Efficient repairing and reinforcement method for AFRD damaged by the earthquake

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ABSTRACT

We developed the effective repairing method for asphalt facing of the Yashio dam, asphalt facing rock fill dam (AFRD) constructed for the upper reservoir of the Shiobara pumped storage power plant of Tokyo Electric Power Company Holdings, where cracks occurred by the 2011 Tohoku earthquake, to complete repairing works in a short period so as to resume power generation immediately. The developed repairing method was consisted of asphalt mastic using asphaltic material developed for the purpose of improving deformation performance under a low temperature, hereinafter we call it “low elastic asphalt”, and asphalt impregnated non-woven sheet. We completed the repairing works in about only one month, because we limited the removing area by covering the low elastic asphalt mastic of 10 cm width and 5 cm thickness, as a buffer part absorbing the strain, on the cracks leaving in the layer underneath from the forth layer to the bottom layer of the asphalt facing consisted of seven layers. In addition, it was estimated that the cracks occurred by the strain concentration of the crest concrete block joint connecting the asphalt facing, the facing near the concrete block joints were also reinforced using low elastic asphalt mixtures.

1. INTRODUCTION

The Yashio Dam, an asphalt facing rock fill dam (for the upper regulating reservoir of the Shiobara Pumped Storage Power Plant of Tokyo Electric Power Company Holdings, Inc.) suffered cracks in its asphalt facing when the 2011 Tohoku Earthquake occurred. To meet power demand after the earthquake, it was necessary to restart Yashio Dam power generation as soon as possible. Accordingly, an efficient crack repair method promising adequate functional restoration was developed and applied to the cracked wall surface, allowing repair work to be completed in a short period of time. The major cause of cracking was inferred to be concentration of strain at the block joint of the crest concrete connected to the asphalt facing, and so corresponding reinforcement work was also performed. This paper describes the results of the investigations that were performed for the purpose of developing the above repairing and reinforcement method.

2. CONDITION OF CRACKS CAUSED BY THE EARTHQUAKE

2.1 Introduction

A standard cross section of the Yashio Dam is shown in Figure 1, and the structure of the asphalt facing is shown in Figure 2.The maximum acceleration observed at the Yashio Dam when the 2011 Tohoku Earthquake occurred was 53x10^{-2}m/s^2 at the foundation (in the left/right bank direction) and 253x10^{-2}m/s^2 at the center of the crest (in the stream direction). Water leakage from the facing, which had not been observed before the earthquake, increased to approximately 300 liter per minute at maximum, and cracks in the facing were discovered in the subsequent visual inspection.

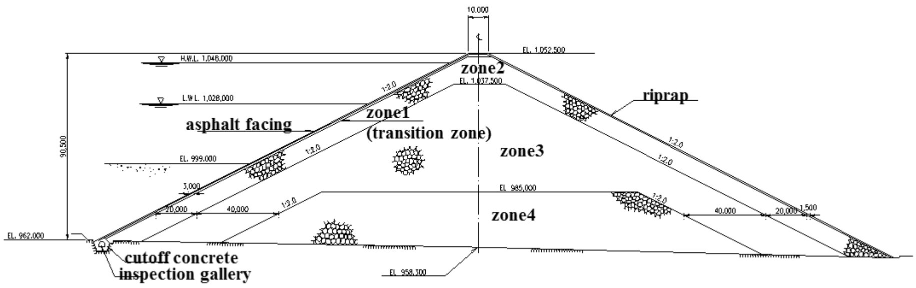


Figure 1. Cross section of the Yashio dam

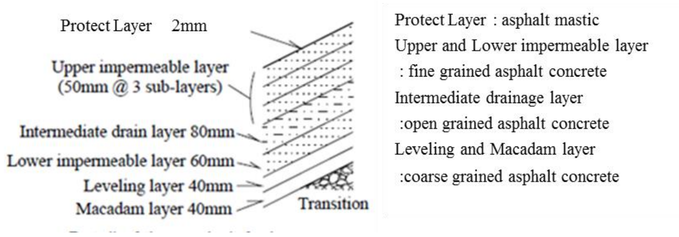
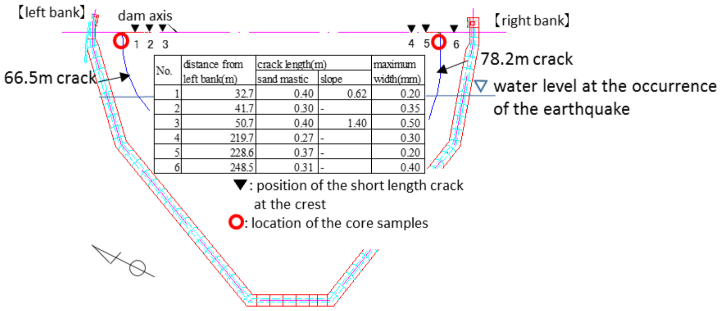


