The Development of Structural Design Method of Composite Pavement in Japan

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Abstract

Zero-maintenance pavements must be a big goal for road administrators around the world. As part of the challenges, a new design of composite pavement that is able to sustain heavy traffic loadings with minimum maintenance for long years was developed in Japan. The new design comprises a porous asphalt surface and continuously reinforced concrete base, which was adopted in the country's alternative beltway project, Shin (New) - Tomei Expressway, connecting Tokyo and Nagoya. The new route was opened to service in April 2012. The design concept of the new pavement is to combine both advantages of asphalt surface and continuously reinforced concrete base; the former assures better riding quality and easier repair job, while the latter provides higher durability for a longer service life. However, it took more than 15 years to finally develop a reliable design method for the pavement. In the process, several full scale test composite pavements were constructed and comprehensively investigated in terms of design, materials, construction and performance. This paper describes the investigation results of the test pavements and the structural design method of the composite pavement that takes into consideration the thermal stress reduction due to asphalt surface and fatigue impact on CRC base.

Introduction

The Shin-Tomei Expressway opened to traffic on April 14, 2012, as Japan's key alternative arterial beltway of the existing Tomei, connecting Tokyo and Nagoya, which has been in operation for over 40 years (A. Hirose 2012). Figure 1 depicts both beltways (Central Nippon Expressway Company Limited 2012).



Figure 1. Shin-Tomei and existing Tomei Expressways

In order to avoid densely populated plains alongside the Pacific Ocean, the Shin-Tomei runs mostly through outskirts of mountainous areas. Therefore the new expressway consists of many big bridges and long tunnels. The bridge sections account for approximately 31% of the total length, while the tunnel sections share approximately 26%.

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The projected commercial vehicles share 50% or more of the total traffic volume. Because of the importance of this arterial road, composite pavement that can assure longer durability was selected at a design stage of one of the country's big road projects (N. Wada et al 2010).

The design concept of composite pavement is to combine both advantages of asphalt and concrete pavements. The former can assure better riding quality and easier repair jobs, while the latter offers higher durability for a longer term. Since this method should achieve longer durability for the Shin-Tomei Expressway, the design term is extended to 40 years. Figure 2 features the pavement structure finally determined.

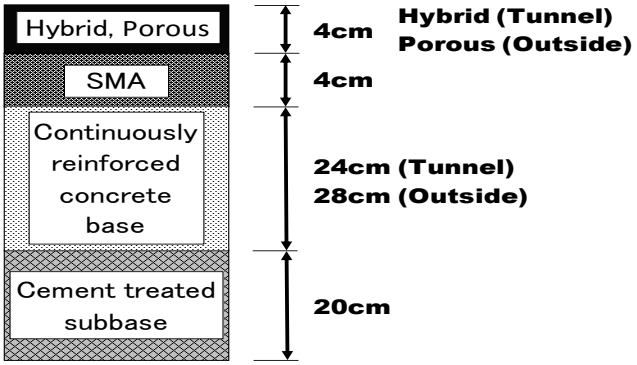


Figure 2. Design structure for the Shin-Tomei Expressway

For keeping higher safety levels, porous asphalt or hybrid mix (R. Kato et al 2010), which is designed to assure higher durability for tunnel sections, was adopted for the road surface. The underlying stone mastic asphalt (SMA) layer was judged imperative to prevent rainwater from infiltrating into the designed hair crack of continuously reinforced concrete (CRC) base. The design thickness of CRC base was the most difficult issue, since there was no applicable design method to match the project in overseas countries. In fact, it took over 15 years until the design method of CRC base was finally established. This paper presents the essence of designing the thickness of CRC base for long years.

Mechanism of Composite Pavement

When the design concept of pavement for the Shin-Tomei was discussed in the late 1980s the existing Tomei partly suffered from severe rutting, as shown in Figure 3 (Y. Mori et al 1990). Since the rutting was deeply rooted to the bottom of asphalt treated base, rutting appeared again soon after the surface layer was replaced with new materials. Therefore an intensive research and study was commenced to realize a basic concept of "no more rutting" in the field.

