Structural Design of Pavement for Cold Regions based on Life-Cycle Cost

Hideto TAKEMOTO, Tateki ISHIDA, Kimio MARUYAMA and Yuichi KUBO
Maintenance and Management Section, Road Division, Civil Engineering Research Institute of Hokkaido

ABSTRACT : Asphalt pavements in Japan are commonly designed with a 10-year life, regardless of the importance and traffic volume of the route. Toward minimizing the life-cycle cost by extending the service life, the Hokkaido Regional Development Bureau recently revised structural design standards for asphalt pavement to extend the design life to 20 years in cold Hokkaido. The revision focused on low-temperature cracking, frost heaving, and phenomena of cold, snowy climates, as well as on the route's importance and traffic volume. Comparison was made between pavement with a 10-year design life and that with a 20-year design life. Analysis based on multi-layer elasticity theory estimated the number of years before fatigue fracture occurs. Performance curves were obtained by regression analysis of data on longitudinal and transverse profile of the road. Based on these, 50-year life-cycle costs were calculated for 10-year and 20-year design life pavements. A separate case study on national highways in Hokkaido confirmed that extending the design life from 10 years to 20 years could reduce the life-cycle cost more than 10 %.

KEY WORDS: Structural design, life-cycle cost, cold regions

1. INTRODUCTION

Many of the roads constructed in Japan during the rapid economic growth of the 1960s have been deteriorating. When designing a road structure, it is important to minimize the life-cycle costs (LCC), from initial construction to subsequent maintenance and repair costs, as well as the losses incurred by road users including from increased vehicle operating costs and delay cost due to traffic restrictions during road works.

The structural design of asphalt pavements in Hokkaido calls for a wearing layer and frost blanket, and takes into account the reduction in subgrade CBR during use. We reviewed such design methods, which are unique to cold regions, toward establishing pavements that would afford a design life cycle of 20 years. Also, we estimated the life-cycle cost of the pavements, toward evaluating the cost reduction that would result from extending the life cycle.

2. THICKNESS OF THE ASPHALT MIXTURE LAYER

2.1 Current state of wear

Regions where use-bans on studded tires have been imposed by the Ministry of Environment (starting with the first group of designated municipalities in 1991 up to the fourth group designated in 1996) have reached 116 cities, towns and villages, but there are 96 towns and villages that are not in regions with use-bans. The rate of studded tire use and changes in the maximum wear of surface course during winter throughout Hokkaido are shown in Figure 1.

Since fiscal 1989, the use of studded tires has dropped significantly, and in fiscal 1993, the use has dropped to less than 10% in major cities. Consequently, the average maximum wear, which was 13 mm in FY1988, was reduced to about 4 mm by FY1989, and to about 1 mm in more recent years. It is believed that the need for a wear course is decreasing.

