated society.

Recycled Hot Mix Asphalt using Natural/Plant-Based Binder Towards Decarbonated Society

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1 INTRODUCTION

It is one of the important issues to address reducing greenhouse gas including carbon dioxide (CO_2). Therefore, the carbon neutral policy is a great task to be achieved for all industries all over the world. The pavement industry is no exception, and lots of studies are continuously conducted for building a sustainable society with harmonizing infrastructure development and environmental protection. These are low-carbon technologies and effective usage of CO_2 for materials of pavement, asphalt plant facilities, paving technologies and so on for more details.

Reducing CO_2 equivalent emission of hot mix asphalt (HMA) is one of the important issues as well as in Japan. Because HMA is the most major paving material in Japan. Figure 1 shows the asphalt pavement related CO_2 equivalent emissions cited from data by Japan Road Association (Japan Road Association 2023a) and a paper (Sakamoto 2023). This figure indicates that 89% of all CO_2 emissions are related to the production of HMA including raw materials like aggregates and binders. The remaining 11% occurs during deliveries of HMA to construction sites and constructions. About the production of HMA, productions and deliveries of raw materials are 34% and the production of HMA itself is 66%. Among these, CO_2 emissions from a petroleum bitumen is high because it is made by petroleum and it is required to be heated at every process of mining, refining, transporting, and using it. Then replacing a petroleum binder with alternate binder is one of the effective ways to realizing decarbonized society.

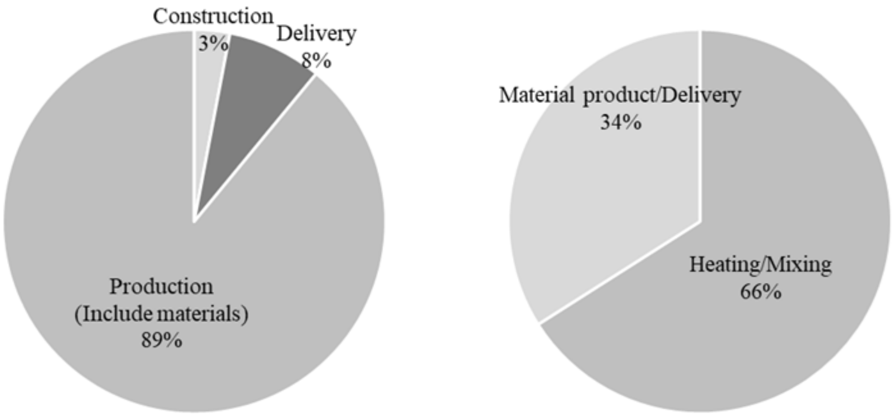

Figure 1 A estimated example of CO_2 equivalent emissions of asphalt concrete pavements (Japan Road Association 2023a, Sakamoto 2023)

The authors are interested in the natural and/or plant base binders and studies the applicability in Japan of one of the commercially available natural and/or plant base binders as an alternate binder. This paper describes some laboratory tests results including binder properties and mixture properties. Test mix results at an asphalt plant and test pavement results using general paving machines are also described in this paper. Finally, an example of reduction of CO_2 equivalent emission is estimated.

2 OBJECTIVES OF THIS STUDY

Objectives of this study are to evaluate the applicability and effectiveness as an alternate binder of the selected natural and/or plant base binder in this study (hereinafter NPB) from the viewpoints of binder properties, mixture properties, manufacturability, workability, surface characteristics and so on from the results of laboratory tests and field tests and estimated reduction of CO_2 equivalent emissions.

3 MATERIALS INFORMATION

3.1 The selected NPB

Composition of a petroleum binder generally contains asphaltene and maltene (Iijima 1978). The NPB has similar composition to a petroleum binder and former is made from cashew nut shells and later is made from natural originated materials. Then some CO_2 emissions are offset because it is based on plants and natural materials. Asphaltene component of the NPB is liquid state and maltene component is powder at a ambient temperature as shown in Photo 1 and Photo 2, respectively. This means that this NPB is not required to be heated during delivery to and storing at an asphalt plant. This is another important factor of reducing CO_2 equivalent emissions. This NPB is thrown into a mixer and melted by the heated aggregates and then acts as a binder.