Figure 2. Detail of asphalt facing of the Yashio dam

2.2 Results of crack investigation

The cracks in the asphalt facing confirmed by inspection are as shown in Figure 3 and Figure 4. There were two cracks of length approximately 70 to 80 m in the left and right bank almost parallel to the both abutments, and a total of six short cracks—of maximum length less than 2 m—were also found. All these corresponded to the position of the joints of the concrete blocks connected to the facing at the crest. From near the crest down to the lowest of the seven layers of the facing, a borehole of diameter 500 mm was drilled into the position of the long crack on each side. From the boring cores obtained, it was confirmed that the cracks near the crest reached the lowest layer (Figure 5). Hence, it became necessary to study repairing methods on the assumption that each crack reached the lowest layer along its entire length.

Figure 3. Asphalt facing of the Yashio dam right after the earthquake



No.	distance from left bank(m)	crack length(m)		maximum width(mm)
		sand mastic	slope	
1	32.7	0.40	0.62	0.20
2	41.7	0.30	-	0.35
3	50.7	0.40	1.40	0.50
4	219.7	0.27	-	0.30
5	228.6	0.37	-	0.20
6	248.5	0.31	-	0.40

Figure 4. Location of main and minor cracks

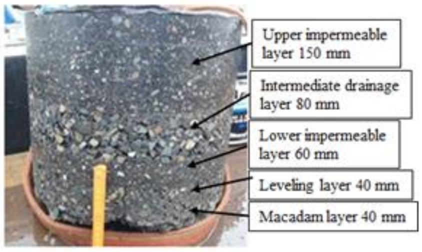


Figure 5. Core sample of the facing

2.3 3D-dynamic reproduction analysis and inference of factors leading to crack occurrence

3D FEM dynamic analysis was performed using the equivalent linearization method in order to reproduce the behavior of the Yashio Dam during the earthquake and infer the factors leading to crack occurrence. However, the cause of the cracking could not be determined by this means, since the analysis revealed that the maximum strain occurring in the facing did not match the crack positions, and that the strain was relatively small, being less than one tenth of the fracture strain of the material. Nevertheless, since the cracking corresponded to the position of the joint of the concrete block connected to the crest section, it may be assumed that the concrete block behaved rigidly, causing intensive strain at the joint (as shown in Figure 6); this being the case, then, analytically, where the cracks initially occurred, fracture strain would be exceeded in the facing, and in the sand mastic (with a still higher level of deformation performance) used in the joint. This was therefore inferred to be the cause of cracking (Tsukada,T et al. 2013).

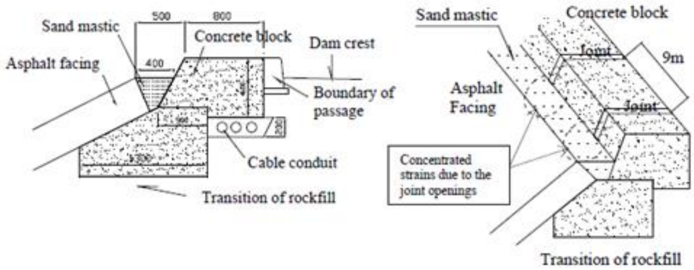


Figure 6. Facing structure at the dam crest

3. STUDY OF CRACK REPAIRING METHOD

3.1 Selection of repairing material and method

Under the low temperature high strain rate conditions of the 2011 Tohoku Earthquake (ambient temperature approximately −5 °C), the reduced deformation performance of the asphalt mixture used for facing was one of the factors resulting in damage. As a typical repairing for asphalt facing layer damaged by the earthquake damage to asphalt facing,we may cite the use of modified asphalt(Super Flexphalt)-developed to exhibit high extensibility even at a low temperature-as a repair material for dense graded asphalt mixture.(herein after SF)This has been used successfully in the Higashifuji (Nakamura,Y et al. 2007) and Futaba Dams(Shimazaki,M et al. 2011 & Kojima,T et al. 2009), both of which are asphalt facing fill dams. One option was to remove all the cracked areas and replace them with the similar material, as in the above cases. However, the earliest possible restart of the Shiobara Pumped Storage Power Plant was required in order to cope with the power shortage that began in the immediate aftermath of the Earthquake, so that rapid restoration of the Yashio Dam was a matter of urgency.