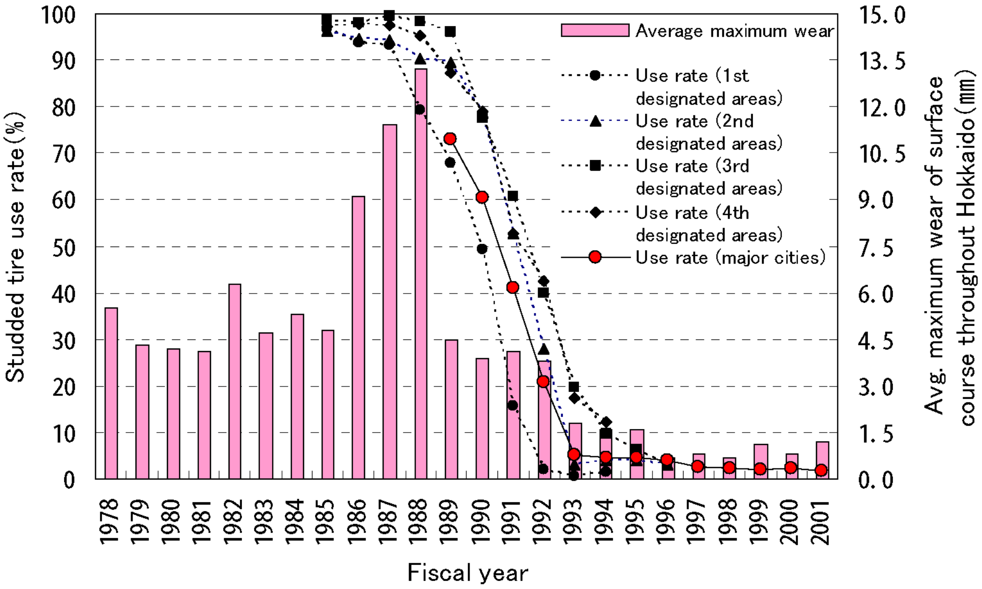


Figure 1: Changes in studded tire use rate and pavement wear

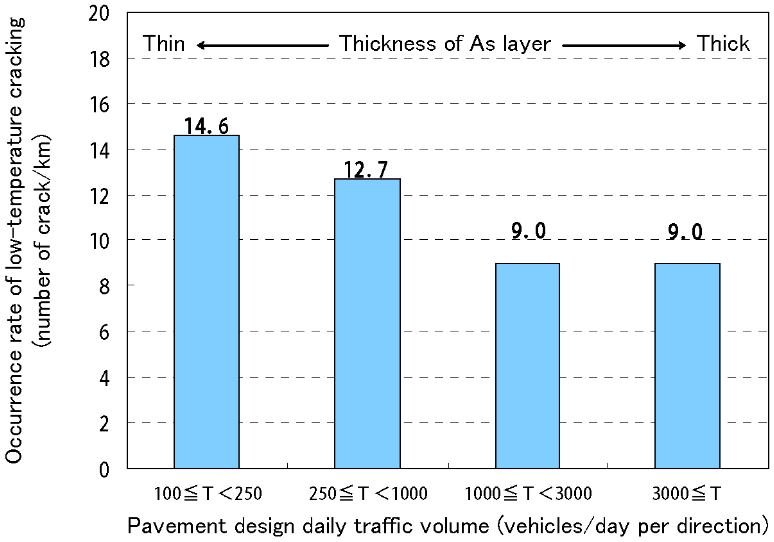


Figure 2: Thickness of As layer and occurrence rate of low-temperature cracking

2.2 Low-temperature cracking

Low-temperature cracking is a major cause of pavement failure in Hokkaido during winter. Low-temperature cracks are thermal stress cracks that occur linearly in the transverse direction of the road.

The occurrence of low-temperature cracking was studied on asphalt paved roads along 20 routes in the relatively cold eastern regions of Hokkaido. Figure 2 shows the occurrence rate of low temperature cracking according to the design daily heavy traffic volume of the pavement and indicates a tendency for the occurrence rate of low temperature cracking to be higher when the asphalt mixture layer (As layer) is thinner. This is because the occurrence rate of low-temperature cracking of asphalt pavement depends on material factors such as rate of shrinkage and stress relaxation ability of the asphalt mixture. Furthermore, it is thought to depend on structural factors because temperature gradient and stress distribution are related to the thickness of the As layer.

Chang et al.[1)] report that the occurrence rate of low-temperature cracking is inversely proportional to the As layer thickness. Therefore, if the wear course is eliminated and the As layer thickness is reduced, there will be concerns about the increase of low-temperature cracking.

