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Performance of Highly Ductile Modified Asphalt for Use in Impervious Facing Zone

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ABSTRACT :
New asphalt bitumen was developed in order to improve the flexibility nature of asphalt mixture to have much more resistance against strong earthquake. Extensive laboratory tests successively brought about new materials for impervious facing zone of earth dams, having high ductility under low temperature and cyclic loading conditions, and also having sufficient resistance against flow under high temperature. Repair works with this new asphalt mixture was made in an earth dam, which was severely damaged by cracking in a medium-scale earthquake, for all area of the impervious facing zone. Around five years after the repair works, follow-up surveys were conducted to examine the performance of the asphalt impervious zone. The surveys include inspection on surface damages, interior survey of the pavement with the electromagnetic wave radar, and several laboratory tests on samples taken in the field. The results then revealed that the repaired asphalt impervious zone had been thoroughly in satisfactory conditions without any sign of deterioration by aging. This paper summarizes such performances of the modified asphalt mixture observed in the repair works and the subsequent follow-up surveys.

Keywords: Modified Asphalt, Impervious Facing Zone, Remedial Work, Follow-up Survey

1. INTRODUCTION

Asphalt mixture has often been adopted in Japan for use as a material for impervious facing zone of earth dams and levees, in view of its high flexibility to allow large deformation during earthquake. With Its much excellent natures of flexibility and low permeability, the use of asphalt mixture as an impervious material has been considered advantageous and successful, and in fact severe damages and extensive repair works for leakage of water had hardly been experienced (Sugawara, 1993). As more than 40 years had passed since asphalt-based impervious wall and zoning was introduced in Japan, some damages due to dilapidation and/or deterioration have often been reported in old facilities constructed at the time. These are, for instance, slope flow, peeling, wearing and tearing by snow-ice, and deterioration by ultraviolet rays of protection layers in facing and lining facilities (Ono et al., 1993, Doi et al., 2002). Other types of damages are opening of construction joints, large differential settlement in embankment and cracking in the impervious zone due to earthquake forces (Matumoto, et al., 1985, JSCE, 1997, Ohne, et al., 2003).

A medium-scale earthquake happened in 1996, causing severe damages in the asphalt facing impervious zone of an earth dam. Many cracks appeared on the slope surface especially near the crest and on the bottom surface of the reservoir, though the dam body itself was scarcely damaged. In planning allover repair for this surface cracking, new asphalt bitumen was studied to develop in order to improve flexibility nature of asphalt mixture to have much more resistance against stronger earthquake. Extensive laboratory tests then brought about new material for impervious zone having high ductility under low temperature and cyclic loading conditions, and also having sufficient resistance against flow under high temperature. Repair works with this new asphalt mixture was made at the dam for all area of the impervious facing zone, in three years from 2003 to 2006.

In August 2011, around five years later the repair works, follow-up surveys were conducted to study performance of the improved asphalt impervious zone. The surveys include inspection of surface damages, interior survey of the pavement with the electromagnetic wave radar, and several laboratory tests on samples taken in the field. The results revealed that the repaired impervious zones were thoroughly in satisfactory conditions without any sign of deterioration by aging. This paper summarizes such performances of the modified asphalt mixture observed in the repair works and subsequent follow-up surveys.

2. ASPHALT FACING EARTH DAM DAMAGED BY EARTHQUAKE

2.1. Dam Dimensions and Facing Structures

The damaged earth dam was constructed in 1971 for irrigation purpose in Shizuoka prefecture, southeast of Tokyo. Fig.1 illustrates the standard cross-section of the embankment and the pavement structures of the facing zone, the pavement thickness being 24cm along sloping surface and 14cm at the bottom of the reservoir.

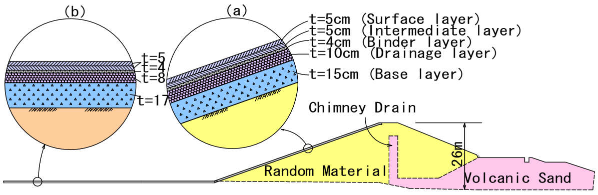


Figure 1. Dam cross-section and pavement structure

2.2. Summary of Earthquake

The East-Yamanashi earthquake of M5.8 happened at midnight on March 3 in 1996, with its epicenter located nearby Kawaguchi Lake, about 15km north from the dam. The maximum accelerations recorded by seismographs in the dam site were 85gals at the base and 380gals on the crest of the dam. According to the data observed by the Meteorological Agency (EL468.00), the temperature at the earthquake event was 1.3℃ and zero at 23pm and 24pm, respectively. Because the dam site is situated on EL670.00, being 202m higher than the observatory, the temperature at the dam site can be estimated to be zero to -1.3℃, considering its elevation difference. Incidentally, the reservoir table was around two-third of the full water level at the time of earthquake.