As an emergency measure taken at the Yashio Dam to cope with power demand after the earthquake, asphalt impregnated non-woven fabric sheets were used to ensure water blocking capability, as shown in Figure 7. These sheets are normally used for roads, and prevent the formation of reflection cracks in the overlayer when overlaying has been performed to cover cracks or concrete joint etc. The effectiveness of the sheet has been confirmed by past experiment (Nishikawa,T et al. 2001). In addition, asphalt mastic using the earlier mentioned SF was applied to the cracks in order to prevent expansion of the crack width during the low temperature period occurring at night. Using this repairing method, emergency repairing work was completed in a period of around 2 weeks. Furthermore, after completion, absolutely no water leakage was observed even when the water level rose or fell as a result of power generation or water pumping. Hence, impermeability of the facing was maintained.

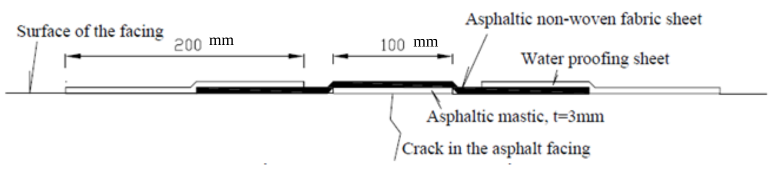


Figure 7. Temporary repairing

Following this, it was decided that permanent restoration be planned in order to cope with increase in power demand in the summer. However, since not much time was left until summer, the permanent repairing work had to be completed in the shortest possible time. With regard to the approach to paving the facing of the Yashio Dam, the construction joints between adjacent paving lanes shall be separated by at least 50 cm from those on the next layer up and down (i.e., no construction joints coincided with those on the upper and lower layers). If this rule were applied to the cutting and removal of existing paving and re-paving, the construction area would be extremely large, as shown in Figure 8, resulting in a long construction period and rendering it impossible to complete the work before the summer.

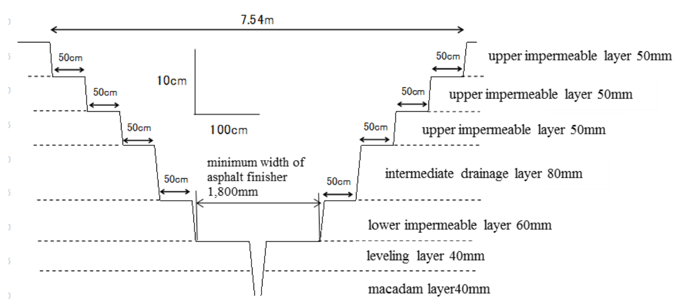


Figure 8. Cross section of repairing work in case of removing all layers around the crack

While the most effective option for reducing the construction period would be to minimize the area of cutting and removal around the cracking, if the material of the facing was cut and removed from a small area down to the bottom layer, then there would be a localized concentration of weakness in the removed section. Therefore, in order both to limit the required work period and avoid weakness, we considered a structure in which the cracks below a certain layer are allowed to remain, whilst also preventing those cracks from affecting the layers above. As shown in Figure 9,the method we proposed therefore involved cutting and removing the material around the cracks down to the depth of the two upper impermeable layers, cutting out the cracks in the third layer along a width of approximately 10 cm, and filling with asphalt mastic that uses SF(herein after SF mastic). Since it was feared that reflection cracks may occur in the upper layers, it was decided to place down asphalt-impregnated non-woven fabric sheets—which were used in the emergency repairing work—in order to prevent drooping (flow) of SF mastic after application, and so that they would function as a covering for the upper layer paving. The reason for cutting and removing only the three upper impermeable layers was that a negative impact on drainage performance was considered likely—due to clogging caused by fine particles generated from cutting—if material down to the intermediate drain layer were cut and removed.