Photo 1 Asphaltene component of the NPB

Photo 2 Maltene component of the NPB

3.2 Recycled Hot Mix Asphalt

About 40 million metric tons of HMA is annually produced in Japan. And about 75% of them is recycled hot mix asphalt (RHMA) with an extent of reclaimed asphalt pavement (RAP) as an aggregate (Japan Asphalt Mixture Association 2022). RHMA is used in this study because RHMA is the major paving material in Japan. A general dense graded mixture is used, and this has 50% of RAP and 50% of virgin aggregates. Table 1 shows the mixture proportions and Figure 2 shows the gradation curve of this mixture. Virgin binder, which is the NPB in this study, content is 3.1%. RHMA with a petroleum binder is also produced as a control mixture. Rejuvenator is not used in this study. Instead, straight-run binder of penetration of 80/100 (hereinafter PB80/100) is used in this case. Target temperature of mixing of PB80/100 is 155-160ºC and target temperature of compaction is 143-148ºC.

For the reference, an amount of RAP for the use of RHMA depends on the amount of milled and/or removed asphalt pavement through processes of rehabilitation works and length of road networks and so on in Japan. Then cities or prefectures sometimes specify the allowable maximum amount of RAP and asphalt plants follow the area-by-area limitations. The asphalt plant, which is used in this study, is located at the area where RAP contents are limited to 50%, this is why mixture with 50% of RAP is used.

Table 1 Mixture proportions

Aggregates	Coarse aggregates		Fine aggregates		Mineral filler	RAP	Total
	Hard sandstone	Hard sandstone	Screenings	Natural sand			
Sieve (mm)	12.5 - 4.75	4.75 – 2.36	2.36 - 0	2.36 - 0	0.3 - 0	12.5 - 0	
Proportion (%)	19.0	15.0	10.0	4.0	2.0	50.0	100.0

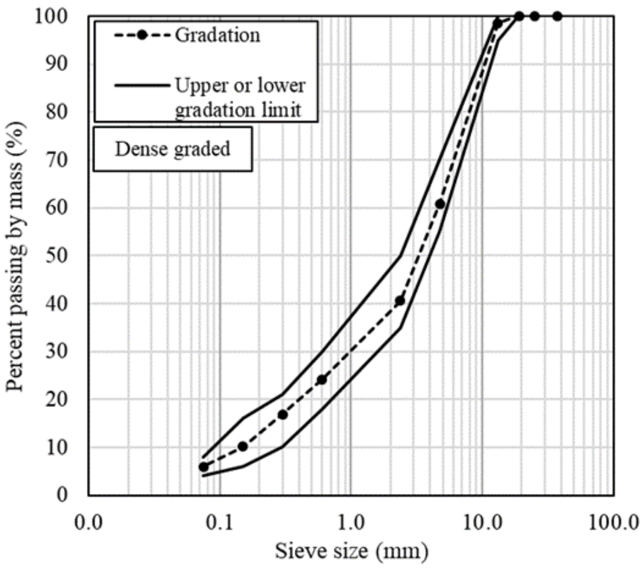

Figure 2 Gradation curve of the RHMA in this study

4 TEST METHODS

4.1 Binder properties

4.1.1 Consistency

Penetration and softening point are mainly used to identify the binder properties in Japan. Penetration and softening point of the NPB and PB80/100 are evaluated using ASTM D5 and ASTM D36, respectively.

4.1.2 Viscoelasticity / Rheological property

Viscoelasticity is one of the important parameters on not only evaluating binder properties but also understanding and evaluating mixture properties. Viscoelasticity of the NPB is measured using the dynamic shear rheometer (DSR) as AASHTO T315 under the test conditions shown in Table 2, while this test method is for asphalt binders.

Table 2 Test conditions of DSR

Test temperatures range	5 to 60ºC
Angular frequency	10rad/s
Strain level	0.05%
Diameter of specimen	25mm
Thickness of specimen	1mm

4.2 Mixture properties

Mixture properties of RHAM with the NPB is evaluated as follows.

4.2.1 Mix design

Marshall mix design method is generally used for HMA and RHMA in Japan. Mix design is conducted as ASTM D1559.

