ASPHALT CONCRETE CORES FOR EMBANKMENT DAMS

BULLETIN...

Final Draft submitted for approval

FEBRUARY 2018

CIGB
ICOLD

2018

NOTICE – DISCLAIMER

The information, analyses and conclusions in this document have no legal force and must not be considered as substituting for legally-enforceable official regulations. They are intended for the use of experienced professionals who are alone equipped to judge their pertinence and applicability.

This document had been drafted with the greatest care but, in view of the pace of change in science and technology, we cannot guarantee that it covers all aspects of the topics discussed.

We decline all responsibility whatsoever for how the information herein is interpreted and used and will accept no liability for any loss or damage arising therefrom.

Do not read unless you accept this disclaimer without reservation.

Committee on Embankment Dams

Chairman:

Canada	Jean-Pierre TOURNIER

***Vice Chairman*:**

South Africa	Danie BADENHORST

Members:

Australia	Gavan HUNTER
Austria	Peter TSCHERNUTTER
Brazil	Carlo VIOTTI
Bulgaria	Netzo DIMITROV
China	Li NENGHUI
Colombia	Alberto MARULANDA
Finland	Juha LAASONEN
France	Jean-Jacques FRY
Germany	Markus LIMBACH
Greece	George DOUNIAS
India	V. K. KAPOOR
Indonesia	D. JAWARDI
Iran	Nasser TARKESH DOOZ
Italy	Francesco FEDERICO
Japan	Hidekazu TAGASHIRA
Norway	Vahid AFSARI-RAD
Pakistan	Waseem ASGHAR
Portugal	E. MARANDA DAS NEVES
Russia	Vadim RADCHENKO
Slovakia	Marian MISCIK
Spain	Antonio SORIANO
Sri Lanka	L. SOORIYABANDARA
Sweden	Ingvar EKSTRÖM
Switzerland	Peter BRENNER
Thailand	A. SRAMOON
Turkey	Nurettin PELEN
United Kingdom	Rodney C. BRIDLE
United States	David PAUL

Venezuela	Gabriel MARTINEZ

Co-opted Members

Canada	Eric PELOQUIN
France	Thibaut MALLET
Turkey	Mehmet Harun ASKEROGLU

TABLE OF CONTENTS

1. FOREWORD

During its meeting in Tehran in 1975, the Sub-Committee on New Materials renamed in 1977 Sub-Committee on Materials for Fill Dams, asked the German National Committee to extend these studies on the use of bituminous mixes for waterproofing of fill dams to bituminous cores. After two draft reports, Bulletin 42 "*Bituminous Cores for Earth and Rockfill Dams*" was approved and published in 1982. This bulletin dealt with design criteria, construction methods and tests with some examples of application and performance. A decade after, in 1992, an update version, Bulletin 84, was published: "*Bituminous Cores for Fill Dams – State of the Art*". At that time more than 60 dams with asphalt concrete cores - in some instances with heights of 100 meters and more - have been built. As a result of that dynamic development, experiences have been gained in design, construction methods and control measures. Bulletin 84, prepared by the German Committee, has taken into consideration the many years of systematic development of this sealing technique for dams which mainly originated in Germany. Some slightly varying methods were based on this standard technique.

Since the last fifteen years, this type of dam is gaining in popularity. Nearly 200 asphalt concrete core embankment dams (ACED) have been built worldwide with excellent field performance. Comprehensive research in the technology and development of asphalt concrete core machinery has been done. The Committee on Materials for Fill Dams, renamed in 2010 Committee on Embankment Dams, has decided to update the Bulletin. That ambitious task was taken by specialists from Austrian, German, Norwegian, Chinese and Canadian national committee representatives.

I wish to record special thanks to Peter Tschernutter who has assured the coordination of the working group and also to Helge Saxegaard, Markus Limbach and Weibiao Wang for their active and constant participation; to all of them, our greatest appreciation. I also express my gratitude to Kaare Hoeg for several comments and to him and Martin Wieland for their contribution on the chapter Seismic Loading and Resistance (4.2.6).

Jean-Pierre Tournier

Chairman

Committee on Embankment Dams

Notes:

1 – *A construction procedure, known as the stone-bitumen-method, has been used in some countries in the period before 1984. This method should not be considered as an asphalt concrete core and is not discussed further in this Bulletin.*

2 – *A different technique has been used in Russia for large embankment dams. The asphalt concrete mix with a bitumen content of 10 to 12 % is supersaturated with bitumen (called "flowing" asphalt concrete or "cat" asphalt concrete). This technique is fairly similar to the machinery placed asphalt concrete core method but not developed further here.*

2. INTRODUCTION

Approximately 5.000 years ago, a small dam was built in the Indus river valley, using asphalt as a mortar between stones. That was one of the first utilization of asphalt as an impervious material. However, the first “modern” asphalt concrete core dam, mechanically placed and compacted, was built in Germany in 1962. This method expanded first in Europe, particularly in Germany and Austria. As of today, almost 200 asphalt concrete core embankment dams (ACED) have been built or are under construction in different countries around the world. Among them, the 170 m high Quxue Dam in China will be the highest; however even higher ACEDs are under design. There are now more than 50 years of successful experience for this dam type.