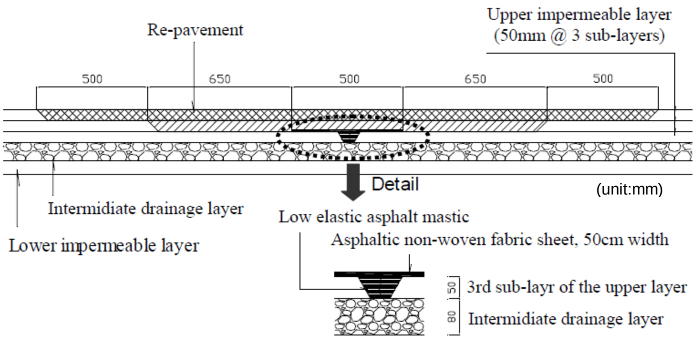


Figure 9. Cross section of repairing work for the upper impermeable layer

It was decided that a flow inhibitor be used for asphalt mastic filling so that, while repairing work was being carried out, flow of the mastic and infiltration into the intermediate drain layer below would be prevented. The flow inhibitor chosen to be mixed into the mastic is a plant fiber that is effective for decreasing the slope flow even at high temperature.(Kainuma,N et al.1995)

For SF and filer to be used as the asphalt mastic filled into the groove of the 10 cm wide cut, the weight ratio was determined based on the compositional ratio of the asphalt mastic used in the protect layer of the existing facing wall. With regard to the mixing ratio of the flow inhibitor, it was important to set this correctly so as to avoid any degradation of drainage performance caused by flow of the material during application on a slope or entry into voids in the intermediate drain layer (open-graded asphalt mixture) lying below the point of application. Three weight ratios, i.e., none, 3%, and 5%, were tested in the laboratory, as shown in Figure 10, and the relevant ratios (case1 to case3) are shown in Table 1.

Table 1. Composition of the low elastic asphalt mastic

	Composition(%)		
	Asphalt	**Filer**	**Plant fiber**
case1	40	60	0
case2	40	57	3
case3	40	55	5

The test results showed that there was significant flow of the mastic with no plant fiber, and that the mastic became too viscous to ensure even mixing and workability when 5% was added. As a result, a weight ratio of 3% (case3) was adopted.

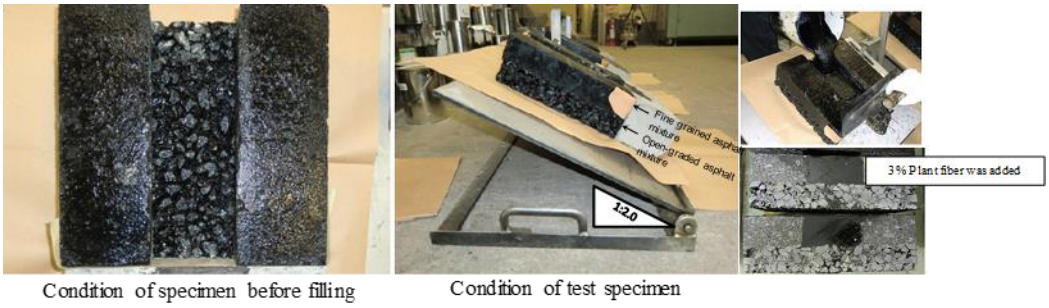


Figure 10. laboratory tests of low elastic asphalt mastic

3.2 Dynamic properties of material used in repairing method

For SF mastic, a bending test (under the condition of -15 °C and strain rate of 10^{-2}1/sec, they are corresponding to large earthquake in winter) showed that strain under the peak stress was 0.36, which is approximately 180 times that of the 0.002 fracture strain of fine grained asphalt mixture. It was confirmed that after the stress level reached a peak, no fracture occurred even though the material was deformed to a strain level of approximately 0.5. A bending test was conducted to check the reinforcing effect provided by the sheet-reinforced fine grained asphalt mixture. The test results showed that, with sheet reinforcement, strength and fracture strain were both approximately twice that without reinforcement. A possible explanation of this is that the sheet disperses the strain (stress) at the lower edge of the beam, which reduces the strain (stress) at the center.

