Case Studies in Construction Materials 7 (2017) 305–316

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Short communication

Investigation of asphalt core-plinth connection in embankment dams

Weibiao Wang*, Shan Feng, Yingbo Zhang

Xi'an University of Technology, 5 Jinhua South Road, 710048 Xi'an, China

ARTICLE INFO

Keywords:
Embankment dam
Asphalt core
Concrete plinth
Connection
Sandy asphalt mastic (SAM)
Model test

ABSTRACT

The asphalt core itself is a no-joint water barrier in embankment dams and is connected to the concrete plinth on the bottom of the core. A reliable asphalt core-plinth connection is crucial and must remain watertight when the core deforms due to deformations in the embankment and foundation and due to reservoir water pressure. A large number of tension tests were conducted to determine the best ratios, joint thickness and suitable additives for the sandy asphalt mastic (SAM) mix used for the connection. With the ratios of bitumen to filler to sand of 20%:35%:45% and by adding 4% SBS in the bitumen, one got a very suitable composition for the asphalt core-plinth connection in tensile conditions. Model tests were conducted to study the connection behavior when subjected to large shear displacements and high water pressure. The joint model test results indicate that the plane-surface plinth, curved-surface plinth, and plinth with or without copper water-stop showed no significant difference for the connection in the joint shear behavior. However, plinth with copper water-stop is suggested to enhance its tensile and shear behavior.

1. Introduction and background

The asphalt core type embankment dam (ACED) with its many advantages has been applied worldwide since 1960s. Among the completed asphalt core dams, the Storglomvatn Dam in Norway and the Yele Dam in China were the highest until 2017, both with a dam height of 125 m [1,2]. In recent years, many investigations and applications for asphalt cores in embankment dams have been done. Wang and Höeg [3] proposed a simplified material model for analyzing asphalt cores in embankment dams based on extensive long-term creep triaxial test results. Wang and Höeg [4] as well as Akhtarpour and Khodaii [5] studied the cyclic behavior of asphalt concrete used as impervious cores in embankment dams for dam sites located in seismic regions. Zhang et al. [6] investigated the conditions that hydraulic fracturing would take place for asphalt cores in very high embankment dams and concluded that hydraulic fracturing would be of no concern. Asphalt concrete used as water barrier in dams provide watertightness, cracking resistance, and self-healing properties [7]. With the experience gained from research and field experience, the dam height of ACEDs has reached a level of more than 150 m. The 174 m high Quxue Dam was completed in February 2017 in China and other high ACEDs are under construction or under final design [8,9]. The 153 m high Zarema Dam is about to be completed in Ethiopia and the Moglicë Dam in Albania is in the early stages of construction and will be about 170 m high [9].

Asphalt core is placed and compacted layer by layer with transition zone on either side of the core with a compacted thickness of 20–25 cm to form a no-joint impervious wall protected by the transition zones in the embankment dam. The interface between asphalt core and transition zones play an important role to transfer stresses and deformations during the dam construction and

---

* Corresponding author.
E-mail addresses: wangweibiao59@hotmail.com (W. Wang), fs-sg3@yeah.net (S. Feng), zhangyb68@163.com (Y. Zhang).

http://dx.doi.org/10.1016/j.cscm.2017.09.002
Received 27 April 2017; Received in revised form 29 August 2017; Accepted 27 September 2017

reservoir impounding. The behavior of the interface of asphalt core-transition zone has not been investigated very much in the published literature. Tajdini et al. [10,11] studied the interface behavior between asphalt concrete and granular materials using direct shear tests. However, they used a small size 10 × 10 × 2.5 cm direct shear box with a cut smooth face of asphalt specimens for testing. The results and conclusions could have some limitations due the small sizes of the test box and the smooth face of asphalt specimens while the interface of the asphalt core-transition zone in a dam is rather rough and interlocked [12,13]. The authors have studied the interface behavior of asphalt core-transition zone in embankment dams using a large shear box with overlapping rectangular steel plates for an interlocking interface, and the results will be published in another paper [14].

In most of the ACEDs constructed so far, the asphalt core rests on a concrete plinth (sill), and the plinth is anchored to the rock foundation to serve as a cap for contact and curtain grouting. In cases where there is deep soil overburden, the plinth may rest on a concrete cut-off wall or jet-grouted wall.

The asphalt core width is conventionally in the range of 0.5–1.2 m, and the core width is doubled toward the contact with the plinth on the foundation and against the abutments. The asphalt core-plinth connection (joint) is crucial and must remain watertight when the core and plinth undergo deformations (displacements) during construction and dam operation. For situations with gentle abutment slopes the connection is subjected to compressive and moderate shear strains that are unlikely to cause any leakage [2,12,13]. Kruntcheva et al. [15,16] studied the layer interface behavior for asphalt pavements. However, the design requirements and purposes of the investigations for asphalt core-plinth connection in an embankment dam are quite different as the connection on steep abutments has to be designed to tolerate large shear and tensile deformations without cracking when the dam embankment and foundation settle during dam construction and operation [2,9]. Previous asphalt core-plinth connection model tests to simulate the conditions at the 125 m high Yele Dam, showed that no leakage was detected even if the shear displacement of the connection reached about 20 mm [2]. However, when the dam height is increased to more than 150 m, and the dam is located in a gorge with very steep abutments, special design considerations are required. An example is the 174-m high Quxue Dam with an abutment slope f 1V: 0.33H (72°) [8]. For that dam the connection on the steep abutment towards the top of the dam may be subjected to tensile strains and significant shear displacements. The asphalt core-plinth connection (joint) for the Quxue Dam was therefore subjected to special experimental investigations and evaluations. Fig. 1 shows the Quxue Dam under construction and the connection of the asphalt core on the steep plinth.

The asphalt core-plinth connection has a stiff concrete plinth on one side, sandy asphalt mastic (SAM) in-between, and asphalt concrete on the other side. The SAM normally consists of sand of either crushed aggregates or natural sand, filler (limestone powder) and different grades of bitumen. In some cases, the SAM contains additives to improve the SAM behavior. The surface of the concrete plinth should be dry and clean and is normally sprayed with a special coating in a quantity of 0.2 kg/m^2. The coating is a mixture of bitumen mixed with a small amount of gasoline to facilitate spraying and absorption by the surface of the plinth. After the plinth surface has dried and the gasoline in the coating has been fully volatilized, the SAM is sprayed and then asphalt concrete is placed and compacted. The SAM is the essential connection material to bond the stiff plinth and the flexible asphalt core. This paper presents the results of experimental studies of: (1) the effects of various ratios of bitumen to filler content, various ratios of filler to sand content and various types of additives in the SAM on the tensile behavior of the connection; (2) the effects of different thicknesses of SAM on the tensile behavior of the connection; and (3) different plinth surface shapes by model testing under large shear displacements and

Fig. 1. (a) The 174-m high Quxue Dam under construction; (b) asphalt core-plinth connection on the dam left abutment with a slope of 1 V: 0.33H (72°).