In order to simulate the field condition on the Tomei, many cases of multi-layered wheel tracking tests were conducted at laboratory. Based on the test results, a full scale rutting test was achieved using accelerated pavement testing machine, as shown in Figure 4.

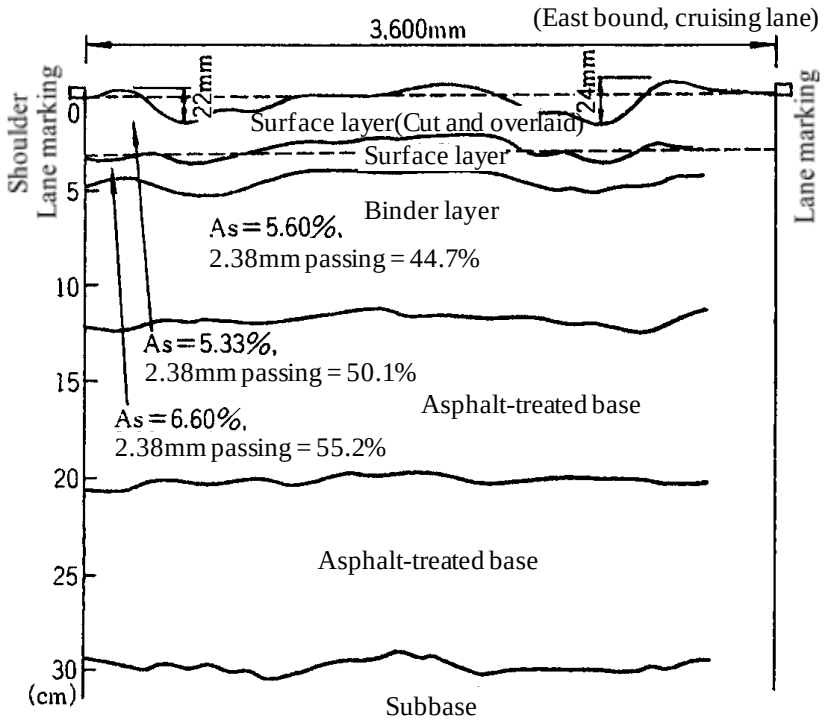


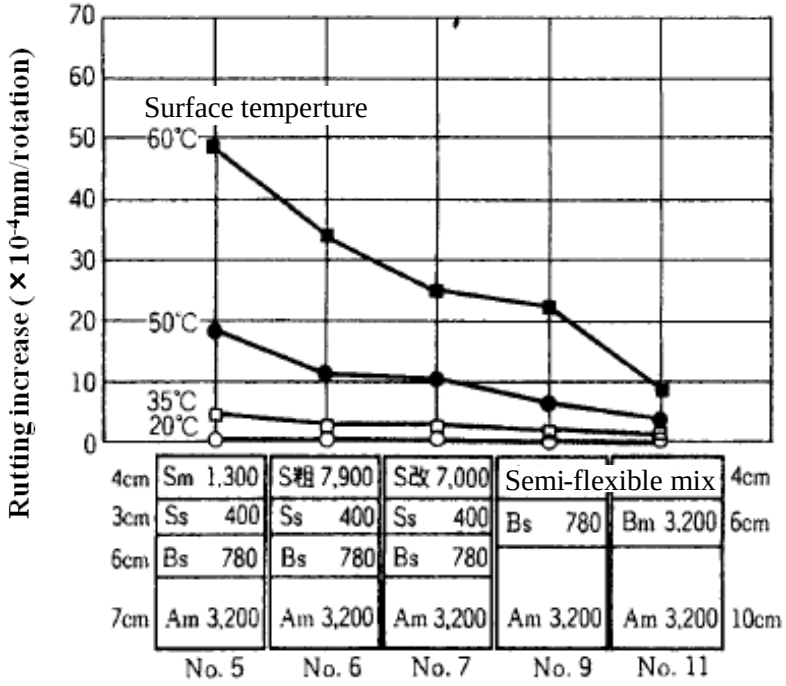
Figure 3. Deeply rooted rutting on the Tomei Expressway