3.3 Dynamic properties of repairing method

Next, an experiment was conducted to examine the effect on a composite structure simulating the actual section to be repaired. Hence, a specimen was prepared as simulated the method used for the Yashio Dam that assuming the cracks were left. Then the bending test was conducted assuming that the left cracks will open in the layers below the intermediate drain layer. Since it constitutes a relatively thin membrane with respect to the body of the dam, the facing is assumed to behave integrally with the dam body, so that strain occurs as it follows the deformation of the dam body's upstream surface. Therefore, assuming that displacement is transmitted from the lowest layer of the facing, a bending test simulating the repairing work was conducted to confirm its ability to follow such deformation of the dam body as would open the cracks remaining in the lower layer of the facing. As shown in Figure 11, a specimen was prepared to model, in the cross-sectional direction of the facing, the second upper impermeable layer, third layer with a central 10 cm wide groove filled with SF mastic, and intermediate drain layer. Slits were created in the intermediate drain layer to simulate the cracks, and loading was applied to the center of the upper edge so that the slits would open. For comparison, the same test was conducted on another specimen simulating the existing section without slits. The resulting load-displacement curves are shown in Figure 12, and it was confirmed that no fracture occurred until the deflection reached three times that at which the specimen simulating the existing section fractured. When loading was continued further, fracture occurred in the upper part of the fine grained asphalt mixture at its boundary with the asphalt mastic, but the connection between the fine grained asphalt mixture and asphalt mastic maintained its close adhesion.

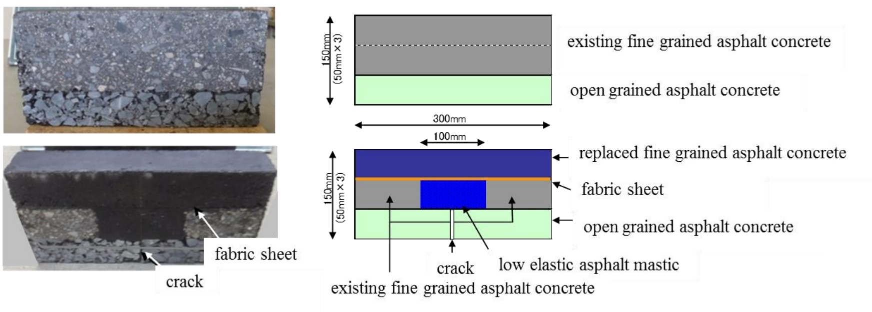


Figure 11. Outline of the bending tests of repairing structure

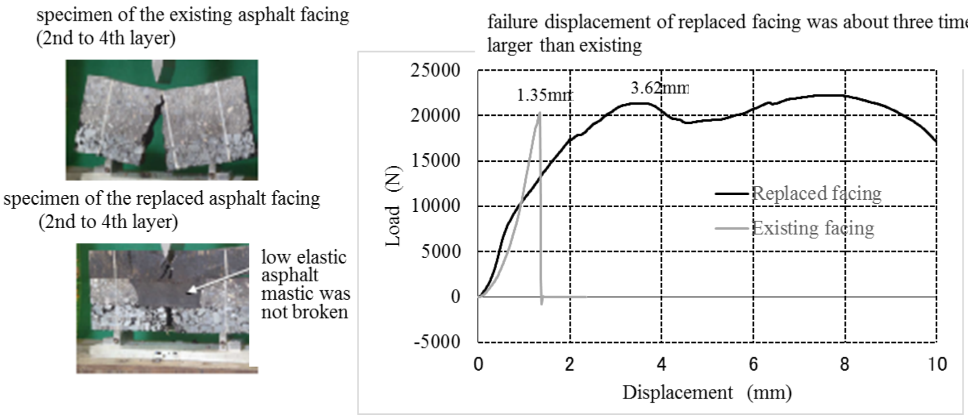


Figure 12. Results of the bending tests of repairing structure

4. REINFORCEMENT WORK

As stated earlier, it is believed that, in the 2011 Tohoku Earthquake, the Yashio Dam suffered cracks due to concentrated strain in the concrete block joints located at the crest, and that these cracks were developed down the slope. As a solution, we studied a structure that is capable of making the facing resistant to damage even when a concentration of strain occurs at the joints.

According to 3D dynamic analysis, the force of the 2011 Tohoku Earthquake caused the crest concrete joints to open to a width of approximately 1 mm, but we developed our design to allow the structure to follow a joint displacement of approximately 50 mm, taking major earthquakes into consideration and looking from the perspectives described below:

- The crest of CFRDs, including the Ishibuchi Dam, settled by several tens of centimeters after the Earthquake.(Matsumoto,N et al. 2016) In consideration of the firm compaction of the dam body of the Yashio Dam due to its careful construction, the relevant displacement with respect to a major earthquake is of the order of a few centimeters, and our goal was to create a structure capable of following this level of displacement.