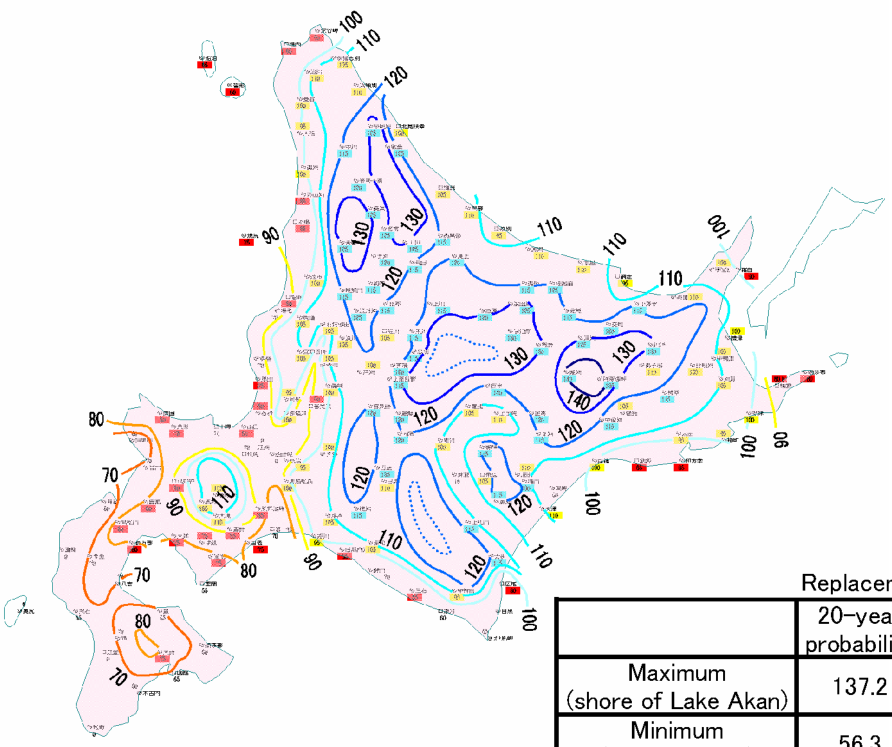
3. REPLACEMENT THICKNESS INCREASE AS A COUNTERMEASURE AGAINST FROST HEAVE

In Hokkaido, damage to road pavements, such as cracking, is caused by frost heave that occurs when the subgrade soil freezes in winter. To counter frost heaving of these roads, subgrade soil that is susceptible to freezing is replaced with frost-resistant material. This replacement thickness (depth) is calculated according to the 10-year freezing probability. For pavements designed for 20 years of service, it is necessary to consider the 20-year freezing probability.

Freezing index according to 10-year and 20-year probability is calculated from the average daily temperature data of the year 1980 to 2000 at 157 locations in Hokkaido.The replacement thickness is 70% of the theoretical maximum depth of frost penetration calculated from Freezing index.

The contour map of replacement thickness for the 20-year probability in Hokkaido is made from these calculation results and is shown in Figure 3.

The replacement thickness obtained using the 20-year-probability freezing index is approximately 4 cm greater on average throughout Hokkaido than the replacement thickness obtained using the 10-year-probability freezing index.



Replacement thickness (cm)

	20-year probability	10-year probability	Difference
Maximum (shore of Lake Akan)	137.2	133.5	3.7
Minimum (Muroran City)	56.3	51.4	4.9
Average	99.7	95.5	4.2

Figure 3: Replacement thickness obtained from the 20-year-probability freezing index

4. DESIGN CBR WITH CONSIDERATION FOR FREEZING AND THAWING OF SUBGRADE SOIL

Subgrade soil taken from 62 locations in Hokkaido was made into test pieces and tested for CBR. The pieces were then frozen, tested for frost heave, thawed, and then retested for CBR. The results of pre-freezing CBR and post-thawing CBR were compared. An example of test results on subgrade soil with less than 20% of fine-grained content (finer than silt) and those with more than 20% is shown in Figure 4. Of the subgrade soils with more than 20% fine-grained content, some show high CBR values before freezing/thawing, but this value is reduced significantly after freezing/thawing. In subgrade soil with less than 20% fine-grained content, such a significant reduction is not observed.