Rutting test condition	
Diameter	6m
Number of Wheel	4 truck tires
Wheel Load	2,000 kg/wheel
Rotation Velocity	20 km/h
Shift in Rotation	±60mm
Number of Specimen	12

Figure 4. Full scale accelerated pavement testing machine at NEXCO RI

Figure 5 (upper) compares rutting increase in case of paving different levels of dynamic stability (DS) or rutting resistance for the surface layer. All pavements were not rutted at the surface temperature 35°C, but the specimens No.5 to No.9 with lower DS at the underlying layer were susceptible to rutting at 50°C or higher. Although semi-flexible case No.11 showed the most promising resistance, it incurred cracking on the surface unfortunately, as shown in Figure 5 (lower). This would be due to the imbalance in strength between semi-flexible surface and its underlying asphalt mix layers.



The number in box indicates dynamic stability.

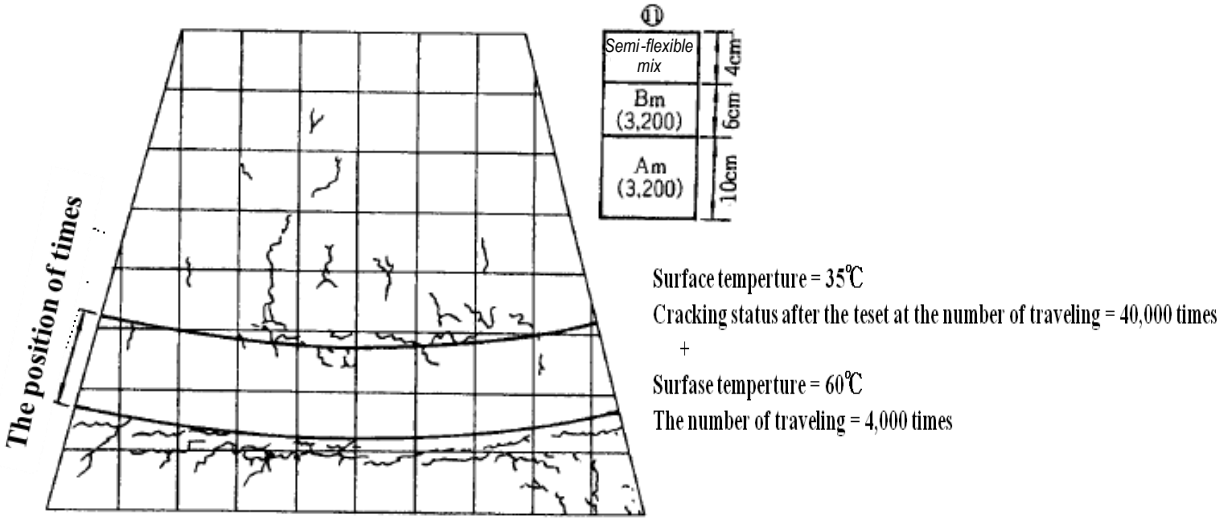


Figure 5. Rutting increase by intensifying surface layer (upper) and crack occurrence (lower)

Figure 6 (upper) demonstrates the superior rutting resistance of composite cases; specimens with roller compacted concrete and semi-flexible bases excelled, compared with conventional bases. Figure 6 (lower) highlights cross sections of the specimens between composite and conventional base types. Since tensile strain at the bottom of asphalt mix on composite base must be lower than on conventional layer, the former strain will be less accumulated, and thus the rutting occurrence on the composite base can be reduced.

In this way, it was determined that rigid materials as composite base are to be used for the Shin-Tomei project.