- Gaps of around 50 to 100 mm were filled with the mastic as part of the crack repair work, and it was considered desirable to limit the width to approximately 100 mm in order to ensure adequate workability (including drooping of the material during work). Hence, if filling a width of 100 mm, the allowable displacement is approximately 50 mm (note that the maximum strain at which no fracture occurs, as confirmed by SF mastic bending test, was 50% (strain of 0.4 at the stress peak (−15°C and a strain rate of 1×10^{-2} 1/sec))).

To study the structure of the reinforcement work, FEM elastic analysis was performed on a two-dimensional model in the axial direction of the dam simulating the case of a 50 mm wide gap in a crest concrete block joint.

With respect to the structure before reinforcement, forced displacement was applied to the crest concrete joint at the lower part of the facing near the crest in order to examine the occurrence of strain in various parts of the facing, as shown in Figure 13. White arrows in Figure 13 indicates the displacement of 50 mm at the crest concrete joint. This indicated the occurrence of a large amount of tensile strain over a wide area. However, when SF mastic was applied at the joint over a width of 100 mm as joint filler, strain concentration occurred at SF mastic, and strain in the surrounding area was reduced. Nevertheless, since strain exceeding the fracture strain (2.3×10^{-3}) of the fine grained asphalt concrete of the existing structure occurred near the boundary with SF mastic, it was judged that the area around SF mastic needed to be replaced by a material with high deformation performance. Fine grained asphalt mixture using SF—as a material with high deformation performance—was therefore utilized, due to its successful use in the Higashifuji dam and Futaba dam.

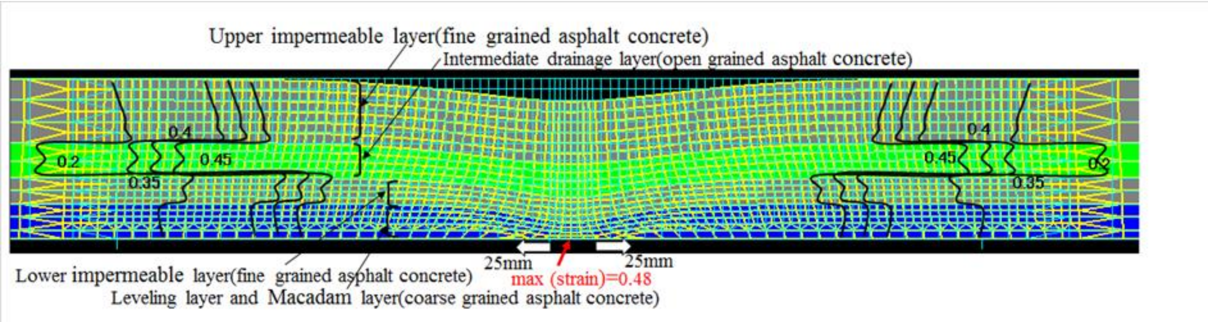


Figure 13. Result of FEM analysis (existing asphalt facing model)

The mix design of the fine grained asphalt mixture using SF was performed in the same procedure as with the conventional method. Hence, in order to ensure adequate water insulation (a void ratio of 3% or under), limitation of slope flow, and flexibility, the amount of asphalt was set to 8.2%, and the mix ratios of the constituent materials to the values shown in Table 2.The additional ratio of plant fiber was 0.2% of the mass of asphalt mixture to satisfy with both slope stability and flexibility.(Kainuma,N et al.1995 & Shimazaki,M et al. 2011)

Table 2. Mix proportion of the low elastic fine grained asphalt concrete

Material	Crushed stone (13-5mm)	Crushed stone (5-2.5mm)	Roughing sand	Screenings	Filer	Plant fiber
Ratio(%)	23.5	11.5	36.5	18.5	10	0.2

The results from a bending test using fine grained asphalt mixture of the above mix ratio indicated a fracture strain of 0.66% at a temperature of −15°C and strain rate of 1 × 10−2 1/sec. This is approximately three times the value for the existing fine grained asphalt mixture.

Whilst changing the regions over which replacement with fine grained asphalt mixture using SF is performed, elastic analysis with 2D FEM was conducted in order to investigate the strain distribution in the facing caused by displacement of the opening (50 mm) at the joint. The results showed that when SF mastic was applied over a width of 100 mm at the upper part of the joint and an area of 400 mm on each side of this 100 mm width was replaced by fine grained asphalt mixture using SF, the resulting strain did not exceed the fracture strain of either material, as shown in Figure 14, and the design was shown to be capable of following tensile strain of up to 50% in the asphalt mastic section.