4.2.2 Water sensitivity

Water sensitivity of RHMA with the NPB is evaluated using the Hamburg Wheel Tracking (HWT) test as shown in AASHTO T324 under the water temperature is 60ºC. This test temperature is also used at other tests considering the high-temperature and humidity during summer in Japan. Maximum passes of wheel load are 20,000, while loading is stopped and data is retrieved when it is impossible to continue the test. Stripping inflection point (*SIP*) is obtained when an intersection of the first steady-state of the deformation curve and the second steady-state of the curve appears.

4.2.3 Rutting resistance

Rutting resistance of HMA and/or RHMA is generally evaluated using a wheel tracking test (WTT) result specified as B003 in the handbook in Japan (Japan Road Association 2019b). For the reference, specimen size is 300mm square and thickness is 50mm. This specimen is compacted using a roller compactor to meet a degree of compaction, which is percent of a compacted density by a design density of the mixture, is 100%±1%. This compacted specimen is cured in a constant temperature chamber at 60^{o}C for 5 through 24 hours. A solid tire, which is 200mm in diameter and 50mm in width, with 686N±10N of load is moved on the cured specimen at a loading speed of 42 passes/minute. Deformations are measured at the center of the specimen with the accuracy of 1/100mm during this loading process. Loading is stopped after more than 60 minutes. And dynamic stability *(DS*) is calculated using the deformations at 45 minutes and 60 minutes as shown in equation 1. *DS* indicates the number of passes until the 1mm of deformation occurs after the deformation shows a steady state. Figure 3 shows an example of a deformation curve of the WTT.

$$DS = 42\frac{t_2 - t_1}{d_2 - d_1} \times c = \frac{630}{d_2 - d_1} \tag{1}$$

where DS : dynamic stability (pass/mm)

t_1 : elapsed time at 45 minutes

t_2 : elapsed time at 60 minutes

d_1 : deformation (mm) at t_1

d_2 : deformation (mm) at t_2

c : correction factor (=1 in this study)

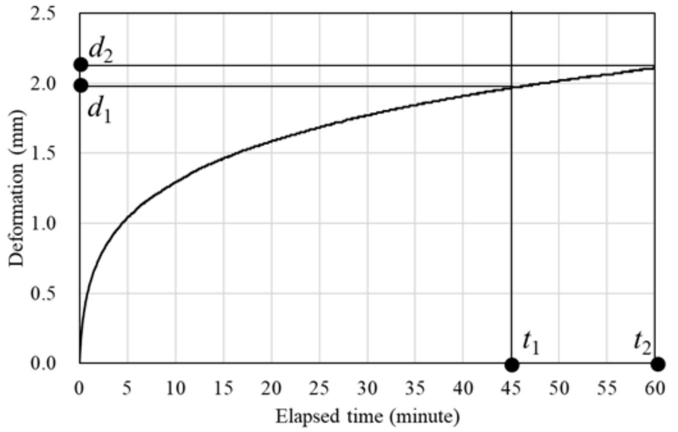

Figure 3 An example of a deformation curve of the WTT

4.2.4 Fatigue resistance

Fatigue resistance of RHMA is evaluated by the four-point bending (4PB) test as shown in AASHTO T321 under the conditions of strain level is 500μ, frequency is 5Hz and test temperature is 5^{o}C. However, size of specimen is 40mm*40mm*400mm and cycle to failure is obtained at the intersection point of the first steady-state of the curve and the second steady-state of the curve according to the Japanese test condition.

4.3 Test mix, test construction and field tests

Test mix is produced at our own asphalt plant in Ibaraki, Japan. Aggregates temperature are set at 174^{o}C and temperature of PB80/100 is set at 148^{o}C, then mixing temperature should be around 155-160^{o}C. The NPB is no need to heat itself, so temperature of RHMA with the NPB will a little lower than that with PB80/100. Produced RHMA with the NPB and with PB80/100 are paved using general paving machines, which are an asphalt paver, a three-wheel steel roller for a breakdown compaction, a pneumatic tire roller for an intermediate compaction and a two-axle tandem roller for a finish compaction. Some specimens are prepared for the laboratory tests using actual produced RHMA. All paving processes are carefully observed by the authors. Some field tests are conducted on the surface including ASTM E965 for texture and ASTM E1911 for surface friction. And International Friction Index (*IFI*) is calculated (Abe et.al. 1999).