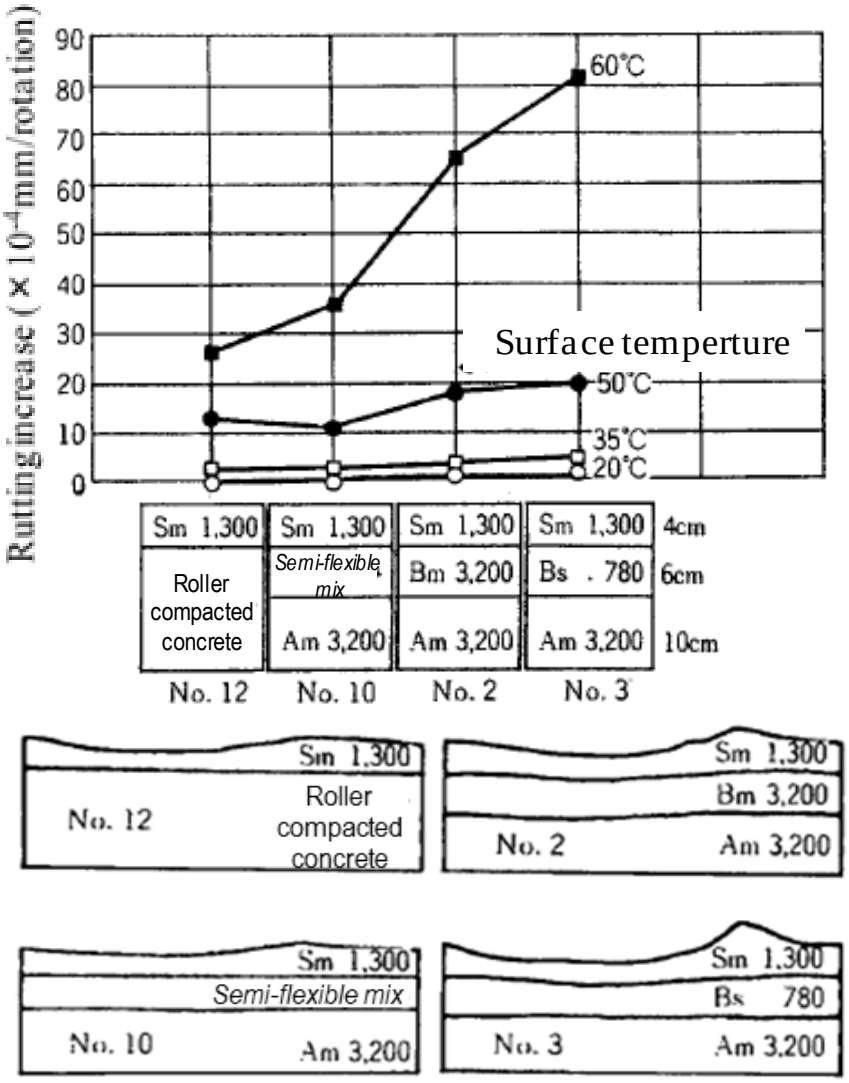


Figure 6. Effect of composite structure (upper: rutting increase, lower: cross section)

Field Experiments

Long Term Performance. A trial construction was conducted in 1990 on the San-yo Expressway in order to evaluate the long term performance of the composite pavements which entail three rigid base materials that are roller-compacted concrete (RCC), RCC (lean concrete) and continuously reinforced concrete (CRC), as shown in Figure 7.

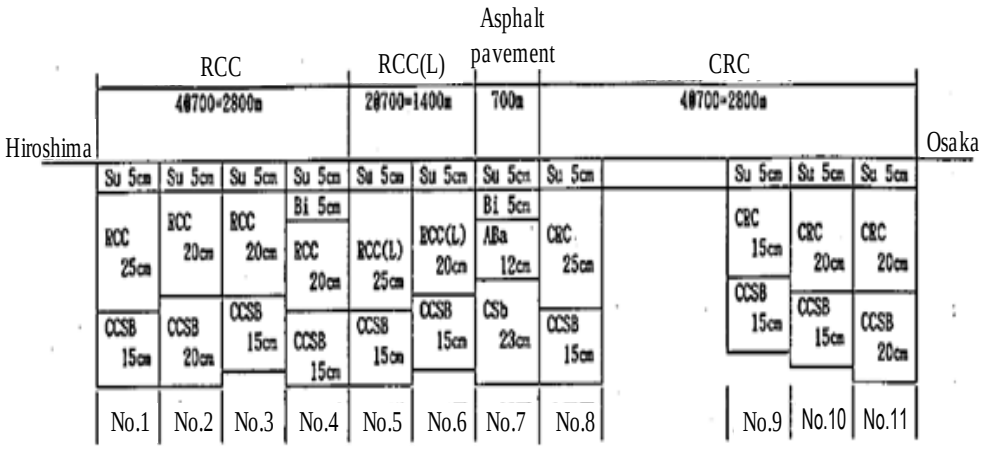


Figure 7. Field experiment of composite structures on the San-yo Exp.