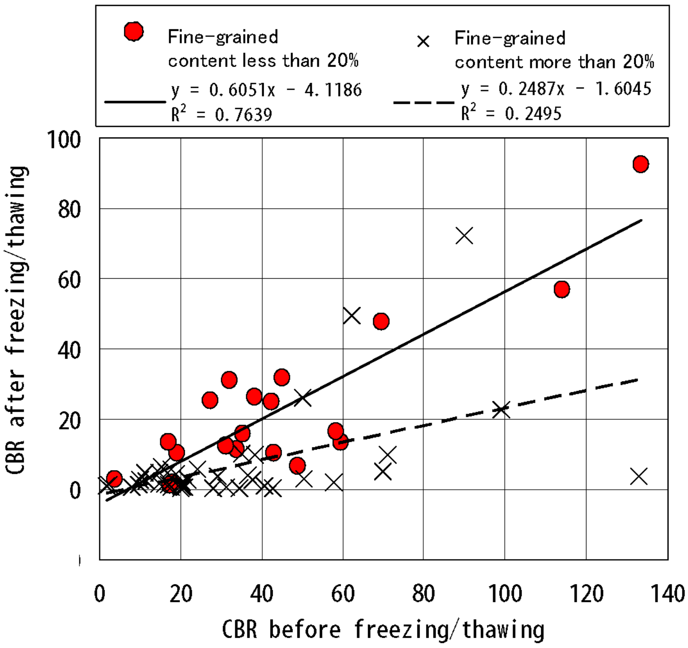


Figure 4: CBR before and after freeze-thaw of subgrade soil according to classification of fine-grained content

In Hokkaido, in light of the reduction in bearing capacity during the thawing period, the design CBR of subgrade soil is uniformly set as 3[2]. By using soil properties to determine the appropriate CBR, the pavement structure will be simplified and a more economical design becomes possible.

Therefore, in deciding the design CBR for subgrade soil in cold regions, the CBR value after freezing/thawing is to be used, because of the reduction in bearing capacity of the subgrade soil that occurs during the thawing period.

5. PAVEMENT STRUCTURE

To reduce the LCC by extending the service life, the pavement structural design that provides a 20-year design service life was performed under the following principle.

1) Eliminate the wear course, because of the reduced wear since the use-ban on studded tires.
2) Maintain the current thickness of As layer, to prevent further increase of low temperature cracking.
3) Determine the pavement structure by the T_A method, an experiential structural design

method that is normally used in Japan[3].

Table 1 shows an example of structural design of a pavement under the design conditions of design CBR = 3, 70-cm replacement thickness for the 10-year design service life, and 75-cm replacement thickness for the 20-year design service life (course-grained frost-resistant material).

The frost prevention layer or the subbase course is 5 to 10 cm thicker in pavements with 20-year design service life than the current standard pavement profile with 10-year design service life specified by the Hokkaido Regional Development Bureau.

Table 1: An example of structural design for As pavements (comparison between 10-year and 20-year design service life)

Pavement design daily traffic volume (vehicles/day per direction)	100≦T<250		250≦T<1000		1000≦T<3000		3000≦T	
Design service life (years)	10	20	10	20	10	20	10	20
profile	A1	A2	B1	B2	C1	C2	D1	D2
Surface course + binder course (wear course)	7 (2)	7 —	9 (2)	9 —	14 (2)	14 —	17 (2)	17 —
Base course (As stabilization)	5	5	6	6	12	12	18	18
Subbase course (granular material)	40	35	55	60	55	60	65	75
Frost-prevention layer (granular material)	20	30	0	0	0	0	0	0

6. ESTIMATING THE NUMBER OF YEARS TO PAVEMENT FAILURE

To calculate the LCC, it is necessary to know the life cycle of the pavement. The number of years to pavement failure was estimated. This was performed as a simulation with the pavement design daily heavy traffic volume of 250 to 1,000 vehicles/day per direction on asphalt pavement with a 10-year design service life (profile B1) and a 20-year design service life (profile B2), as shown in Table 5. First, the tensile strain at the bottom surface of the As layer and the compressive strain at the upper surface of the subgrade are calculated using Elastic Layer System Analysis[4][5] (ELSA), a multi-layer elasticity analysis application. These strains are calculated on the pavement structure designed according to the TA method with the 10-year design service life (with 2 cm of wear course removed from the standard profile) and the 20-year design service life. The analyzed models are the two types of pavement structure shown in Figure 5. Each is subject to multiple wheel loading conditions. The conditions for pavement temperature and elastic modulus are shown in Table 2.