4.4 Recommended compaction temperature of the NPB

Recommended mixing and compaction temperatures of a petroleum binder as well as PB80/100 is based on the viscosity in Japan. Same temperatures as PB80/100 are adopted for the NPB in this study. The authors notice the possibility of reducing mixing and compaction temperatures from the test construction. Therefor relationship between the mixture temperature and compacted densities is evaluated using a gyratory compactor.

5 TEST RESULTS AND CONSIDERATIONS

5.1 Binder properties

Evaluated binder properties are as follows.

5.1.1 Consistency

Penetration values of the NPB when varying the blending ratio of the two components, which are asphaltene and maltene, are shown in Figure 4. From this result, it is possible to adjust penetration of the NPB. PB80/100 is the control binder in this study, then the amount of asphaltene is decided to 51.5% from the regression equation.

Table 3 shows the penetration test result and softening point test result of the NPB when 51.5% of asphaltene and 48.5% of maltene are blended. This blended NPB meets specifications of penetration and softening point of PB80/100 in Japan. Both values of PB80/100 are shown in this table for the reference.

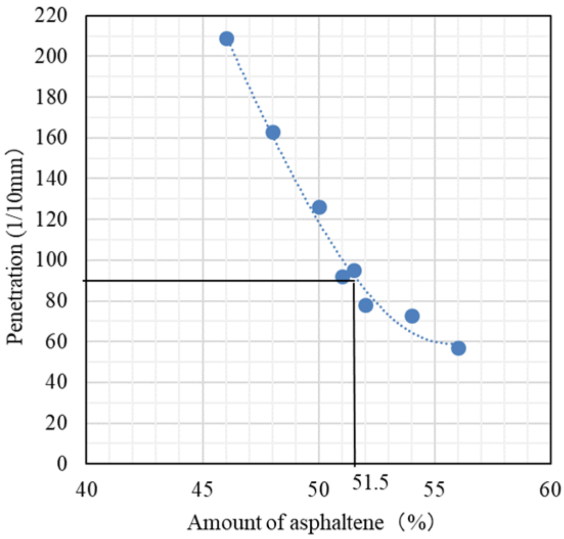

Figure 4 Penetration values according to amount of asphaltene

Table 3 Penetration and softening point test results

Binder	Penetration (1/10mm)	Softening point (ºC)
NPB	96	49.9
PB80/100	81	44.8
Specification of PB80/100 in Japan	80 -100	42.0 – 50.0

5.1.2 Viscoelasticity

DSR test is conducted on three binders, which are PB80/100, the NPB and a polymer modified binder type II (hereinafter PMBII), which is commercially available in Japan, to evaluate their viscoelasticity properties. PMBII is one of the modified binders widely used in Japan. PMBII is made by adding several percent of the SBS (styrene-butadiene-styrene) as a modifier to a petroleum binder and this binder is widely used not only for roads but also for parking lots and so on where rutting resistance are required. Figure 5 shows the test results.

Complex modulus (G^*) of the NPB is like that of PB80/100 at lower temperature and is like that of PMBII at higher temperature. It is expected that this NPB has a higher rutting resistance property than PB80/100.

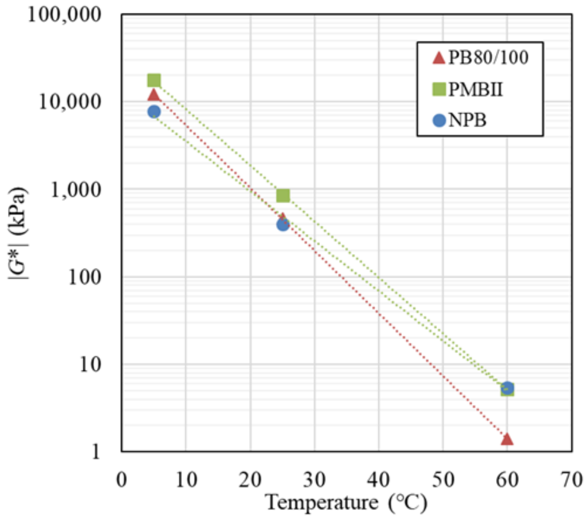

Figure 5 Complex modulus of the NPB, PB80/100 and PMBII

5.2 Mixture properties

Mixture properties of RHMA with the NPB and RHMA with PB80/100 are shown below.