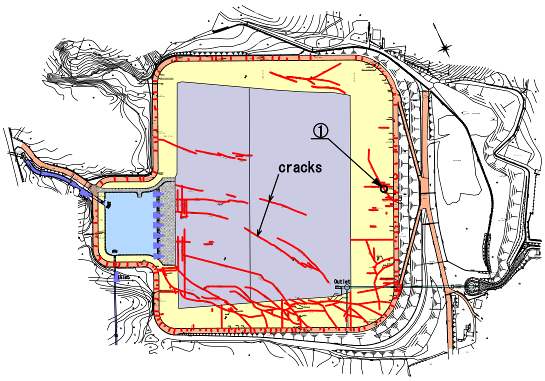


Figure 2. Plan view of reservoir and cracking damages

2.3. Damage Conditions of Asphalt Facing

As taking the reservoir level down after the earthquake, extensive surveys were conducted on the circumference of the reservoir, the embankment body and the reservoir bottom. Although the dam body itself was scarcely damaged, many cracks were detected over the asphalt facing zone of the embankment slope and the reservoir bottom, as shown in Fig.2. The locations of cracking and the total extension lengths of cracks observed in the site are summarized in Table 1. On the slope surface, most of cracks appeared running across the slope, having the maximum width of 10 to 15mm. Fig.3 shows a few core samples taken from the cracks. The maximum depth of cracks reaches to about 10cm, and most of them penetrated to the extent of the surface impervious layer.

Table 1. Cracking locations and extensions

Location of cracking	Total extension (m)
Facing zone	Slope: 2,088 Bottom: 1,649 (Total: 3,737)
Intersection of coffer dam and facing zone	131
Intersection of facing zone and crest	1,297
Crest road	845

Figure 3. Core samples taken from ① in Fig.2

3. REPAIR WORKS OF ASPHALT FACING

3.1. Development of Highly Ductile Modified Asphalt

Asphalt is generally known as a material having different phases, from liquid state to solid one, corresponding to its temperature. Such temperature dependent state change is evaluated as a character of temperature susceptibility. The asphalt with high susceptibility must be easy to flow at high temperature situation in summer, and that with low susceptibility to be much brittle at low temperature in winter. The latter asphalt is considered favorable in general for use in the pavement for its good performance in service, though the former one, easy to soften in high temperature, is predominant in view of mixing process of asphalt mixture and its field placement conditions.

Highly ductile modified asphalt, here denoted bellow as HPAs , adopted for use in the repair works of the dam was developed to obtain higher resistance of the facing against earthquake, by improving its ductility to endure high rate cyclic excitation. The concept of improvement then laid emphasis on high ductility at low temperature by reducing temperature susceptibility stated above.
The fundamental properties of HPAs are compared in Table 2 with straight asphalt 60/80, denoted by StAs60/80 below, which is usually used in pavement

construction. It is recognized that HPAs has higher test values both in penetration ratio and softening point. The index PI, which is calculated by the above two indices, expresses the temperature susceptibility. The value of PI of asphalt usually used in pavement construction ranges from -1.5 to -0.5, and the susceptibility is considered higher as the index PI gets lower value taking in the minus side. It is therefore concluded that HPAs has much more low susceptibility against temperature, the value being 9.3 in HPAs as compared with -0.95 in StAs60/80. The coefficient of viscosity measured at 60 degrees, which roughly corresponds to the temperature at the surface of the asphalt pavement road in summer season, is an index property to represent consistency of asphalt, indicating remarkably high resistance of HPAs against plastic flow deformation. In addition, the bending strain measured at -10 degrees of HPAs showed eight times as much as that of StAs60/80, which represents very high flexibility in low temperature conditions.