From the calculated strain, and using Equations from the basic formula for failure of the Asphalt Institute in the U.S[6]., we obtain the number of wheel loading cycles to fatigue failure, to cracking ratio of 20% and to structural rut depth of 15 mm. Then the number of years to failure is obtained from the ratio between the number of wheel loading cycles to fatigue failure acquired above, and the number of wheel loading cycles to fatigue failure of 1,000,000 cycles/10 years. The number of wheel loading cycles to fatigue failure of 1,000,000 cycles/10 years is the number of cycles for 10-year design service life of the pavement design daily heavy traffic volume of 250 to 1,000 vehicles/day per direction based on the pavement standards. Using the TA method, the number of years to failure (As layer and subgrade) is estimated to be 16 years for the 10-year design service life, and 34 years for the 20-year design service life, under this traffic volume (Table 3).

Table 2: Temperature conditions and elastic modulus for As pavement

Temperature conditions	1	2	3	4
Pavement temperature (℃)	0	10	20	30
Number of months	4 months; Jan., Feb., Mar., Dec.	2 months; Apr., Nov.	3 months; May, Jun., Oct.	3 months; Jul., Aug., Sept.
Elastic modulus of As mixture (Mpa)	12000	8000	4000	2000

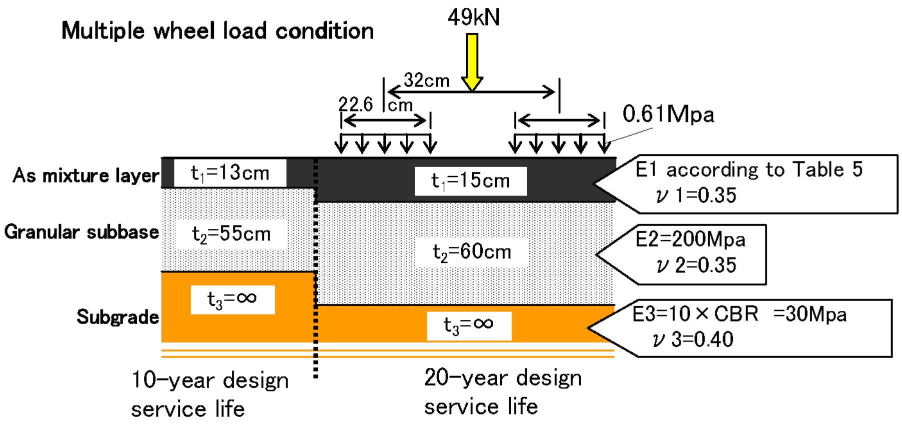


Figure 5: The 10-year and 20-year design service life pavement structure, and the material and wheel loading conditions for each layer

Table 3: Number of years to failure of the As layer and subgrade of the B1 profile and B2 profile with 10-year and 20-year design service life

Design service life (years)		10				20			
Temperature conditions		1	2	3	4	1	2	3	4
Lower surface of As layer	Tensile strain ($\times 10^{-6}$)	116	149	219	300	98	127	191	269
	Fatigue failure wheel loadings	2, 207, 873				3, 375, 656			
	Number of years to failure (years)	22				34			
Upper surface of subgrade	Compressive strain ($\times 10^{-6}$)	351	388	448	501	282	315	367	414
	Number of wheel loading cycles to fatigue failure	1, 555, 843				3, 783, 777			
	Number of years to failure (years)	16				38			

7. LCC

For the 300m-long pavement section, the LCC was compared for a period of 50 years with the social discount rate of 4% on profile B1 of 10-year design service life and profile B2 of 20-year design service life.

First, it was decided to compare road administrator costs such as initial construction, repair, and reconstruction costs for cases of 10-year and 20-year service life pavement designs. The performance curves of these pavements are shown in Figure 6. The Maintenance Control Index[7] (MCI), which indicates the degree of road surface deterioration, is obtained from rut depth, cracking ratio, and longitudinal smoothness. It is used in deciding whether the pavement needs repair.

A perfect road surface has an MCI of 10, and as the road surface deteriorates this value decreases. A road surface immediately after opening to service will have an MCI of 8 to 9, and a desirable control level is $\mathrm{MCI} \geqq 5$. An MCI of $\leqq 3$ calls for immediate repair.

The method for repair and renovation of the pavement is to implement milling and overlay when the MCI value becomes lower than 4, and to fully replace the As layer at the earliest year of subgrade failure by the As layer according Table 3. Predictions of the pavement conditions are performed according to the prediction formula[8] from the Pavement Management Assistance System. This formula was produced by performing multiple regression analysis on data such as rut depth, cracking ratio and smoothness that are collected by road surface inspection vehicle. Those data were classified into two categories: pavement design daily traffic volume, and region, and the multiple regression analysis was performed for both categories.