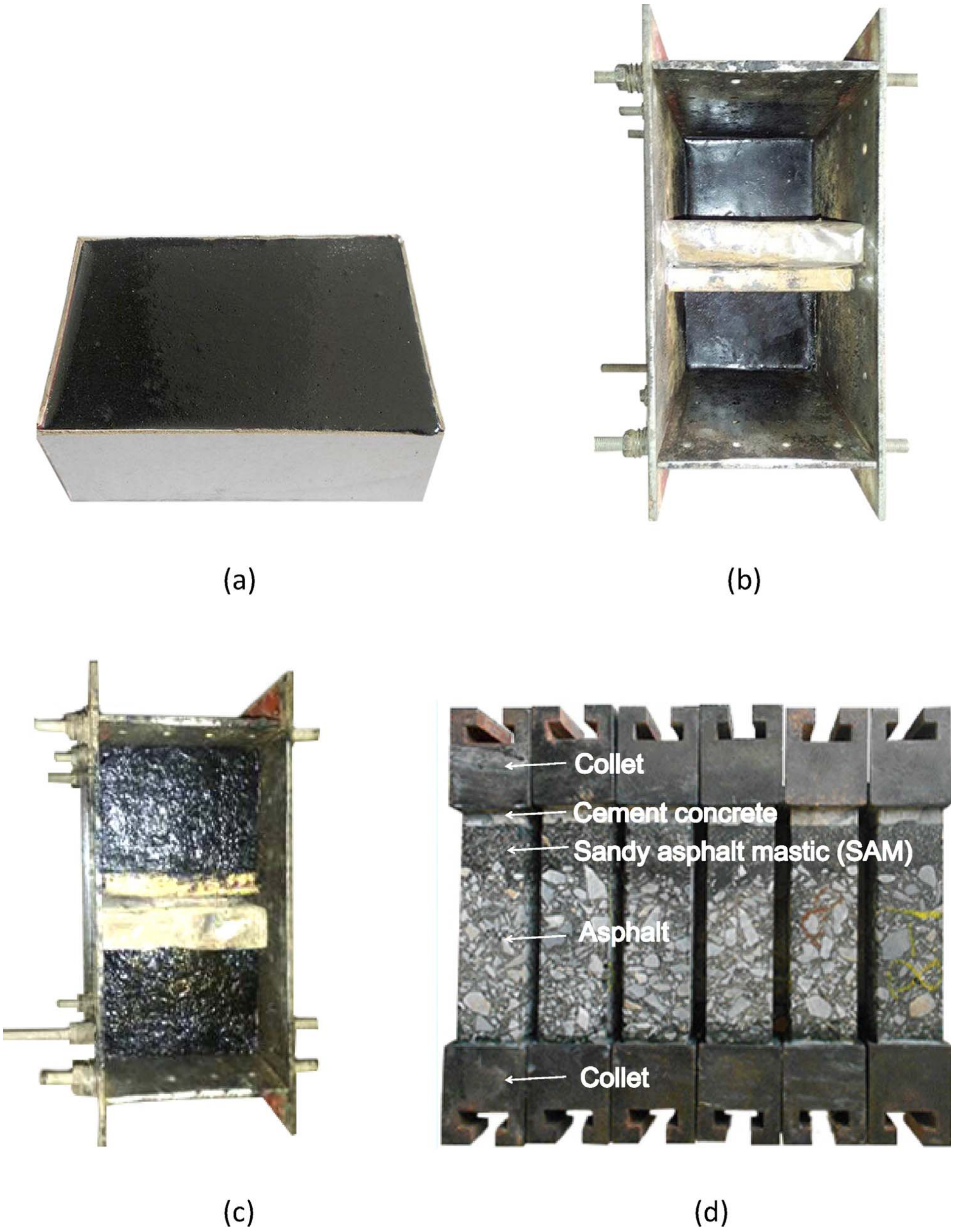

Fig. 2. Asphalt-SAM-concrete connection specimen preparation.

water pressure.

2. Test method and evaluation

In order to study the connection behavior concrete blocks were prepared with dimensions of 40 mm (thick) × 100 mm (wide) × 140mm(long). The sizes of the concrete blocks were determined with the aim to prepare 6 asphalt-SAM-concrete connection specimens after cutting. The surface of the blocks was brushed and made clean and dried and then sprayed with the coating. After the gasoline in the coating was fully volatilized the SAM was placed. The asphalt-SAM-concrete connection specimen preparation is shown in Fig. 2. Fig. 2(a) shows the top surface of a concrete block covered with a layer of SAM(20 mm thick); Fig. 2(b) shows the two concrete blocks covered with different ratios of SAM put on the bottom of the steel mould and separated with wooden plates; Fig. 2(c) shows the hot asphalt filled in the steel mould and compacted; and Fig. 2(d) shows after cooling the asphalt-SAM-concrete block with a section of 100 mm × 140 mm and 200 mm in length cut into six asphalt-SAM-concrete connection specimens, and the two ends of each of the six specimens fixed within the collets for tension testing. The specimen in the length direction was

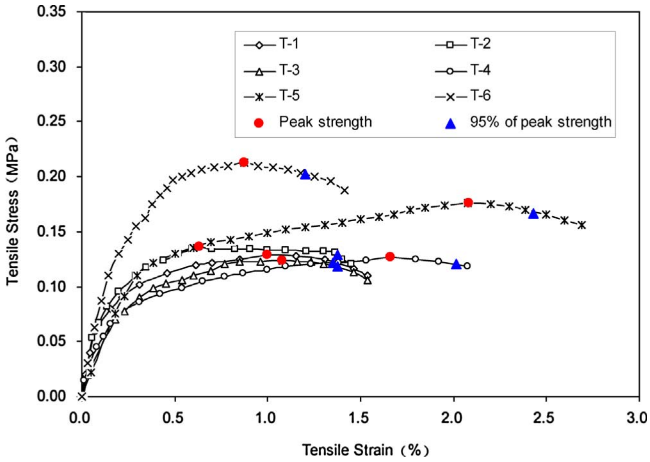

Fig. 3. Tensile stress versus tensile strain curves of 6 asphalt-SAM-concrete connection specimens.

140 mm for asphalt, 20 mm for SAM and 40 mm for concrete. The two ends of the specimens were fixed in the collets (30 mm in its cavity), and the effective length of the test specimen was 130 mm. The tension tests for the specimens were carried out at a displacement rate of 1.3 mm/min or a strain rate of 1.0%/min, and the tests were performed at a temperature of 15 °C.