Table 2. Fundamental properties of Asphalt

Item	Unit	HPAs	StAs60/80
Penetration ratio	1/10mm	177	69
Softening point	℃	84.0	48.0
Flash point	℃	321	316
Viscosity at 60℃	Pa・s	11,300	208
Bending strain at -10℃	($\times 10^{-3}$)	384	49
PI	—	9.3	-0.95

Table 3. Results of compression tests

Temperature at test ℃	Asphalt	Stress at failure σ_{cf} (Mpa)	Strain at failure ε_{cf}(mm/mm)	Modulus of elasticity E_{cf}(Mpa)
5	①StAs	17.19	0.0116	1,482
	②HPAs	6.49	0.0851	76
	②/①	0.38	7.34	0.05
0	①StAs	24.42	0.0089	2,744
	②HPAs	8.47	0.0679	125
	②/①	0.35	7.63	0.05
-5	①StAs	32.59	0.0062	5,256
	②HPAs	12.01	0.0398	302
	②/①	0.37	6.42	0.06

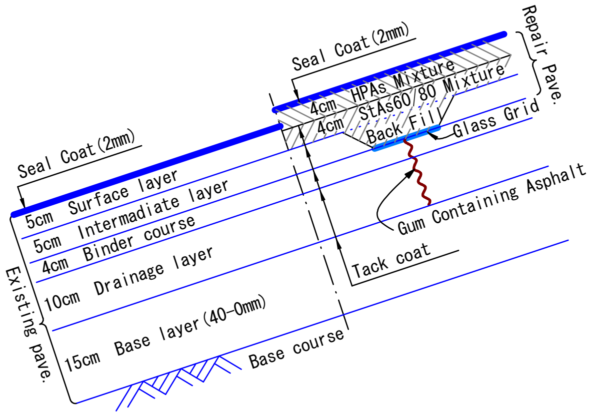
Table 4. Mix proportion asphalt mixture (%)

Amount of asphalt	Plant fiber	Proportion of aggregate (by weight)				
		Crushed stone #6	Crushed stone #7	Coarse sand	Fine sand	Filer
8.5	0.15	24.0	16.5	37.5	8.0	14.0

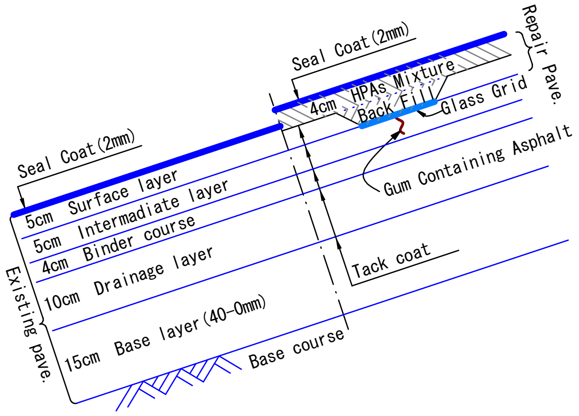
Table 3 compares the results of unconfined compression tests on samples composed of both HPAs and StAs60/80 asphalt, where specimens were prepared by cutting out in a column of 60mm×60mm×150mm in size, and tested under three different temperature conditions -5, 0, 5℃ at a constant strain rate of 0.01 (1/sec). The mix proportions of asphalt mixtures tested are listed in Table 4. It should be noted in the ratio of the measured values of HPAs to StAs60/80, the value of ②/① in the table, that HPAs is much superior in ductility, irrespective of temperature, taking around one order difference in the stress at failure σ_{cf} by about 0.4, the strain at failure ε_{cf} by about 7.1 and the modulus of elasticity E_{cf} by about 0.05.

3.2. Planning of Repair Works

As cracking was widely spread over the facing zone of the embankment slope and the reservoir bottom, and some cracks were noticed penetrating through the surface two layers of pavement of the impervious zone, the repair works were basically conducted by adopting the cut and overlay procedure, where new asphalt pavement is placed after cutting and removing whole old pavement. The cross-sections of the facing zone to be repaired were then planned, according to the frequency and the depth of cracking, by dividing the area into the northern and southern parts of the reservoir, as presented in Fig. 4.



a) Section for south part



b) Section for north part

Figure 4. Cross-sections of repaired facing zones

The standard section adopted for the southern part is illustrated in Fig. 4a). The repair work is planned to conduct in the following sequence; 1) the surface layer is cut and removed by 1 cm in thickness because asbestos was included at the time of construction of the existing asphalt pavement. 2) The layer is moreover removed by 4 cm, and overlaid with the asphalt mixture of StAs60/80 in 4 cm. 3) the asphalt mixture of HPAs is subsequently overlaid in 4 cm and followed by surface treatment. At the point where cracking reached to the intermediate layer, additional treatments are required in the process as, cutting the pavement along the crack, filling it with gum containing asphalt, and back filling with a material to prevent reflection crack such as glass grid.