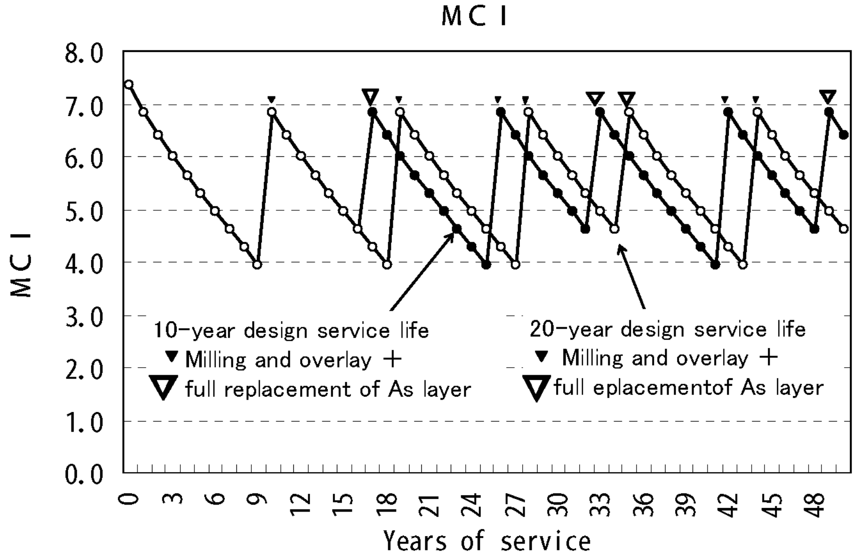


Figure 6: MCI calculated according to the 10-year and 20-year design service life

The road administrator costs estimate, for initial construction, repair, and renovation, will be shown in Figure 7.

For a 20-year design service life pavement, the As layer is 2 cm thicker and the granular subbase is 5 cm thicker than that for a 10-year design service life pavement, and this makes the initial construction cost slightly higher for the 20-year pavement. However, extension of the period up to when the As layer needs replacement from fatigue failure reduces the total renovation cost, which makes 20-year design service life pavement more economical than 10-year design service life pavement.

Estimates of the increase in vehicle travel costs for daily traffic volume 6,977 vehicles/day (heavy traffic : 1,432vehicles/day , light traffic : 5,545vehicles/day)resulting from deterioration of the road surface, calculated from the relationship between MCI and travel cost[9] are shown in Figure 8. Pavements with 10-year and 20-year design service life both require milling and overlay. However, the pavement with a 10-year design service life has a shorter replacement cycle; therefore, 10-year design service life pavement has superior surface conditions and slightly reduces vehicle travel costs.

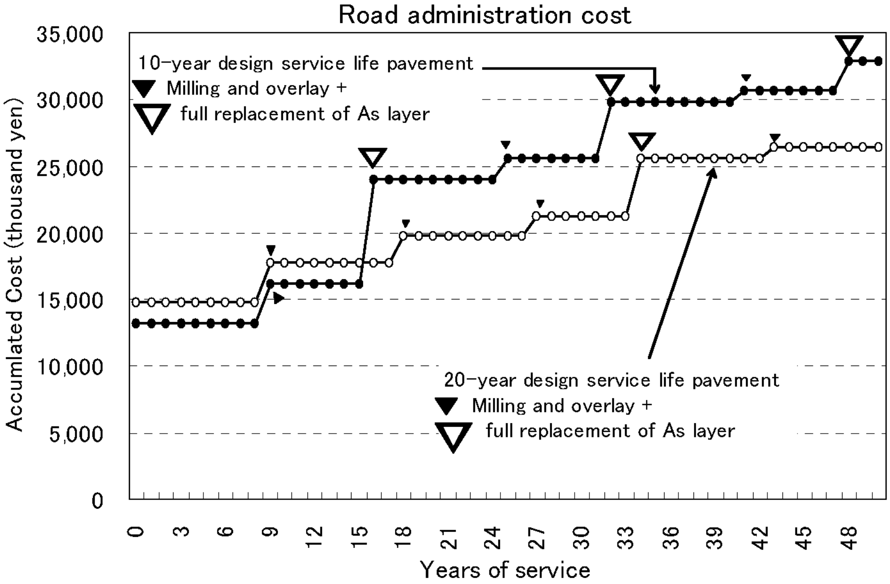


Figure 7: Road administrator costs calculated according to 10-year and 20-year design service life pavement