Typical tensile stress versus tensile strain curves of six asphalt-SAM-concrete connection specimens are shown in Fig. 3. The SAM contained 2% tristearin by bitumen weight (see Fig. 7). Fig. 3 shows that five of the six specimens gave relatively equal stress-strain curves for strains lower than 1.0%, while the T-6 specimen gave higher tensile strength. When the hot asphalt with maximum aggregate particles of 19 mm was placed on the uniform SAM, a few large particles were unavoidably penetrated into the SAM that could cause the T-6 specimen to give higher tensile strength with smaller tensile strain. Asphalt and SAM behavior are very temperature-dependent and strain rate-dependent, and the tensile behavior of asphalt and SAM mainly depends on the binder (bitumen) property at 15 °C. Fig. 3 shows that the tensile stresses increased quickly under the strain rate of 0.1%/min, approached 70%–80% of peak strength within 0.4% tensile strain, and then the curves flattened. The peak strength occurred at somewhat random strain values. The strains at peak strength varied from 0.6% to 2.1% for the six specimens, and the average strain was 1.2%. The strains of the specimens mainly came from the 20 mm thick SAM, and all the cracks of the specimens occurred in the interface between the SAM and concrete after the peak strength had been reached. For the asphalt-SAM-concrete connection behavior the tensile strength is very temperature-dependent and strain rate-dependent. The temperature of an asphalt core is about 5 °C for embankment dams located in sub-arctic climate, and about 20 °C in sub-tropical climate [1–3,6,17]. Wang and Höeg [4] found the cyclic modulus to increase from 900 MPa at 20 °C to 2500 MPa at 3.5 °C in the cyclic strain range of 10^{-4}–10^{-3}. Gheibi et al. [18] carried out resonant column tests on asphalt specimens and found the dynamic shear modulus to be about 8000 MPa at 22 °C, being about 10000 MPa at 0 °C in the strain range of 10^{-8}–10^{-7}. At low strain rates or creep rates the strength of asphalt is significantly affected by the magnitude of strain rates while the strain at cracking is insignificantly affected [7]. The tensile stress of asphalt relaxes or dissipates very quickly with time due to the material viscosity and creep [7]. Therefore, the strain at which the interface of the SAM and concrete cracks is a main consideration. In this study, the peak strength and the tensile strain when the post-peak stress had reached 95% of the peak strength, were used for comparison among the test results. The temperature of 15 °C was used in the study based on the consideration that is the approximate average temperature for asphalt cores in operation for ACEDs in China. Fig. 3 shows that the strains at 95% of peak strength were from 1.2% to 2.4% and the average strain was 1.6% which was 33% larger than the average strain of 1.2% at peak strength. The irregular nature of the interface between the SAM and concrete caused a relatively large scatter in the data of tensile strength and strain, and therefore six specimens were used for the same test conditions to obtain a better understanding of the asphalt-SAM-concrete connection behavior.

3. Effect of various ratios of bitumen to filler content in SAM on tensile behavior of the connection

The SAM consisted of crushed limestone sand (maximum particle size less than 4.75 mm and with good gradation), limestone filler (95% passing the sieve size of 0.075 mm) and bitumen (B70). The grade of B70 has been widely used for bitumen in asphalt cores in embankment dams in China as B70 has higher quality than B60 in Chinese bitumen standards [19]. Several asphalt core embankment dams have used the ratios of bitumen to filler to sand for the SAM of 15%–25%:15%–40%:40%–60% [19]. As the ratios have not been systematically investigated so far, the content of crushed limestone sand was fixed at 65% by the SAM weight in the first series of tests, and the weight ratios of bitumen to filler were selected as 15/20, 20/15 and 25/10 to study the effect of ratio of bitumen to filler on the connection behavior. The asphalt-SAM-concrete connection specimens were prepared and tested applying the method described in Section 2 and shown in Fig. 2 for the three different SAM mixes. The tensile peak strength and strain at 95% of peak strength versus the ratio of bitumen to filler are shown in Fig. 4.

Fig. 4(a) shows that tensile peak strength was reduced from the average value of 0.34 MPa to 0.20 MPa when the bitumen content was increased by 5% (from 15% to 20%) and accordingly the filler content was reduced by 5% (from 20% to 15%) when the sand

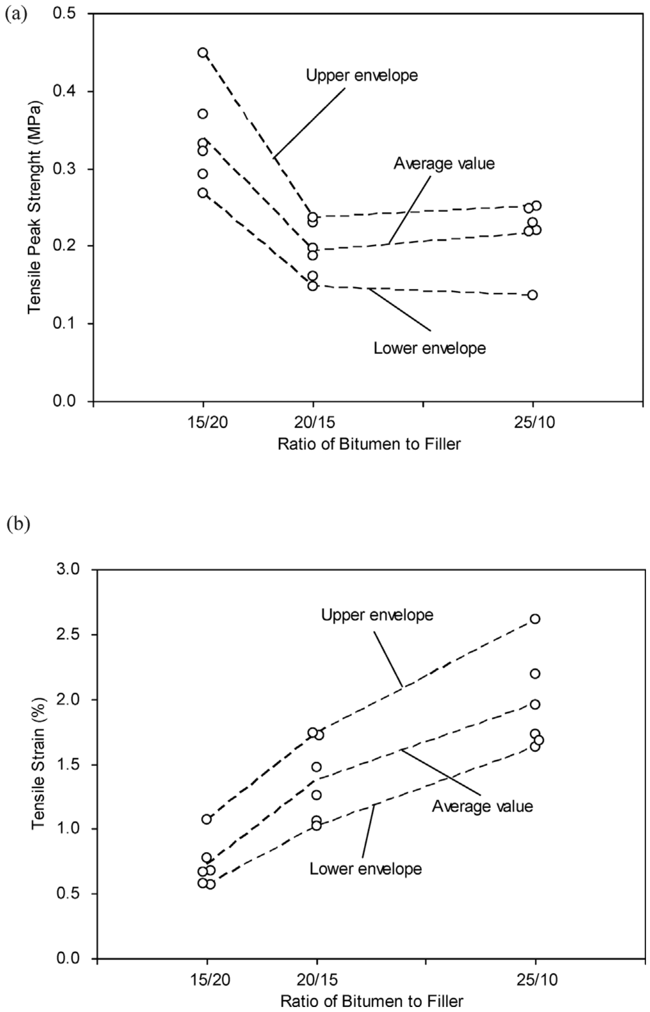

Fig. 4. Tensile peak strength (a) and strain at 95% of peak strength (b) versus ratio of bitumen to filler content under a constant sand content of 65% for the SAM in specimens.