The gain of popularity, particularly the last fifteen years, in the water retaining, hydropower and mining industries, follows the excellent recorded field performance and behavior for this type of dam, and also comprehensive researches in the technology and development of asphalt concrete core machinery.

This Bulletin covers the state-of-the-art of current practice after the important development in design and construction during the last 25 years. It addresses all aspects of the design, construction, performance and operation. Characteristics of asphalt concrete cores, requirements for the mix design, laboratory testing and quality control are discussed. Technical specifications are also presented and proposed. Finally, several typical case histories with characteristics and performance are given in Appendices.

3. CHARACTERISTICS OF ASPHALT CONCRETE CORES

3.1 DESIGN CHARACTERISTICS OF ASPHALT CONCRETE CORES

The basis for application of bituminous cores in dams is an elasto-plastic behavior of the asphalt concrete as a building material. This characteristic helps to prevent cracks in the core subsequent to deformations of the embankment, thus ensuring the imperviousness of the core.

The specific design characteristics of asphalt concrete cores are:

- Low permeability to ensure water tightness
- High resistance to all loading forces
- High flexibility preventing cracking due to imposed embankment deformations
- Resistance to aging
- The asphalt concrete mix of the core can be designed to achieve the expected load impacts and deformations
- Good self-healing capacity and resistance against erosion

3.2 SPECIAL FEATURES OF ACEDS

3.2.1 Main Advantages of ACEDs

- Performance records from existing ACEDs show no leakage through the asphalt concrete core, if the dam was well designed and constructed.
- ACEDs are fast and easy to construct and the construction is much less impacted by weather conditions. In areas with much rain, the overall construction time for an asphalt concrete core can be shortened in comparison with most of other dam types. Inside the embankment the asphalt concrete core is embedded under ideal conditions and independent from external climatic impacts. It will remain flexible and impervious over the dam’s lifetime.
- An asphalt concrete core can generally be built very fast. The limiting factor for the construction schedule is basically the progress of the embankment construction. It is important to consider and calculate the potential shorter construction time for an ACED.
- Asphalt concrete cores in the interior of dams provide the highest protection against damage caused by acts of war or sabotage.
- Compatibility and high shear resistance between the asphalt concrete and the materials of the embankment as well as a sufficiently high support by the adjacent earth or rockfill zones
- An asphalt concrete core is a homogenous impervious element without joints.

- ACEDs are also suitable in earthquake areas due to the high flexibility of the asphalt concrete mix.
- Due to the very ductile behavior of the asphalt concrete and its ability to remain impervious in case of large embankment deformations, ACEDs can also be designed and constructed if only poor material for the embankment is available.
- As no water penetrates through the asphalt concrete core, the filter criteria for the adjacent zones to the core are very relaxed compared to other strong criteria for most other embankment dam types.
- Asphalt concrete core materials are insoluble in water, environmentally compatible and have been proven to be non-harmful for drinking water.

3.2.2 Issues to be considered for ACEDs:

- The asphalt concrete core is in the middle of the dam and it is complex and costly to perform any repair work if later required. However, with more than 190 ACEDs being built (2017), no repair work has been required for asphalt concrete core dams.
- Asphalt concrete core construction requires specialized equipment and experienced personnel and such services are often not locally available. The specialized services are considered as necessary due to the high quality requirements for the asphalt concrete core in the dam. However, the construction work can be performed by local workers, given preliminary training and thereafter under supervision by experienced personnel.
- The asphalt concrete core construction and the central embankment construction cannot commence until the concrete plinth and the grouting work in the central part is completed. However, the upstream and downstream shoulders can be built up within limits.

Figure 3.1 Earthwork sequence and following ACED placing (Rennersdorf Dam, Germany, 2010)

- An ACED can be built very fast (see Appendix B, Foz de Chapeco dam) and the reservoir impounding can be performed as the dam construction progresses in comparison to some other dam types.
- If additional foundation grouting is foreseen after the dam was completed, a gallery under the asphalt concrete core should be included in the design.