5.2.1 Mix design

Marshall test results are shown in Table 4. All results meet the specifications for dense-graded mixtures in Japan. Marshall mix design method can be adapted to the NPB and this NPB can be an alternate binder.

Table 4 Marshall tests results

Binder	Bulk density (g/cm^3)	Air voids (%)	Void filled with binder (%)	Stability (kN)	Flow (1/10mm)
NPB	2.362	3.8	76.7	8.7	29
PB80/100	2.379	3.1	80.1	11.3	24
Specification* in Japan	N/A	3 - 6	70 - 85	4.9 and higher	20 - 40

* Specification for dense-graded mixtures

5.2.2 Water sensitivity

Table 5 shows the HWT test results. *SIP* is found in the RHMA with the NPB and PB80/100 and *SIP* and rut depths after 6,000 passes for both mixtures are compared. Note that this test is performed under severer test condition in water of 60ºC as noted previously. RHMA with the NPB shows equal or better water sensitivity than RHMA with PB80/100.

Table 5 HWT test results

Indicator	NPB	PB80/100
SIP (pass)	1,890	1,690
Rut depth after 6,000 passes(mm)	27.6	26.8

5.2.3 Rutting resistance

WTT results are shown in Table 6 and the specimens after WTT are shown in Photo 3. A greater *DS* shows a higher rutting resistance. RHMA with the NPB has about twice *DS* of mixture with PB80/100. And rut depth after 60 minutes of RHMA with the NPB is less than that of RHMA with PB80/100. From these, RHMA with the NPB has greater rutting resistance than PB80/100. *DS* is specified in the technical standards for pavement in Japan and *DS* shall be more than 3,000 (pass/mm) for the use of heavy-duty roads with a daily heavy traffic volume of more than 3,000 (heavy vehicle/day/direction) and more. Note that this traffic volume is equivalent to 6,700 ESAL/day and more, because Japan uses a single axle load of 98kN. This NPB meets this requirement.

Table 6 WTT results

Indicator	NPB	PB80/100
DS (pass/mm)	3,940	1,970
Rut depth after test completed (mm)	2.12	2.92

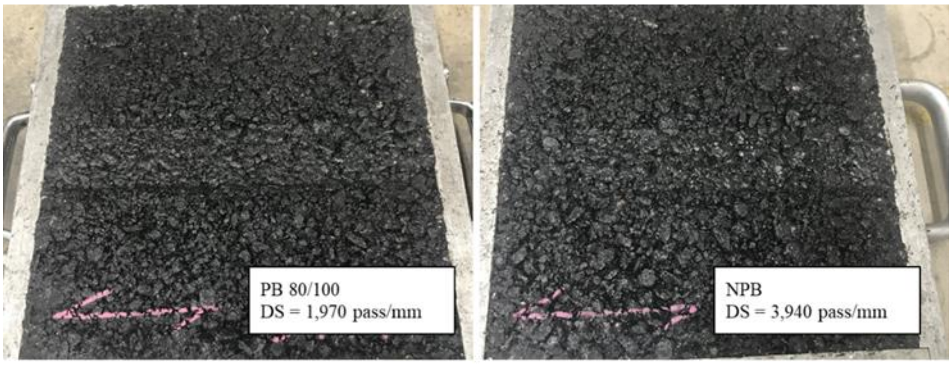

Photo 3 Top view of the specimen after WTT

5.2.4 Fatigue resistance

4PB test results are shown in Table 7. These test results indicate RHMA with the NPB has more than twice fatigue resistance of RHMA with PB80/100.

Table 7 4PB test results

Used binder	Cycles to failure
NPB	3,940 ± 330
PB80/100	1,435 ± 154

5.3 Field test

5.3.1 Mixture properties

Table 8 shows test results using RHMA produced at the actual asphalt plant. Marshall stability of RHMA with the NPB is about 35% higher than RHMA with PB80/100. For water sensitivity by HWT test, *SIP* is found at both mixtures. *SIP* of the specimen with PB80/100 is greater than the laboratory test results and *SIP* of the specimen with the NPB is almost equal to the laboratory result as previously shown in Table 5. For rutting resistance by *DS* values, *DS* of the specimen with PB80/100 is smaller than the laboratory test result and *DS* of the specimen with the NPB is greater than the laboratory result. The later is 6,300 (pass/mm) and this level of RHMA is fully applicable to heavy-duty roads. For fatigue resistance by 4PB test, cycles to failure of the specimen using the NPB is greater than that using PB80/100 and these are almost similar to the laboratory test results.