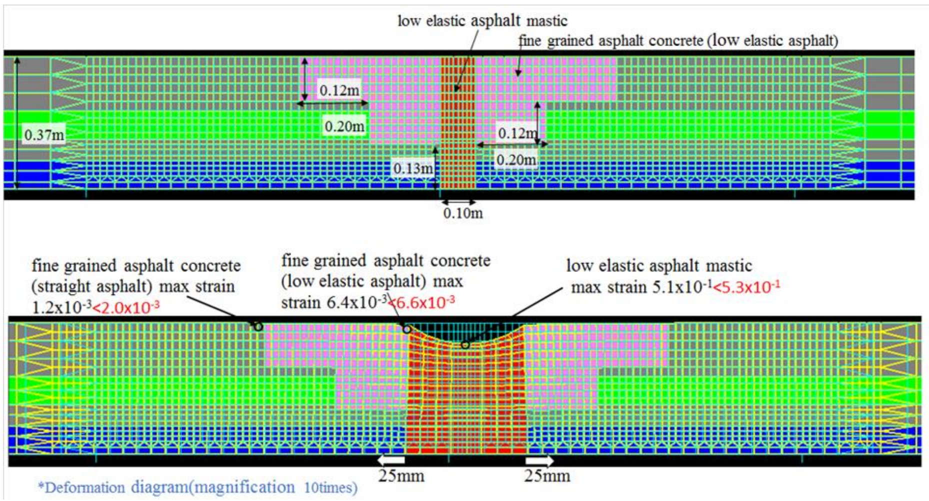


Figure 14. Result of FEM analysis (reinforced structure model)

The physical properties assigned to each material in the analysis are shown in Table 3. The reinforcement structure near the crest concrete of the Yashio Dam, developed based on these analysis results, is shown in Figure 15.As explained above, use of SF as joint filler achieves the capability to follow strain of up to 50%, and so may be regarded as useful in the construction of new dams of the same type or as a method of improvement for existing dams of the same type in which there is a concentration of strain.

Table 3. Physical properties used in the FEM analysis

Mixture	Use	Modulus of Elasticity (N/mm2)	Poisson's ratio	Tensile failure strain (%)	Analytical maximum tensile strain (%)
Existing fine grained asphalt mixture	Upper impermeable layer	4,020	0.25	0.26	0.12
Existing open grained asphalt mixture	Intermediate drainage layer	1,560	0.3	0.16	Less than 0.12
Existing coarse grained asphalt mixture	Macadam leveling layer	3,505	0.3	0.2	Less than 0.12
SF mastic	Filling over the joint	14	0.25	53 or more	51
SF fine grained asphalt mixture	Repaving	1,417	0.25	0.66	0.64

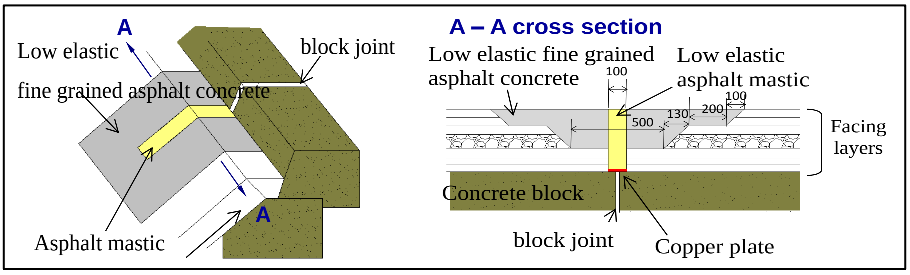


Figure 15. Structure of the facing around the crest concrete block joints

5. RESULTS FROM ACTUAL USE

5.1 Repairing work

The repairing work of the cracks of the Yashio Dam started with cutting of the left bank on April 16, 2011 and was completed with application of the protective coating to the repaired areas on May 22, 2011. An outline of the repairing work is shown in Figure 16. A low water level was maintained in the reservoir during the repairing work to allow cutting of the cracked sections down to the bottom of the cracking. In order to ensure efficiency and quality, cutting was performed using a cutter designed for slope work and an asphalt finisher, and this allowed the cut to be made in the form of a strip. Developed view of the repairing work are shown in Figure 17. Since completion of repairing work, no drainage has occurred from the intermediate drain layer, and no anomalies have been observed on the surface, so that the integrity of the repairing has been confirmed. However, we will continue to perform measurement, monitoring, and visual inspection.