Although CRC base was the most costly white base, a few years after opening to traffic, reflective cracking propagated on the entire road surface of RCC and RCC (lean concrete) sections. Hereafter, CRC base was only used for the other composite constructions.

In 2002, a long-term monitoring report concluded that CRC base is the only promising white base, and that the thickness should exceed 15cm, as CRC base with this thickness failed in 10 years.

Mechanical Analysis. As composite pavement comprises asphalt layer and its underlying CRC base, the hybrid type of structure is considered to fit multiple-plate theory, as shown in Figure 8. However, the two materials are expected to perform very uniquely, because of the differences in elasticity and susceptibility to the surrounding temperatures.

In order to understand the levels of AC elasticity and examine the applicability of multi-plate theory, loading test was conducted to gather actual data on another San-yo Exp. project. While loading was applied up to 196 kN on a 30-centimeter plate, strain inside CRC base was measured at two sections during a year. The test covers the conditions before and after paving an AC layer on CRC base. Table 1 summarizes the measurements of strain.

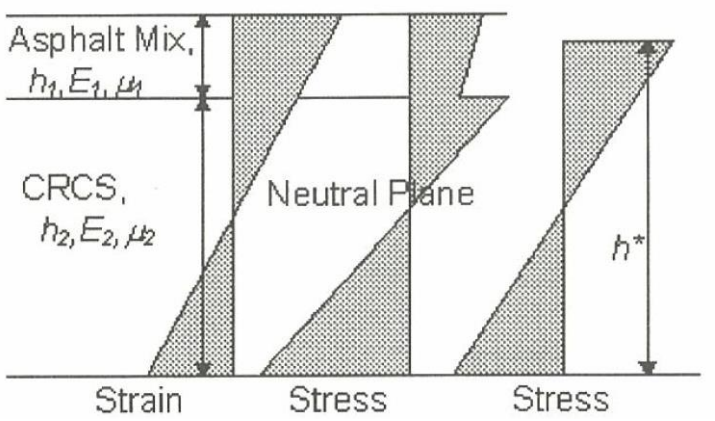


Figure 8. Multiple-plate theory

Table 1. Strain inside CRC measured

Loading condition	Strain ($\times 10^{-6}$)		Ratio (%)
	Center	Edge	
Section A (220mm-thick CRC)			
Feb (CRC)	82	153	-
May (CRC)	81	143	-
Aug (80mm AC + CRC)	56	139	94
Oct (80mm AC + CRC)	18	58	39
Section B (250mm-thick CRC)			
Feb (CRC)	97	148	-
May (CRC)	75	145	-
Aug (50mm AC + CRC)	73	148	93
Oct (50mm AC + CRC)	51	125	73

Understandably, strains inside CRC were measured to decrease after constructing an AC layer on CRC base. A ratio of strains after and before placing the AC was lower in October than that in August at both sections. The reason of a higher reduction ratio in Section A than Section B is probably the effect of the thicker thickness of the AC layer.

Based on the results of the loading test, Table 2 lines up estimated AC elastic modulus at each section in August and October.

Table 2. Estimated AC elastic modulus

	Section A (MPa)	Section B (MPa)
Aug	9,000	8,000
Oct	50,000	25,000

As even in the summer time, the AC modulus showed higher levels than those normally considered like 5,000 to 10,000 MPa. For safety reason in design, however, it was concluded that that the maximum AC modulus be 10,000 MPa.