The NPB can be an alternate binder of PB80/100 for RHMA produced at the asphalt plant from above test results.

Table 8 Mixture properties using RHMA produced at the asphalt plant

Mixture property	Indicator	NPB	PB80/100
Marshall stability	stability (kN)	16.6	12.3
Water sensitivity	*SIP* (pass)	1,730	2,140
Rutting resistance	*DS* (pass/mm)	6,300	1,050
Fatigue resistance	cycles to failure	2,540±295	1,350±434

5.3.2 Test pavement result

1) Workability / constructability

Test pavements are constructed in early March 2023. RHMA with the NPB is produced at a batch mixing plant and general RHMA is supplied from a storage silo, which is a general way in Japan. As the result, production temperature of RHMA with PB80/100 and the NPB are 162ºC and 152ºC, respectively. These mixtures are paved on a milled asphalt concrete surface with 3.5m in width and 50mm in thick. This is intended to the major repair method of asphalt pavement, which is a mill and overlay, in Japan. A general wheeled asphalt paver to lay RHMA, 10 metric tons of steel roller for a breakdown compaction, 12.5 metric tons of pneumatic tire roller for an intermediate compaction and 3.5 metric tons of tandem steel roller for a final compaction are used in this study. Two examples of construction conditions are shown in Photo 4. RHMA with the NPB is laid at temperature of 141ºC and RHMA with PB80/100 is laid at temperature of 151ºC and temperatures during construction are measured as shown in Figure 6. Temperature drop trends are similar for both with the initial temperature difference remaining. RHMA with the NPB is fully workable. No differences are observed during constructions including mixtures, placement, compactions and so on even though all measured temperatures for RHMA with the NPB during construction are lower than PB80/100 cases.

Photo 4 Examples of construction conditions

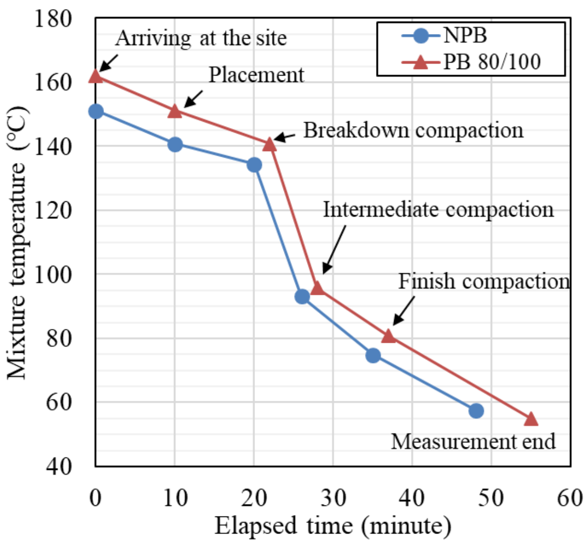

Figure 6 Temperature measurement results during constructions

2) Surface texture

Top views of constructed RHMA are shown in Photo 5 with measured surface texture of the Mean Profile Depth (*MPD*). No differences are found there. Both surfaces show similar *MPD* values. RHMA with the NPB can be finished by a general paving machines like general RHMA.

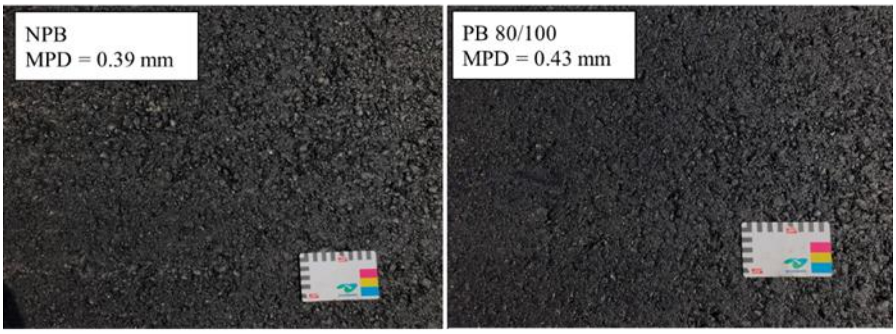

Photo 5 Top views of constructed RHMA and measured MPD

3) Skid resistance

International Friction Index (*IFI*) parameters are calculated using *MPD* and skid resistance by dynamic friction tester and these are shown in Table 9. Two parameters, which are the speed constant, *Sp*, and the friction number, *F*60, show almost same values. RHMA with the NPB is expected to have similar skid resistance to PB80/100 cases.