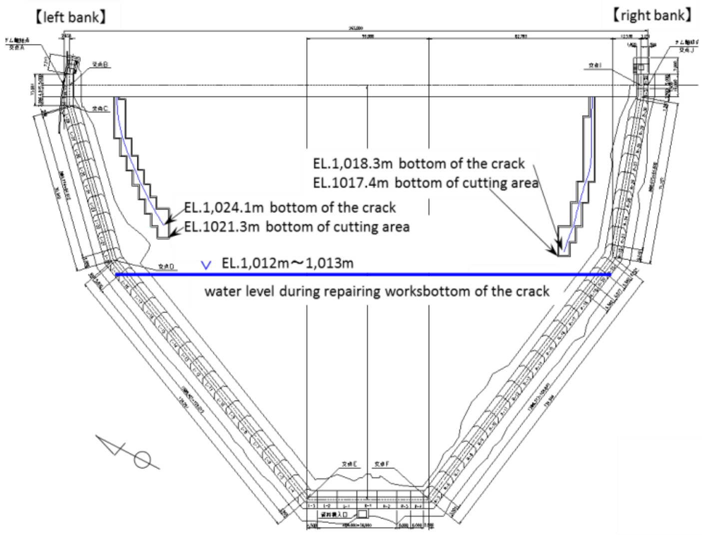


Figure 16. Developed view of the repairing works of the facing

Figure 17. Situation of the repairing works

5.2 Reinforcement work

Reinforcement work for the crest concrete started on October 22, 2012, and was completed on January 31, 2013. Pictures of the reinforcement work are shown in Figure 18.

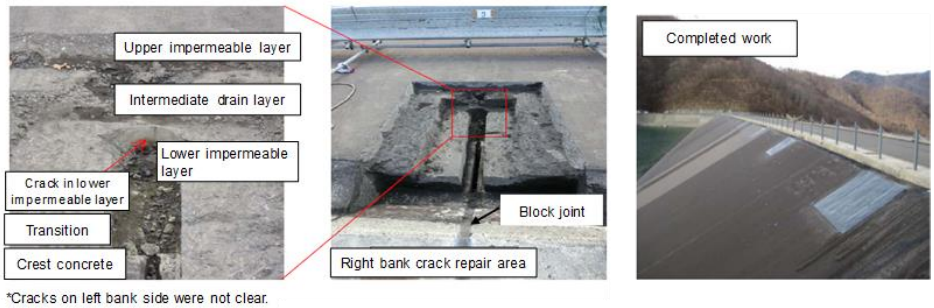


Figure 18. Situation of the reinforcement works of the facing around the crest

6. CONCLUSION

- Compared to ordinary asphalt materials, SF mastic ensures high deformation performance against the large tensile strain, even in severe low temperature and high strain rate environments. In addition, since it does not fracture even after the peak stress has been reached, its use as joint filler at the connections between facing and different types of structures (such as concrete) enables the creation of a structure capable of mitigating the large strain concentrations generated when a major earthquake occurs. The test, conducted under conditions of −15°C and a strain rate of 1×10^{-2} 1/sec, revealed that the material did not fracture at a tensile strain of approximately 0.4, reached at the time of peak stress, nor thereafter up to the maximum tensile strain of approximately 0.5.

- Since the cracks in the lower layers were not removed, sheets designed to control reflection cracks were used (which have proved practically effective for roads), with asphalt-impregnated unwoven fabric sheets being selected in consideration of their low permeability.

- Asphalt-impregnated non-woven fabric sheets improve the deformation performance of the fine grained asphalt.

- When asphalt mastic using SF and anti-crack sheets are used, the resulting structure ensures that even though cracks occur in the lower layer they are largely prevented from spreading upwards. The bending test under conditions of −15°C and a strain rate of 1×10^{-2} 1/sec confirmed that the structure has a deformation performance which is approximately three times that of the existing structure.

- As a solution to the opening of crest concrete block joints, asphalt mastic using SF was applied to the upper part of the joint as joint filler, and fine grained asphalt mixture using SF was used to replace the surrounding material. As a result, the improved structure was able to resist up to 50% tensile strain, constituting a significant improvement in deformation performance.

- The proposed reinforcement structure may serve as a useful option for the construction of new dams of the same type, or for improvement of the seismic performance of existing dams of the same type in which there is a concentration of strain.

7. ACKNOWLEDGEMENTS

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