content was fixed as 65%. When the bitumen content was further increased by 5% (from 20% to 25%) and the filler content was accordingly reduced by 5% (from 15% to 10%), the tensile peak strength was not significantly changed. The change was not a single parameter change for the test, as when bitumen content was increased the filler content was reduced and the behavior was affected by complicated coupling effects. That the tensile peak strength was significantly reduced for the first step of bitumen content increase and not for the second step could possibly be because the volume increase of the bitumen and filler (asphalt mastic) to a point that the sand had more effect on the strength reduction of the connection. Fig. 4(b) shows that the tensile strain at 95% of peak strength was increased from the average value of 0.7% to 1.4% to 2.0% when the bitumen content was increased from 15% to 20% to 25% and accordingly the filler content was reduced from 20% to 15% to 10%. When the SAM with a bitumen content of 25% with a thickness of 20 mm at a temperature of 150 °C was placed on a concrete block with a slope of 1V:0.33H (72°as for Quxue Dam) it was difficult for the SAM to resist downhill flow. When the bitumen content in the SAM was reduced to 20% the SAM was found to be stable on the slope. Therefore, the SAM with a bitumen content of 20% was selected for the following study.

4. Effect of various ratios of filler to sand content in SAM on tensile behavior of the connection

The bitumen content was fixed at 20% in the tests and the ratios of filler to sand content were selected as 15/65, 35/45 and 45/35. The asphalt-SAM-concrete connection specimens were prepared and tested applying the method described in Section 2 and shown in Fig. 2 for the three different SAM mixes. The tensile peak strength and strain at 95% of peak strength versus the ratio of filler to sand content are shown in Fig. 5.

Fig. 5(a) shows that tensile peak strength was increased from the average value of 0.20 to 0.27 to 0.47 MPa when the filler content was increased from 15% to 35% to 45% and accordingly the sand content was reduced from 65% to 45% to 35%. Fig. 5(b) shows the tensile strain at 95% of peak strength presented an insignificant change when increasing the filler content and accordingly reducing

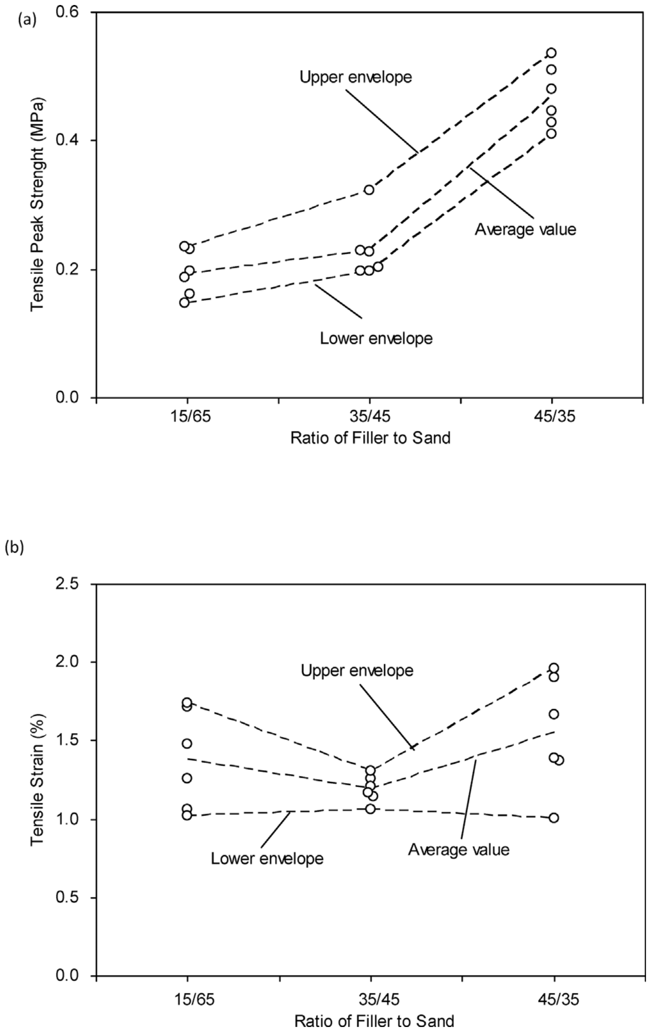

Fig. 5. Tensile peak strength (a) and strain at 95% of peak strength (b) versus ratio of filler to sand content under a constant bitumen content of 20% for the SAM in specimens.

the sand content. Increasing the filler content in the SAM caused a significantly increase in the viscosity strength. The tensile strain was mainly governed by the bitumen content in the SAM. The coupling effect of filler content increasing and sand content reducing by the same quantity made the tensile strain of the SAM not to be significantly affected. The high filler content of 45% in the SAM was made it hard to mix and spray, and thus the SAM with the ratio 35/45 of filler to sand content was selected for the following study.

5. Effect of different thicknesses of SAM on tensile behavior of the connection

The ratios of bitumen to filler to sand for the SAM were 20%:35%:45% by weight, and the thicknesses of SAM were selected as 10,20,30,40 and 50 mm for testing, respectively. The asphalt-SAM-concrete connection specimens were prepared and tested applying the method described in Section 2 and shown in Fig. 2 for the five different thicknesses of the SAM mix. The tensile peak strength and strain at 95% of peak strength versus the SAM thickness are shown in Fig. 6.

It was interesting to discover that the thickness of 10 or 20 mm for the SAM yielded a high tensile peak strength of around 0.25 MPa while the thickness of the SAM of 30, 40 and 50 mm gave a tensile peak strength of from 0.15 to 0.10 MPa, shown in Fig. 6(a). The peak strength values of the specimens with the 10 or 20 mm thick SAM were more scattered than those of the specimens with 30,40 and 50 mm thick SAM. Fig. 6(b) shows that the tensile strain at 95% of peak strength was gradually increased from 0.8% to 2.4% when the thickness of the SAM was increased from 10 to 50 mm in 10 mm steps. The strain values at 95% of peak strength for the specimens with 30, 40 and 50 mm thick SAM were more scattered than those of the specimens with 10 and 20 mm thick SAM.