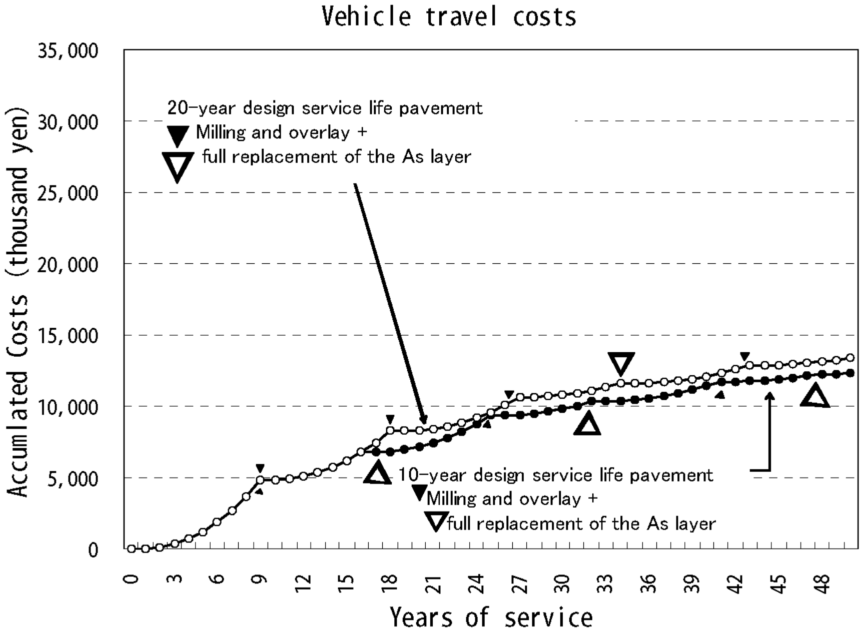


Figure 8: Vehicle travel cost calculated for 10-year and 20-year design service life pavement

The losses incurred under traffic restrictions from roadwork have been estimated according to the time value basic unit price$^{10)}$ and fuel loss basic unit price$^{11)}$ as shown in Figure 9. The loss of time is obtained with the travel time delay due to construction set at 2 minutes. The loss from increased fuel cost is obtained under the assumption that the travel speed of 60 km/h will be reduced to 20 km/h at the section under construction. With the 20-year design service life, traffic restrictions will be reduced; therefore, the 20-year design life is more economical than the 10-year design life.

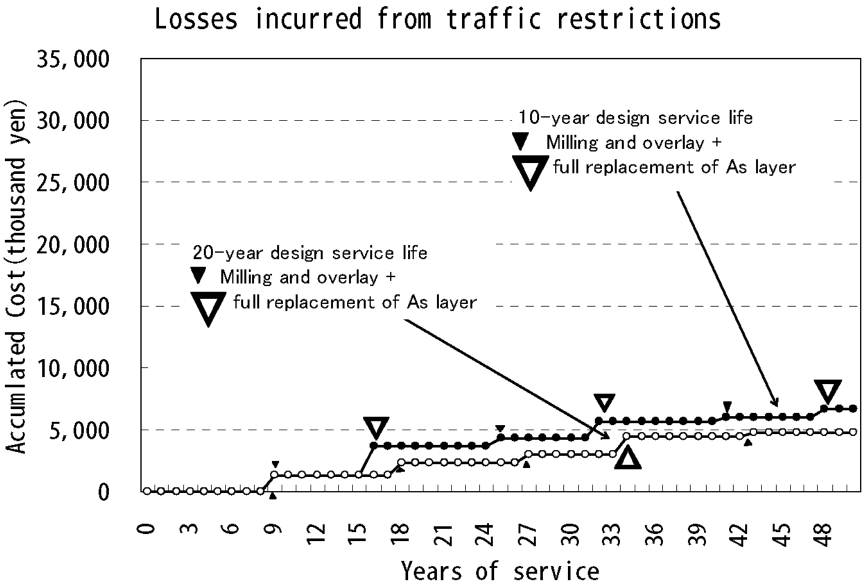


Figure 9: The losses incurred under traffic restrictions calculated for 10-year and 20-year design service life pavement