Table 9 Calculated *Sp* and *F*60

IFI parameters	NPB	PB80/100
Speed constant, *Sp*	35.17	38.91
Friction number, *F*60	0.19	0.20

5.4 Recommended temperatures of the NPB

From above, RHMA with the NPB has as same properties as RHMA with PB80/100 when produced and constructed at the similar temperatures as PB80/100. On the other hand, it is reported that some natural and/or plant base binders have possibilities to be used at lower temperature than general petroleum binders from literature review results (TRB 2012, WSP New Zealand Limited 2021). And this is expected from the test construction. Then relationship between mixture temperature and compaction property is evaluated. Figure 7 shows the relationship between the number of gyrations between the degree of compaction at several test temperatures, which are decreased by 10ºC from 144ºC. This figure includes the test result of PB80/100 as a control specimen at 144ºC.

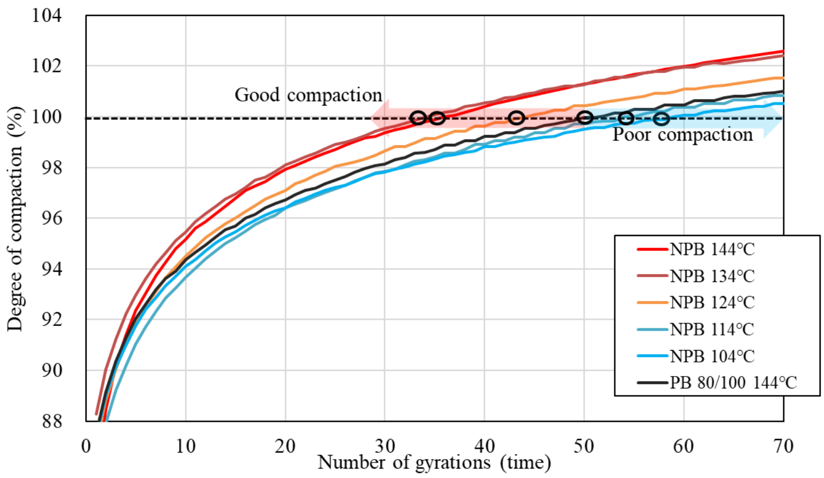

Figure 7 Relationship between the number of gyrations and the degree of compaction

It is found that RHMA with the NPB has equal or better compactability when compaction temperature is 124ºC or higher comparing to RHMA with PB80/100 at 144ºC. RHMA with the NPB at 114ºC has a little worse compactability than RHMA with PB80/100 at 144ºC but this is within the acceptable range. Sampling temperatures are at 10ºC intervals and so the recommended temperature for compaction of the NPB is about 114ºC, which is about 30ºC lower than a petroleum binder used in this study. From this, mixing temperature is expected to decrease about 20-30ºC comparing to PB80/100. This means that heating temperatures of aggregates are also expected to be lowed. This leads to decreasing the amount of heavy oil to heat aggregates, resulting in lower CO_2 equivalent emissions.

5.5 Applicability of the NPB as a paving material

RHMA with the NPB shows similar mixture properties to RHMA with PB80/100. RHMA with the NPB can be produced properly and it is capable to pave using general construction machines and construction management. The NPB and RHMA with the NPB are applicable to a paving material. Furthermore, the NPB is expected to be used at lower temperature than PB80/100 and this is also expected to reduce CO_2 equivalent emissions comparing to general petroleum binders. Of course, medium to long term pavement performance should be observed and confirmed and whether it will be approved as a material for the public roads is unknow at this time.