After the SAM was placed on the surface of the concrete block, the hot asphalt concrete at a temperature of 150 °C was placed and compacted on the SAM. The SAM was easily melted by the hot asphalt and some large aggregate particles (maximum 19 mm) penetrated and were mixed with the SAM during the compaction. When the SAM was only 10 mm or 20 mm thick, the strength was

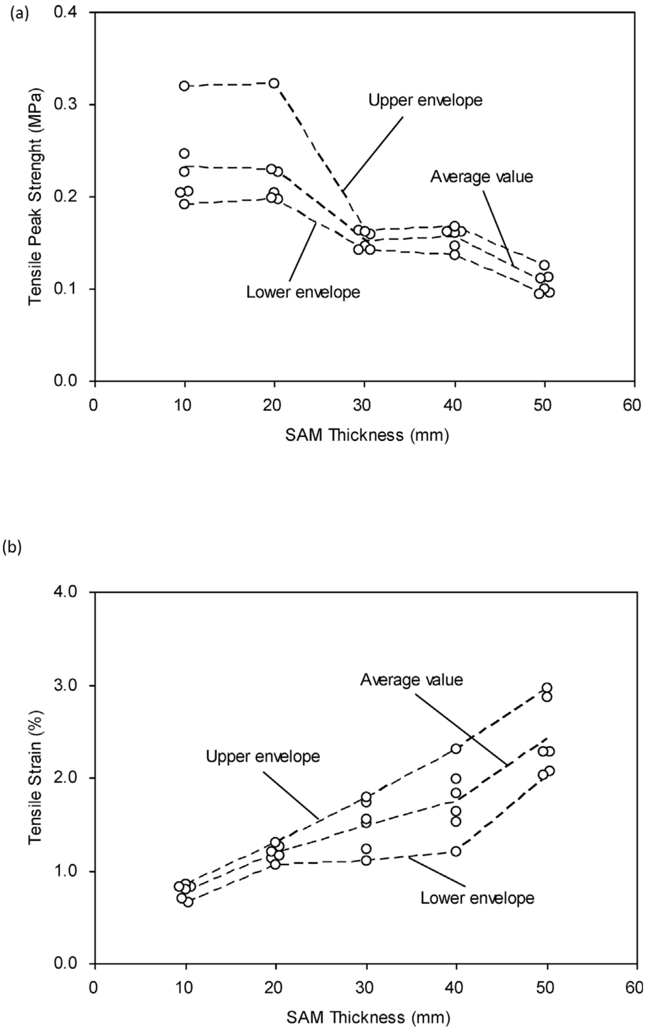

Fig. 6. Comparisons of tensile peak strength (a) and strain at 95% of peak strength (b) for the SAM with different thicknesses in specimens.

strengthened possibly due to the particle penetration into the SAM. When the thickness of the SAM was increased to be more than 30 mm, the thicker SAM layer was kept in the connection and caused the strength to be reduced significantly. Practically, the thickness of SAM is designed to be 10 to 20 mm as thicker SAM is difficult to place on a steep plinth unless special techniques are used [12].

6. Effect of various types of additives in SAM on tensile behavior of the connection

It is common practice to add some additives in the SAM or asphalt in order to improve the behavior of the joint. Stearin acid may be added in the SAM to secure good asphalt core-plinth connection [13]. Styrene-Butadiene-Styrene (SBS) has been added in the asphalt that has been used as the impervious facings of the upper reservoirs of Xilongchi and Huhehaote pumped storage projects, and the facings have successfully experienced air temperature as low as −38 °C for Xilongchi since 2007 and −45 °C for Huhehaote since 2015, respectively [7]. Polyester is commonly used in the asphalt to improve the slope stability for asphalt facings [7]. Therefore, various types of additives such as tristearin, SBS (Styrene-Butadiene-Styrene), polyester, were chosen for the study. The contents of the additives in the SAM were determined based on application practices. 2% tristearin of bitumen weight, 4% SBS of bitumen weight and 0.2% polyester of the SAM weight were separately added when the ratios of bitumen to filler to sand were fixed as 20%:35%:45%. The asphalt-SAM-concrete connection specimens were prepared and tested applying the method described in Section 2 and shown in Fig. 2 for the SAM mix added separately with three different additives. Fig. 7 shows the comparisons of tensile peak strength and strain at 95% of peak strength of the specimens which contained the SAM without additive and with various types of additives.

Fig. 7(a) shows that the tensile peak strength of the specimens was generally reduced by separately adding the three types of additives in the SAM. Adding tristearin in the SAM yielded the lowest tensile peak strength, i.e., the average value of 0.22 MPa was

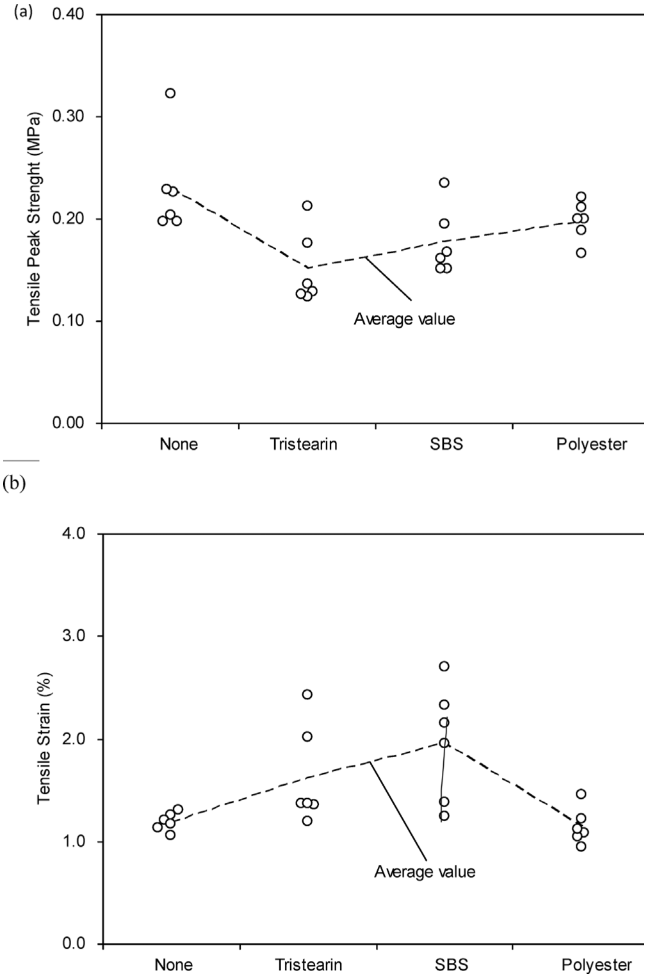

Fig. 7. Comparisons of tensile peak strength (a) and strain at 95% of peak strength (b) for the SAM with various types of additives in the specimens.

reduced to 0.15 MPa. Adding SBS and polyester gave tensile peak strength of 0.18 and 0.20 MPa, respectively. Fig. 7(b) shows that the tensile strains at 95% of peak strength were increased by separately adding the three types of additives in the SAM. Adding SBS in the SAM produced the largest tensile strain, i.e., the average value of 1.2% was increased to 2.0%, and it also gave the most scattered strain data.