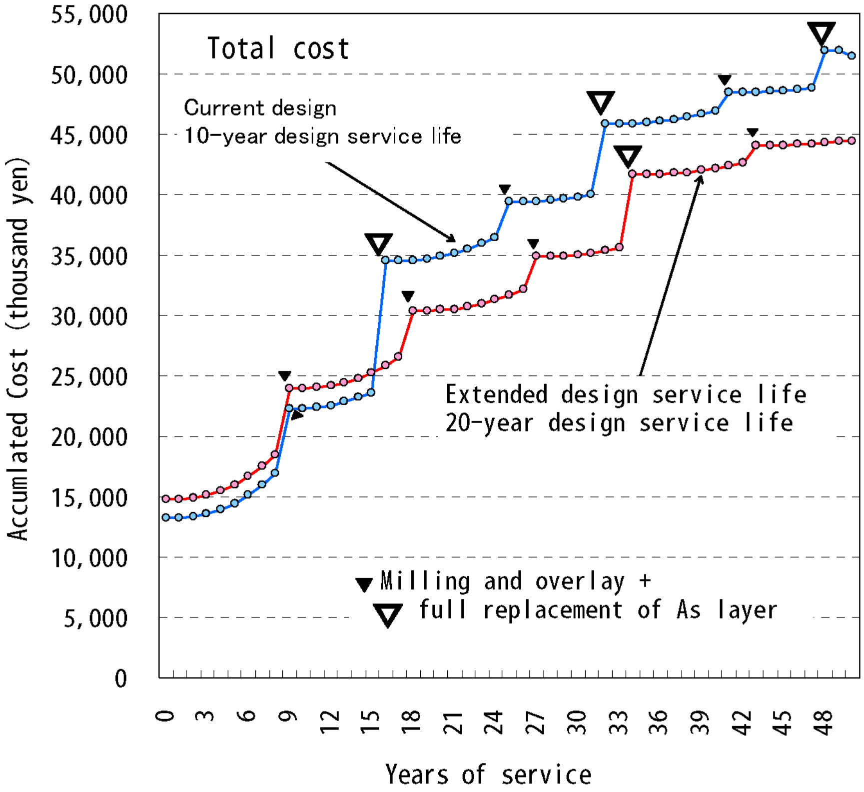


Figure 10: Total costs calculated for 10-year and 20-year design service life

The life cycle cost calculated by totaling these road administrator costs, vehicle travel costs and losses incurred from the roadwork traffic restrictions are shown in Figure 10. It shows that the 20-year design service life is more economical than the 10-year design service life and confirms the cost-reductions afforded by extending the life span.

8. CONCLUSION

The effects on the reduction of LCC and the pavement structure resulting from an increase in the design service life from 10 years to 20 years were considered. Together with this, by reconsidering the need for a wear course, as well as the replacement thickness that is sufficient to prevent frost heave and the appropriate design CBR for the subgrade, the following have become apparent.

(1) Since the use-ban on studded tires, there has been less wear on pavements in Hokkaido, and the need for the wear course is decreasing.
(2) As the thickness of the As layer decreases, there is a greater tendencies for low-temperature cracking to occur.
(3) For roads with a service life of 20-year probability in Hokkaido, the overall average replacement thickness should be approximately 4 cm greater than that for 10-year probability.
(4) In deciding the design CBR of subgrade soil for economical structural design in cold regions, it is preferable to use the CBR value after freeze-thaw, in light of the bearing capacity reduction of the subgrade soil that occurs during the thawing period.
(5) The case study showed that the total costs are less for a pavement profile a with 20-year design service life than for one with a 10-year design service life, and that the LCC reduction comes from extending the life span.

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