Based on the above field data, the effect of AC elasticity on reducing loading stress on CRC's bottom was calculated. In the calculation, multi-plate theory and more sophisticated axisym finite element method were used. Figure 9 shows a gradual reduction of the loading stress as AC modulus increases for both Sections A and B. This indicates that the loading stress on the CRC base reduces, as AC modulus increases. Interestingly, can also be seen a generally good fitness for both models at each of the two sections. This matching can be assured with AC elasticity less than 25,000 MPa, which is enough reliable in the design. Therefore, it was concluded that multiple-plate theory can be used practically for the design.

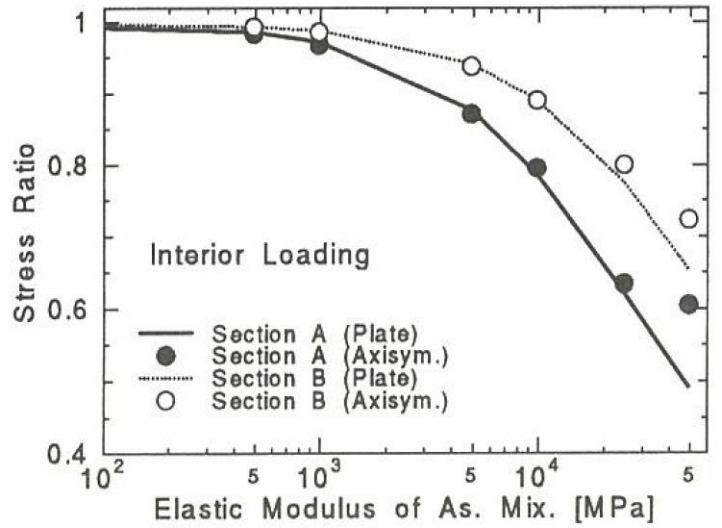


Figure 9. Effects on AC elasticity at center

Thermal Differential Effect. It was also important to find out how much of the CRC thickness can be reduced, depending on the thermal stress of CRC base caused by the surrounding temperature. Temperature at the upper part of the CRC base differs from that at the base, regardless of with and without an AC layer on it. However, the temperatures at the upper and base parts differ less with an AC on it, which is composite structure, than without an AC, which is the normal CRC pavement.

In order to find such temperature differential, several composite structures were constructed and temperatures of each CRC base were monitored for over a year. Figure 10 summarizes the relation between the ratio of temperature differential (CRC_{top} - CRC_{bottom}) of CRC base and the thickness of Asphalt layer on the CRC base. As AC thickness increases, the ratio of temperature differential can be reduced, meaning thermal stress inside CRC base to be reduced as well. Finally the CRC base thickness can also be thinner. This effect is significant especially in tunnel sections where the ratio is much lower than outside sections (T. Nishizawa et al 1997).

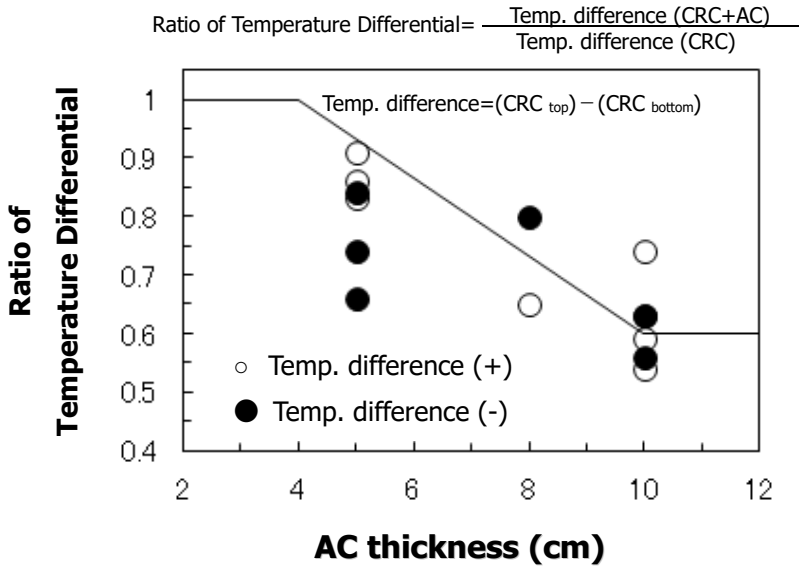


Figure 10. Ratio of temperature differential and AC thickness on CRC base

Fatigue Calculation

Based on the above findings through field performances, sensitivity analysis of fatigue was carried out using a FEM program on several selected composite structures. The analysis conditions were summarized in Table 3.