Adding 2% tristearin in the bitumen made the SAM softer and reduced the strength while increasing the tensile strain. Adding 0.2% polyester in the SAM would modify the SAM behavior but seemed to have insignificant effects on the connection behavior as the strength and strain was measured at the cracking for the interface of the SAM and concrete. Among the three additives 4% SBS in the bitumen presented significant increase for the tensile strain of the asphalt-SAM-concrete connection. From the comparisons of the test results for the effects of separately adding the three types of additives in the SAM on the peak strength and strain at 95% of peak strength SBS was selected as additive in the SAM.

It should be noted that the test results and conclusions are only valid for the tension testing on the asphalt-SAM-concrete connection behavior. If the tests had been in compression or compression and shear, the results and conclusions would have been different.

7. Comparison of different plinth surface shapes by model testing under large shear displacements and water pressure

Fig. 8 shows the schematic for the model test. The equipment consists of two main boxes and the inside clear sizes of the two boxes are 120 mm wide and 400 mm long. The upper box with a height of 330 mm can move freely in the vertical direction. The lower box holds the concrete plinth and can move horizontally from left to right. Eight stacked rectangular steel rings with a thickness of 5 mm were put between the upper box and the lower box to give the test materials more uniform shear deformation. Steel roller pins with a diameter of 1.6 mm were arranged with center-to-center interval distance of 80 mm and put between the rings to reduce the horizontal friction forces. The total height of the rings with the pins between the rings is 54.4 mm.

Three surface shapes of the plinths with dimensions of 40 cm (long) × 11 cm (wide) × 20 cm (high) were prepared for the model

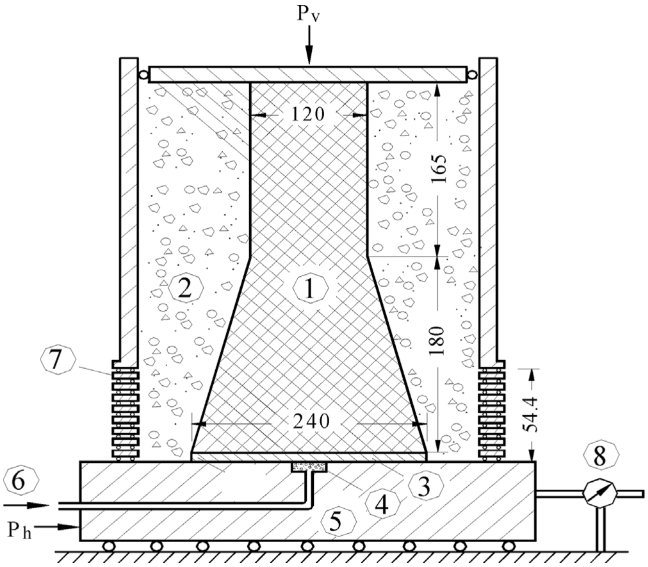

Fig. 8. Schematic diagram (unit: mm) for asphalt core-plinth connection model test to study different plinth surface shapes when subjected to large shear displacement and high water pressure. The figure shows the plane-surface plinth. 1. Asphalt concrete; 2. crushed limestone aggregates (< 20 mm); 3. 20 mm thick SAM; 4. fine sand; 5. concrete plinth; 6. water pressure; 7. stacked rectangular steel rings; 8. displacement meter.

tests, see Fig. 9. In the center of the plinth surface a concave with dimensions of 7 cm (long) × 4 cm (wide) × 1 cm (deep) was made and filled with fine sand. Water pressure was applied to the concave through a copper tube during the model testing. The plinth surfaces were placed with the 20 mm thick SAM using the ratios of bitumen: filler: sand = 20%:35%:45%, adding 4% SBS in the bitumen.

The plinth was fixed in the lower box, and the upper box was mounted on the equipment. The prepared hot asphalt and crushed limestone aggregates were simultaneously placed and compacted with a compacted layer thickness of about 3 cm in 12 layers.

The asphalt core–plinth model tests were run at a temperature of 15 °C. As shown in Fig. 8, a vertical stress of 1.5 MPa was exerted on the top of the materials through a rectangular steel plate by a jack and kept constant during the testing. The water pressure under the interface was kept constant at 0.5 MPa (i.e., 50 m water head) during the first part of the test. Then the plinth was pushed horizontally by a jack and the induced displacement was measured by a dial indicator. The shear stress required to make the plinth begin to move was about 0.3 MPa, and the plinth displacement rate was then kept at 0.1 mm/min. The resulting shear stress was increased from 0.3 to about 0.7 MPa during the shearing process. After 400 min of testing, the horizontal displacement of the plinth reached the maximum shear displacement of 39 mm that the model allowed, but no leakage was detected even when the water pressure was increased in steps from 0.5 to 2.4 MPa (i.e., 240 m water head) in 3 h. The vertical stress, shear stress, shear displacement, and water pressure versus time for the plane-surface plinth model test are shown in Fig. 10.

The model tests for the curved-surface plinth (Fig. 9b) and the plane-surface plinth with two rows of copper stops (Fig. 9c) were carried out following the exact same procedures as for the plane-surface plinth model. The test results were very similar for the three cases.

The model test results document that the asphalt-SAM-concrete connection in the asphalt core-plinth model tests could undergo a horizontal shear displacement of 39 mm without suffering any water leakage in the joint. Under a vertical stress of 1.5 MPa and such large shear strain the connection could withstand water pressure as high as 2.4 MPa (i.e., 240 m water head) without fracturing. This is in agreement with the findings for hydraulic fracturing model test results with high water head as high as 350 m [6]. The reason that the SAM and asphalt was kept watertight during the testing through the large shear displacements and shear strains is that the uplift water force was smaller than the vertical force in the large surface area of the plinth, as the 2.4 MPa water pressure was limited to a small local area of (7 cm × 4 cm) within the large area under the SAM. It may imply that even if the concrete plinth has some cracks caused by undetected construction defects or subsequent loading the connection may still be watertight.

Installing water-stops through the SAM connection increase the tensile strength of the connection, however that was not modeled in the horizontal shear model tests. On a steep plinth it may be necessary to embed one or two rows of water-stops in the plinth to penetrate into the SAM and asphalt core to reinforce the asphalt core-plinth connection.

The model testing was carried out to compare different plinth surfaces with the same SAM under compressive and large shear displacements and water pressure. For compression and shear tests other techniques such as adding different kinds of polyesters, natural rubber and tyre powder or other materials in the SAM would improve the compressive and shear behaviors on the asphalt core-plinth connection [20,21]. However, the compression and shear behavior on the asphalt core-plinth connection in the low part of the asphalt core in the embankment dams are normally of any concern as ordinary SAM without additives can fulfill the design requirements for the connection. The tensile behavior or tensile-shear behavior in the upper part of the core along the dam abutments is the major concern as studied in the previous sections.