In the northern part, on the other hand, the asphalt mixture of HPAs is directly overlaid in 4 cm to cover the surface after the removal process of 1 cm thick, as shown in Fig. 3b); that is, the processes of 4 cm extra cut and the subsequent 4 cm overlay with the asphalt mixture of StAs60/80 are cut down. At the point where cracking reached to the intermediate layer, penetrating into the upper surface of stone sheet, additional treatments are planned by cutting the pavement with a margin of 4 cm along the crack and, after back filling with the StAs60/80 mixture, HPAs mixture is overlaid and followed by the final surface treatment.

3.3. Repair Works

The repair works were conducted first by cutting and removing the old pavement, see Fig. 5, and then by overlaying new asphalt pavement, see Fig. 6. In whole process of works along the embankment slope, a winch machine called by Winch-porter was set on the crest to draw up and down the cutting machine, the asphalt finisher and the vibration roller, which were specially prepared for works on sloping surfaces. In overlay works, the placement of new asphalt mixture composed of high performance HPAs was successfully done without any trouble, similarly as in the case of the usual mixture.

Figure 5. Cutting & removing process

Figure 6. Overlay pavement

4. FOLLOW-UP SURVERYS

The follow-up surveys were carried out while the reservoir was in service, so that along the upper part of the embankment slope from the fluctuating water table to the crest. The surveys include 1) inspection survey on the surface damages of the facing zone, 2) investigation of the interior of the asphalt pavement with the radar, and 3) laboratory tests on samples and core specimens taken in the field. The procedures and the results of these surveys are summarized below, to evaluate field performance of the improved asphalt impervious zone, at the time of around five years after the repair works,

4.1. Inspection Survey of Surface Damages

By walking around the reservoir, surface damages of the facing zone were detected by inspection, and recorded them in details for every item of damage pattern, location at occurrence, scale of damage and so on. According to the investigation reports on other facing type dams, damage patterns frequently observed are cracking, slope flow and blistering, so that the inspection this time was also done mainly for these representative patterns.

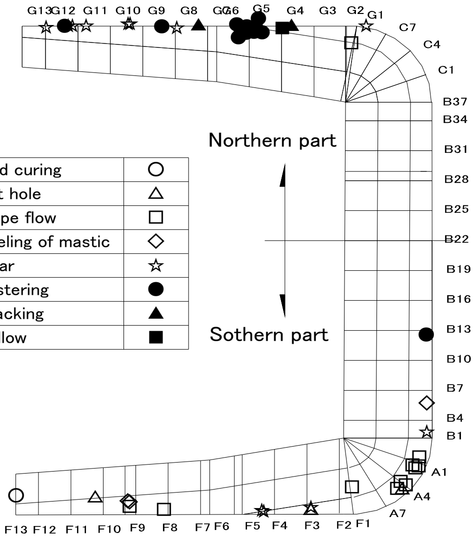


Figure 7. Location of damages

Table 5. Summary of inspection survey

Location	Damage pattern	Region	Number
Sothern part 22 locations	Mud curing	Protection layer	1
	Pot hole	Protection layer	3
	Slope flow	Protection layer	10
	Peeling of mastic	Protection layer	3
	Wear	Protection layer	4
	blistering	Impervious layer	1
Northern part 25 locations	Slope flow	Protection layer	1
	Wear	Protection layer	8
	blistering	Impervious layer	13
	Cracking	Impervious layer	2
	Hollow	Impervious layer	1

Results of the inspection survey are presented in Fig. 7 and in Table 5, summarizing location of damages and detail item records. Figs. 8 and 9, respectively, show example damages appeared in the field of slope flow and blistering. Total number of damages detected was 47 points, 30 of them in the protection layer and 17 in the impervious layer. The frequency and level of these damages were recognized rather usual, similarly found in other earth dams, and not so serious to affect on the essential function of the impervious zone. Comparing the southern and northern parts of the reservoir, frequency of damages was almost the same. In the southern part, most of damages occurred in the protection layer, and very few worse conditions such as blistering, which usually appear in the early stage of service, were noticed in the impervious layer. In the northern part, on the contrary, blistering was found at many points in the impervious layer, but the damage situation was considered, judging from experience, not so severe and irregular.