Table 3. Fatigue analysis condition

Design period	40 years
10 ton equivalent single axle loads	1,043,070,813
Probability of fracture	5%
AC resilient modulus (E1)	9800 MPa
Width of CRC	4.5m
CRC's crack interval	every 1m
Concrete elasticity	34,300 MPa
Concrete poison's ratio	0.2
Subgrade K-value	98 MN/m^3,196 MN/m^3,294 MN/m^3, 392 MN/m^3

Figure 11 shows the calculation results on the degree of fatigue in a case, where probability of fracture is 5 percent and AC resilient modulus is 9800 MPa. It features the relation between CRC's thickness (h_2) and AC's thickness (h_1) on a curve representing the fatigue degree of 1.0. Each curve changes as a parameter of subgrade K-value. The more the slope of the resulting curve is steep, the less indicating that it does lead to a decrease in h_2, despite an increase in h_1.

Meanwhile, the increase of AC thickness (h_1) from 4 cm to 10 cm greatly affects the thickness (h_2) of CRC base, indicating that thickening of h_1 can significantly make h_2 thinner. As for subgrade strength, reduction of 1.5 cm in h2 is seen while K-value increases from 98 MN/m3 to 196 MN/m3. However, only the reduction of 0.5 cm can be achieved even with the increase from 285 MN/m3 to 382 MN/m3. Thus subgrade K-value can contribute the reduction of the CRC base thickness up to a point, but this cannot be significant after that.

In addition, one more important requirement for designing composite pavement is that rain water should never penetrate hairline cracks on the CRC surface, which is to be propagated as a design feature. This is critical especially in Japan, since the nation, unlike many other industrialized countries, has much of annual rainfall. Therefore, AC thickness must be thick enough to prevent rainfall from coming inside the CRC base. For this reason, it was concluded that the AC thickness should be 5 cm around or more (T. Nishizawa et al 1997).

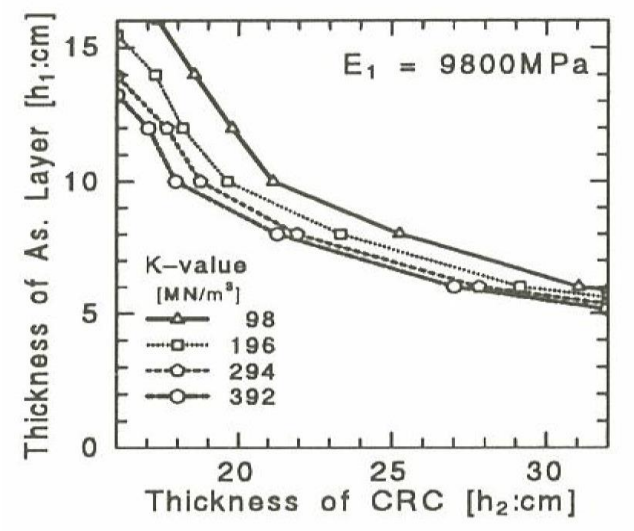


Figure 11. Asphalt surface layer thickness and CRC thickness

Design Thickness of CRC Base

From serviceability of composite pavements on San-yo Expressway, minimum thickness of CRC base proved to be 15 centimeters. As a result of calculating CRC's fatigue, the relation between CRC's thickness and AC's thickness was obtained on a curve representing the fatigue degree of 1.0. These finding were a basis of developing how to design thickness of CRC base. However, for the purpose of aiming at zero-maintenance, many cases of CRC's thickness and field performance in overseas countries were investigated. By putting together the new information with all above mentioned, design thickness of CRC base was finally as drawn in Figure 12.