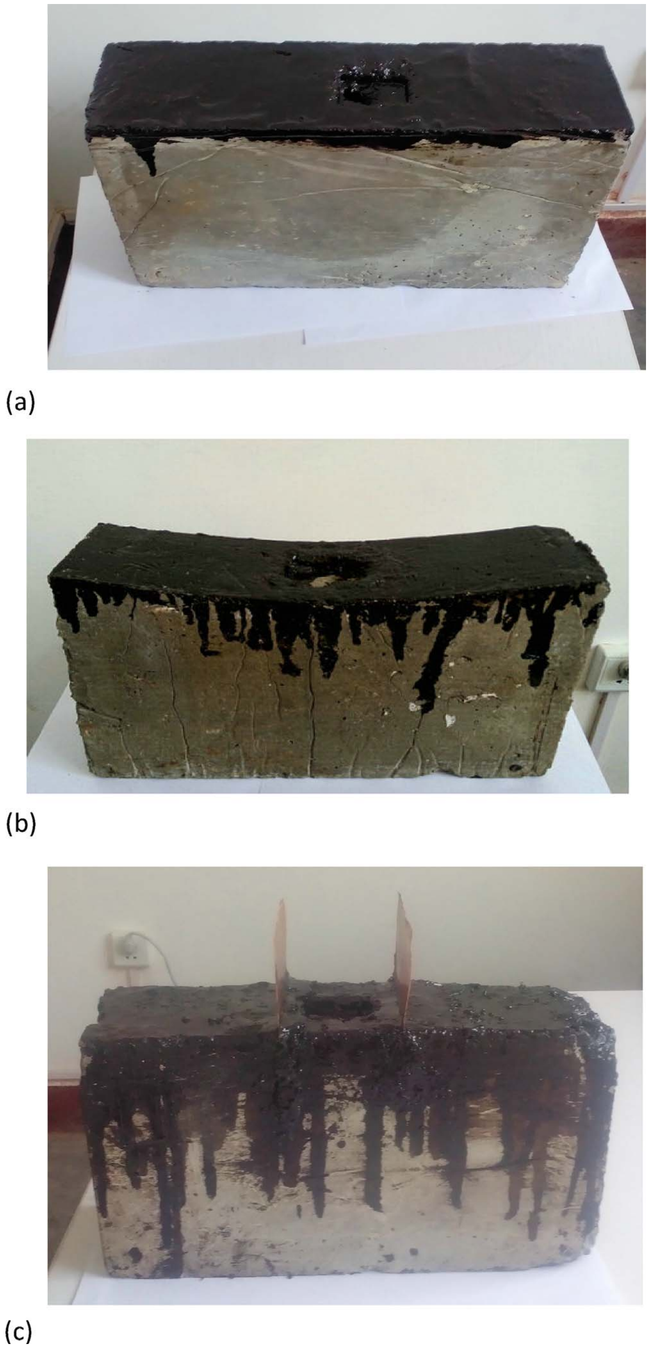

Fig. 9. Three surface shapes of the plinths for the model tests. (a) Plane-surface plinth; (b) curved-surface plinth; and (c) plane-surface plinth with two rows of copper stops.

8. Summary and conclusions

Asphalt core is a no-joint impervious barrier in embankment dams and has to be connected with the concrete plinth. The asphalt core-plinth connection is crucial and must remain watertight when the core and plinth undergoes deformations (displacements) during construction and operation with full reservoir pressure. For asphalt core dams located in gorges with steep abutments the asphalt core-plinth connection towards the top of the dam may be subjected to tensile strain and significant shear displacements. In practice, sandy asphalt mastic (SAM) is used between the asphalt and plinth as a connection material. A large number of tension tests were conducted to determine the best ratio, joint thickness and suitable additives for the SAM mix.

The temperature of an asphalt core is about 5 °C for embankment dams located in sub-arctic climate, and about 20 °C in sub-

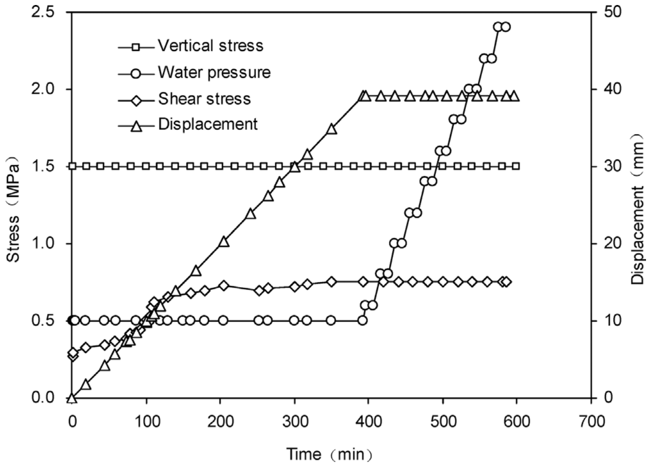

Fig. 10. Measured stresses and displacements versus time for the plane-surface plinth model test to study the asphalt core-plinth connection behavior when subjected to shear displacements and high water pressure.

tropical climate. The temperature of 15 °C was used in the study based on the consideration that is the approximate average temperature for asphalt cores in operation for ACEDs in China. Temperature has a significant effect on strength and stiffness (deformation modulus). Wang and Höeg [4] found the cyclic modulus to increase from 900 MPa at 20 °C to 2500 MPa at 3.5 °C in the cyclic strain range of 10^{-4}–10^{-3}. Gheibi et al. [18] carried out resonant column tests on asphalt specimens and found the dynamic shear modulus to be about 8000 MPa at 22 °C, being about 10000 MPa at 0 °C in the strain range of10^{-8}–10^{-7}. At low strain rates or creep rates the strength of asphalt is significantly affected by the magnitude of strain rate while the strain at cracking is insignificantly affected [7]. The tests reported herein were run at a strain rate of 1.0%/min to investigate the asphalt core-plinth connection behavior mainly for dam construction and normal dam operation conditions.