One of the reasons of these differences might be thought largely based on the difference in cross-sections adopted at the repair works, as already noted in Fig. 4. In the southern part of repair, after removing the existed surface layer, the regular asphalt mixture of StAs60/80 was first placed, and then the new asphalt mixture of HPAs was subsequently overlaid. In the northern part, on the other hand, the new mixture was overlaid after removing only the protection layer to cover the existed surface layer. Deterioration by aging of the remaining existed layer is supposed ready to come out to the surface and to be one of influential factors to cause higher level of damages observed in the northern part of the facing zone.

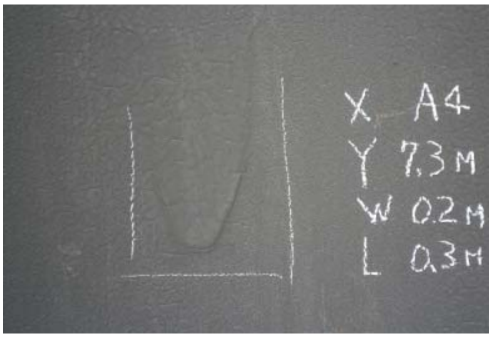


Figure 8. Slope flow in the protection layer

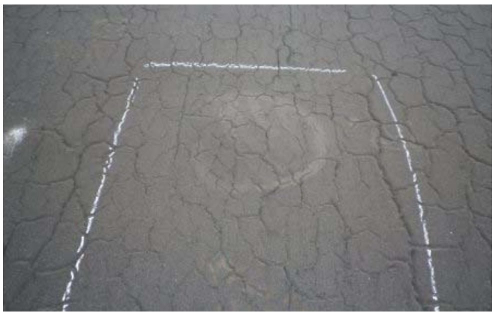


Figure 9. Blistering in the impervious layer

4.2. Interior Survey of Pavement

Interior survey of the impervious zone was made to confirm existence of trapped water and cavity in the pavement and its extent, by utilizing the electromagnetic wave radar. The measurement system of the radar is shown in Fig. 10. The system consists of the transmitter part, which radiates pulse wave of about 1 nano-second (10^{-9} second) into the ground through the antenna, and the receiver part to get its reflection wave. Some part of radiation wave is reflected directly at the ground surface, and the remaining enters into the ground and reflected at the surface of the substance having different electric properties, relative permittivity, from surrounding ground.

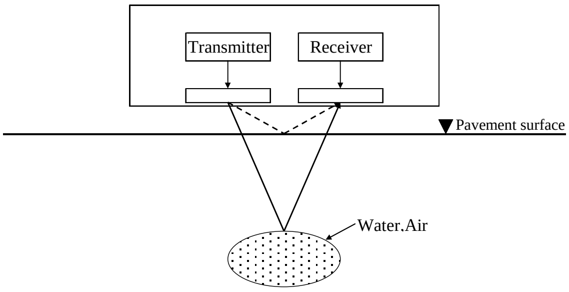


Figure 10. Measurement system of radar survey

The depth d (cm) to the surface of the detected object can be calculated from relative permittivity (ε_γ) and reflection time t (sec.), by the following Eq. 1, where c_0 denotes the rate of transmission of the electromagnetic wave under vacuum (2.997×10^8 m/s), and $v=c_0/(\varepsilon_\gamma)^{1/2}$ means the rate through the medium of the object.

$$d = \frac{v \times t}{2} = \frac{c_0 \times t}{2\sqrt{\varepsilon_\gamma}} \tag{1}$$

The measurement was done in the area where damages had been detected by inspection survey, at the points of intersection of lines parallel and normal to the dam axis drawn in a specified distance, as indicated in Fig. 11.