The projected Shin-Tomei's total commercial vehicles of 100 million levels during 40 years is to point to the design thickness of 24cm for tunnel sections and that of 28cm for outside sections, as introduced in Figure 12.

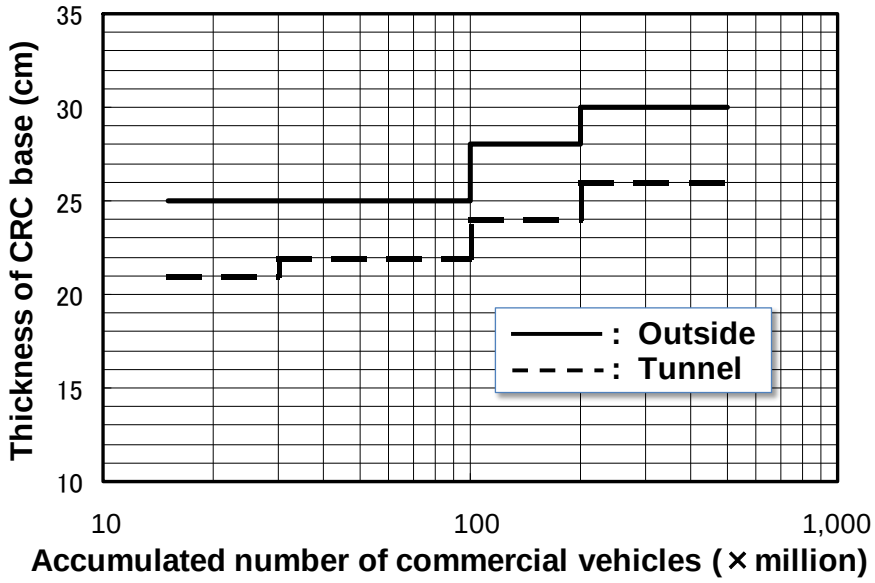


Figure 12. Design thickness of CRC base

Summary and Conclusion

For the purpose of realizing long lasting durable pavements on the Shin-Tomei, a concept of "no more rutting" reached composite pavement more than 25 years ago. Since then, intensive research and study were conducted at laboratory and in the field. Here is the summary of technical results, as all mentioned above.

1. According to the full-scale accelerated rutting test, composite pavements showed superior rutting resistance than conventional asphalt pavements even with an intensified surface layer using modified bitumen or semi-flexible mix.
2. The mechanism of the composite structure is considered as follows. Since tensile strain at the bottom of asphalt mix on composite base must be lower than on conventional layer, the strain will be less accumulated, and thus the rutting can be reduced.
3. A long term monitoring of trial composite pavements on the San-yo Expressway revealed that CRC base is the only promising white base and that the thickness should exceed 15 cm. Composite pavements with RCCP and RCCP (lean concrete) bases were not long lasting, due to reflective cracking.
4. Judging from full-scale loading tests over a year in the field and the following theoretical calculation, it was concluded that multiple-plate theory can be used practically for the design of composite pavement. It was also revealed that the maximum AC modulus be 10,000 MPa.
5. As a result of field monitoring of CRC's thermal conditions, it was found that placing an AC layer can reduce the temperature differential at the upper and base parts of the CRC base. The effect of then reducing thermal stress inside the CRC base finally contributed to the reduction of its thickness, especially in tunnel sections.
6. According to sensitivity analysis of fatigue, which was carried out using a FEM program on several selected composite structures over 40 years, the increase of AC thickness from 4 cm to 10 cm can make thinner the thickness of CRC base. For sufficiently protecting CRC base against high rainfall in

Japan, it was concluded that the AC thickness should be 5 cm around or more.

7. In addition to the above findings, by considering opinions of overseas performance of CRC, design thickness chart of CRC base was finally established (SHRP 1993).

The authors understand that composite pavement having costly white base cannot be widely used everywhere. However, set aside the use of CRC base, one of the most important ideas that the authors have learned long years from this study is that the base layers under AC mix should be stiffly built up and protected from rainwater. This will surely work for rutting resistance.

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