The unavoidable irregular nature of the interface between the SAM and concrete caused a relatively large scatter in the data of tensile peak strength, and therefore six specimens were used for the same test conditions to obtain a better understanding of the asphalt-SAM-concrete connection behavior. The cracks of the specimens occurred on the interface between the SAM and concrete after the peak strength had been reached, and the magnitude of strain at which the cracks opened was studied. The peak strength and the tensile strain when the post-peak stress had reached 95% of the peak strength were used for comparison among the test results. Furthermore, model tests including the variation of several parameters were conducted to study the connection when subjected to large shear displacements and high water pressure. The following conclusions may be drawn based on the test results:

- All the cracks in the specimens occurred on the interface between the SAM and concrete, which indicates that the treatment of the plinth surface is important for the asphalt core-plinth connection.
- The asphalt-SAM-concrete connection tension test results showed the best SAM ratios to be 15%:20%:65% by weight for bitumen, filler and sand, respectively.
- The thickness of the SAM has a significant effect on the tensile strain on the asphalt core-SAM-plinth connection. The asphalt-SAM-concrete connection tension test results showed that the tensile strain at 95% of peak strength was gradually increased from 0.8% to 2.4% when the thickness of the SAM was increased from 10 to 50 mm in 10 mm steps.
- The asphalt-SAM-concrete connection tension test results showed that the connection allowed the largest strain by adding SBS in the SAM. Three types of admixtures were tested, tristearin, SBS and polyester. Adding SBS (4% of bitumen weight) in the SAM increased the tensile strain at 95% of peak strength for the asphalt-SAM-concrete connection from 1.2% without additive to 2.0% with the SBS additive.
- The asphalt core-plinth model test results were very similar for the plinth plane surface, the curved-surface and the plane-surface with two rows of copper stops. The asphalt-SAM-concrete connection in the model tests could undergo a horizontal shear displacement of 39 mm without suffering any water leakage in the joint.

On a very steep plinth it may be advisable to embed one or two rows of water-stops in the plinth to penetrate into the SAM and asphalt core to reinforce the asphalt core-plinth connection.

The investigations were carried out based on the conventional field placing techniques for the SAM. Therefore, there were limitations for the bitumen content and thickness of the SAM placed on steep abutments. If a prefabricated technique for preparing the SAM is developed, the limitations would be relieved and the asphalt-SAM-concrete connection behavior would be further improved. However, this needs to be further investigated.

The materials used for the SAM were crushed limestone for the sand, ground limestone powder for the filler and B70 for the bitumen with additives of tristearin, SBS and polyester. It should be emphasized that the asphalt-SAM-concrete connection test results quoted above are limited to the SAM with the bitumen, filler, sand and additives used in the experiments. If other kinds of materials had been used in the tests, the results and conclusions may have been changed. This recommended SAM ratios may be used as a reference, but tests have to be performed for the SAM to be used in the connection for an asphalt core-plinth design especially for high ACEDs with very steep abutments.

Acknowledgments

The research work for the paper was partly supported by the National Natural Science Foundation of China (No. 51179155) and by Program 2013KCT-015 for Shaanxi Provincial Innovative Research Team. The authors appreciate the assistances of Yaqiang Han and Zheng Ying of the Xi'an University of Technology, China, during the experimental work.

References

[1] K. Höeg, T. Valstad, B. Kjaernsli, A.M. Ruud, Asphalt core embankment dams: recent case studies and research, Int. J. Hydropower & Dams 13 (5) (2007) 112–119.
[2] W. Wang, K. Höeg, Y. Zhang, Design and performance of the Yele asphalt-core rockfill dam, Can. Geotech. J. 47 (12) (2010) 1365–1381.
[3] W. Wang, K. Höeg, Simplified material model for analysis of asphalt core in embankment dams, Constr. Build. Mater. 124 (2016) 199–207.
[4] W. Wang, K. Höeg, Cyclic behavior of asphalt concrete used as impervious core in embankment dams, J. Geotech. Geoenvironmen. Eng. (ASCE) 137 (5) (2011) 536–544.
[5] A. Akhtarpour, A. Khodaii, Experimental study of asphaltic concrete dynamic properties as an impervious core in embankment dams, Constr. Build. Mater. 41 (2013) 319–334.
[6] Y. Zhang, W. Wang, Y. Zhu, Investigation on conditions of hydraulic fracturing for asphalt concrete used as impervious core in dams, Constr. Build. Mater. 93 (2015) 775–781.
[7] K. Höeg Y. Zhang, W. Wang, Watertightness, cracking resistance, and self-healing of asphalt concrete used as a water barrier in dams, Can. Geotech. J. 50 (3) (2013) 275–287.
[8] W. Wang, Y. Zhang, T. Xu, Design and construction of the Quxue asphalt core rockfill dam, Hydropower & Dams 25 (4) (2017).
[9] K. Höeg, W. Wang, Design and construction of high ACEDs, International Symposium Based on Knowledge Engineering, July 5, Prague, Czech Republic, 2017.
[10] M. Tajdini, R. Mahinroosta, H. Taherkhani, An investigation on the mechanical properties of granular materials in interface with asphaltic concrete, Constr. Build. Mater. 62 (2014) 85–95.
[11] M. Tajdini, A. Rostami, M.M. Karimi, H. Taherkhani, Evaluation of the geo-mechanical parameters of the interface between asphalt concrete and sand with applying direct shear test and numerical modeling, Adv. Mater. Res. 587 (18) (2012) 116–121.
[12] ICOLD, Asphalt cores for embankment dams, Bulletin, International Commission on Large Dams, Paris, France, (The new bulletin will be published in 2018).
[13] K. Höeg, Asphaltic Concrete Cores for Embankment Dams, Stikka Press, Oslo, Norway, 1993.
[14] W. Wang, S. Feng, Y. Zhang, Investigation of core asphalt-transition zone aggregate interface in embankment dam, Cases Study Constr. Mater. (2017) (in preparation).
[15] M.R. Kruntcheva, A.C. Collop, N.H. Thom, Effect of bond condition on flexible pavement performance, J. Transp. Eng. (ASCE) 131 (11) (2005) 880–888.
[16] M.R. Kruntcheva, A.C. Collop, N.H. Thom, Properties of asphalt concrete layer interfaces, J. Mater. Civil Eng. (ASCE) 18 (3) (2006) 467–471.
[17] W. Wang, K. Höeg, Developments in the design and construction of asphalt core dams, Int. J. Hydropower & Dams 17 (3) (2010) 83–91.
[18] E. Gheibi, I. Sasanakul, M.V. Sanin, H. Puebla, Effect of temperature on dynamic properties of asphaltic core for earth dam, Geo-Chicago (2016) 265–275.
[19] Ministry of Water Resources of the People's Republic of China, Specifications for Construction of Hydraulic Asphalt Concrete. State Water Industry Standard SL 514, China Water and Power Press, Beijing, 2013 [in Chinese].
[20] W. Wang, Y. Zhang, K. Höeg, Y. Zhu, Investigation of the use of strip-prone aggregates in hydraulic asphalt concrete, Constr. Build. Mater. 24 (11) (2010) 2157–2163.
[21] M.M. Khabiri, A. Khishdari, E. Gheibi, Effect of tyre powder penetration on stress and stability of the road embankments, Road Mater. Pavement Des. 18 (4) (2017) 966–979.