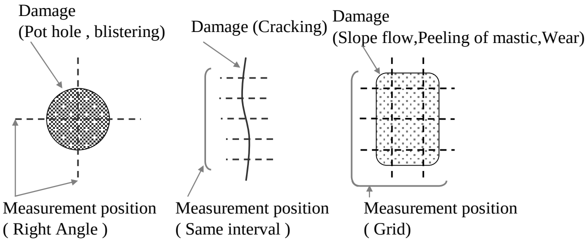


Figure 11. Measurement points of radar survey

The results of wave radar survey generally revealed satisfactory performance of the facing zone. In the northern part of the facing zone, however, some trapped water was found at a few points, between the overlaid layer and the existed pavement, where blistering had been detected in the inspection survey. This situation is considered natural, because blistering may happen under the condition that water is trapped in some reasons in the pavement as placed or in service and evaporates and expands in volume at high temperature during summer.

4.3. Laboratory Tests on Field Samples

In order to confirm extent and degree of deterioration of the impervious zone during service, laboratory tests were conducted on samples taken in the field, as follows.

4.3.1. Unconfined compression test

Test samples were taken at the time of the repair works as a part of quality control tests of pavement. Specimens were cut in 30mm×30mm×80mm, and tested under a temperature conditions of 5℃ and at a strain rate of 0.01 (1/sec).

The strains at failure measured in this series of compression tests, 5yrs after service, are compared with those of quality control tests made at the time of construction, as in Table 6. It is seen that the failure strains of 5yrs after service show almost equal values irrespective of locations, and also with those measured at construction without any remarkable difference. It is then concluded that deterioration and ductility loss by aging of the impervious zone are not so serious to be worried.

Table 6. Stain at failure (compression test)

Location	Strain at failure (mm/mm)
Southern part, at construction	0.089
Southern part, 5 yrs after service	0.085
Northern part, at construction	0.084
Northern part, 5 yrs after service	0.094
Average, at construction	0.087
Average, 5 yrs after service	0.090

4.3.2. Stress relaxation test

In the stress relaxation test, a beam specimen in a state fixed on both ends is forced to reduce its temperature at a constant changing rate, and to be broken apart by tensile stress developed in the specimen. The temperature at failure, called by the ultimate temperature of stress relaxation, is evaluated in this test. The test was done on specimens of 25mm×25mm×250mm, from the initial temperature of 10℃ at a rate of -3℃/hr.

The values of the ultimate temperature measured in the tests are listed in Table 7. It is recognized that the test values are almost equal irrespective of locations and duration experienced, and that deterioration by aging is not in an extent to be concerned as noted similarly in the former compression test.

Table 7. Ultimate temperature of stress relaxation

Location	Ultimate temperature (℃)
Southern part, 5 yrs after service	-31
Northern part, 5 yrs after service	-31
At development	-30

4.4. Summary of Follow-up Surveys

(1) Relatively good performance was observed in general in the inspection survey. Especially in the southern part of the reservoir, worse conditions such as blistering were scarcely noticed.

(2) The results of wave radar survey revealed satisfactory performance of the facing zone, though trapped water was found at a few points in the northern part. The extent and level of these damages are considered ordinarily acceptable.

(3) Laboratory tests on samples taken in the field also showed good performance in the required properties for high rate deformation and stress relaxation at low temperature, so that deterioration and loss of ductility by aging are not in an extent to worry about.

(4) General remark is then drawn from the above that the impervious zone repaired with the new asphalt mixture of HPAs reveals rather favorable performance and keeps fairly sound conditions even after five year service.

5. CONCLUDING REMARKS

In an earth dam with asphalt facing impervious zone, which had been suffered from severe earthquake cracking damages, new asphalt bitumen was developed and the repair works were done by use of this modified asphalt mixture, to get much more ductile and resistance to endure stronger earthquake than encountered. In the follow-up surveys conducted around five years later, the repaired asphalt impervious zone was thoroughly in satisfactory conditions both on the surface and in the interior. Test results also showed fairly good performance in ductility and to temperature change, without any sign of deterioration by aging. It should be emphasized moreover that none of damages had appeared in the dam and its impervious facing zone against a much stronger earthquake of the intensity 6- that happened in March 2011. Successive long term follow-up surveys are required in the future to evaluate and confirm the efficiencies of the newly developed asphalt of HPAs.

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