5.6 Estimation of CO_2 equivalent emissions

Reducing CO_2 equivalent emissions are estimated when the NPB is used to RHMA comparing to PB80/100. Some published documents and public data are used for these estimations. Estimated CO_2 equivalent emissions include on producing and transporting raw materials and producing RHMA at an asphalt plant. CO_2 equivalent emissions are calculated as following.

$$\text{Total } CO_2 \text{ equivalent emissions} = \sum \left(V_m \times EF \right) \qquad (2)$$

where V_m : Volume of material used (unit depends on material like metric tons, liters or kWh)
EF : emission factor of each material

This calculation method is referred to two documents (Japan Road Association 2023a, Kawakami et al. 2009, Nishizaki et al. 2014) published in Japan and emission factors are cited from data published by the Ministry of the Environment (the ministry of the environment, Japan. 2023). The calculation result is shown in Figure 8. For materials, reducing rate of CO_2 equivalent emissions is 38% using the NPB comparing to PB80/100 due to the carbon-neutral feature of the NPB. For mixture productions, reducing rate of CO_2 equivalent emissions is 2% using the NPB comparing to PB80/100 because the NPB does not require heating at storage. And totally 16% of CO_2 reducing rate is estimated when lower producing temperature is considered as noted above. For delivering materials, all are estimated as equal values in this case, because origin of materials and location of asphalt plants may vary and then it is assumed that the locations are the same. Then estimated total reducing CO_2 equivalent emissions is 9% and it is 19% when considering lower temperature on using the NPB instead of PB80/100 to produce RHMA. Note that 30ºC of temperature drop is assumed in this case. An alternate binder like the NPB contributes well to a decarbonated society when considering that 89% of CO_2 emissions of asphalt pavement construction is due to producing HMA as already shown in Figure 1.

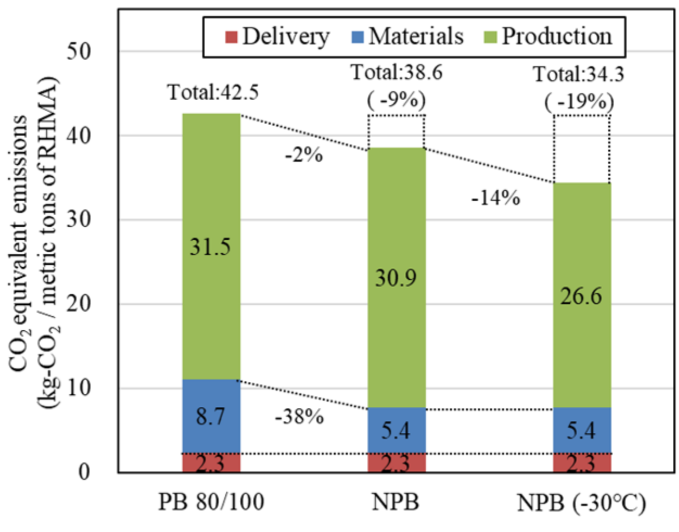

Figure 8 Estimation results of CO_2 equivalent emissions

6 SUMMARYS AND CONCLUSIONS

This paper is summarized as follows.

- The selected NPB can be adjust its penetration value with changing the two components of asphaltene and maltene.
- The NPB can be mix designed replacing it to a petroleum binder of RHMA.
- Mix properties of RHMA with the NPB is same or greater than that with PB80/100 and it has better rutting resistance, especially.
- RHMA with the NPB can be produced at a general asphalt plant and this can be paved using general construction machines.
- Surface characteristics of paved RHMA with the NPB is similar to that with PB80/100.
- RHMA with the NPB can reduce the construction temperatures comparing to using PB80/100 and it is 20-30ºC lower than PB80/100.
- CO_2 equivalent emissions can be reduced 38% for materials, 2% for mix productions and 9% for all stages including hauling when using the NPB.
- CO_2 equivalent emissions can be reduced 19% in total when using the NPB considering a possibility of production temperature drop.

From these, it is possible to replace a petroleum binder with the selected NPB. There are some commercially available natural and/or plant base binders in the world, so the authors expect that such natural and/or plant base binders will be widely used. Cost or price will be one of the keys and this will be resolved to some extent as the market scale of natural and/or plant base binders increases. But raw materials for such natural and/or plant base binders are finite. There will be a price equilibrium point somewhere. While taking these points into consideration, the authors hope that social infrastructure including pavement is properly maintained to a sustainable and environmental-friendly society.

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