3.3 ECONOMIC CHARACTERISTICS

Cost estimation:

The unit costs for the asphalt concrete core material and the construction of an ACED cannot easily be calculated and depend on local circumstances and the main items listed below:

- Rental and establishment of a suitable asphalt mixing plant (batch plant) on site is a major cost item unless there is an existing plant within reasonable distance to the dam site
- Costs for the bitumen depending on the content in the mix (usually between 6.5 to 7.5 % measured by weight)
- Equipment, transportation and personnel costs for placement related to construction period or construction schedule
- Other specific influences of the project
- The price will accordingly be high when the asphalt concrete core volume is fairly small and dependent on the construction schedule.

Other aspects:

- Dams with asphalt concrete cores permit impounding during construction, allowing seasonal water to be collected prior to full completion of the dam and to generate electricity. Cofferdam design can often for the same reason be simplified.
- ACEDs are in general maintenance free.
- With asphalt concrete cores, the many scars from clay or earth borrow pits are eliminated.
- The concrete plinth as foundation for the asphalt concrete core is much simplified in comparison with a CFRD design according to the simplified forces acting on, and the plinth is shorter in length as it is in the center line of the dam.
- It is common practice and frequently believed that ACEDs require very solid and sound aggregates as used for road asphalt. If such aggregates are not available, materials with reduced quality may also be used, however, the reduced properties of the aggregates must not jeopardize the lifetime of the dam.

3.4 CLIMATE INFLUENCE – COLD/HOT WEATHER, PRECIPITATION

The special asphalt concrete material for ACEDs is much more dense and viscous than the ordinary road asphalt. The recommended production temperature depends on the bitumen type and grade. The layers are placed with a thickness of 20 to 25 cm and the material will remain hot and viscous inside the core for a considerable time even if the outer parts of the core has cooled down. When a new asphalt concrete layer is placed on top of the previous one (minimum temperature required for that layer before placing the new one), the contained heat will warm up the top of the previous layer sufficiently and the two layers will melt together without any detectable joint. A tack-coat between the layers is therefore not required, unless in very special cases. Asphalt concrete core paving is thus very different from ordinary road paving.

All modern core paving machines are today equipped with an infrared heater in front of the machine. The main purpose of this is to evaporate potential moisture on the previously placed layer, secondary is also to warm the top of the underlying layer. Potential moisture will increase the volume tremendously when it turns to vapor and in order to ensure a good bond between the layers it is important to prevent moisture becoming interlocked between the layers. The filter zones placed on both sides of the asphalt concrete core will provide lateral, horizontal support on the core when compacted. This will give the asphalt concrete core a slight concave surface which is very beneficial during rainy conditions during which water could flow to the filter zones. In special cases, it can also be recommended to remove debris and rain water from the previous layer with compressed air in front of the core paving machine or with a mechanical brush.

These techniques and equipment makes ACED construction very favorable in cold and wet climatic conditions. The asphalt concrete material can be produced at the asphalt mixing plant even in sub-zero temperatures as long as the aggregates are in workable conditions. The construction season can therefore be extended compared to other dam types.

Figure 3.2 Knezovo dam, Macedonia, December 2009

The asphalt concrete work on the dam is normally stopped for winter because of other construction limitations such as frozen fill materials and pipes, for water sluicing, snow etc.

For the required hand placement towards the abutments and the first layers above the concrete plinth, careful heating with propane burners are required in order not to burn or oxidize the asphalt concrete surface. Hand placement of the asphalt concrete material and compaction has to be performed in quick succession under cold or wet environment conditions.

In hot and sunny environment, asphalt concrete core placement is very straight forward and the material properties can be modified by changing the bitumen content and type. (See Chapter 4.3.3 Bitumen) Special attention may be required if the underlying layers placed pervious days are not sufficiently stable.

Core drilling for void content measurements in hot climate can take many days as the asphalt concrete needs longer time cooling down. Special measures can be taken to reduce the waiting time before coring (see Chapter 5.3.4 Site laboratory).

In cold climate and at high altitude the construction season can be short and it is essential to utilize every working day of the short construction season. Such locations have frequently also high precipitation. The construction problems with clay or moraine cores in such locations are well known with frequent waiting for the clay or moraine placing to obtain the required optimum water content. An ACED is fairly independent from the weather. Work may need to stop temporarily during heavy rain, but can restart as soon as the weather improves.

Where clay or moraine material is available, initial cost estimates are frequently in favor of a clay core design, but such calculation seldom takes into account the standstill time due to weather conditions. With an ACED design, standstill time and construction time can be reduced and the total construction costs for the ACED will be favorable.

Figure 3.3 Murwani Dam, Saudi Arabia, very hot climate conditions

3.5 TAILING DAMS AND WASTE DISPOSALS

Asphalt concrete sealing elements are well suited for tailing dams and waste disposals. Damages by chemicals can only occur if the tailings include solvents in higher concentrations. Bitumen is affected only by a few chemicals, mostly acids at higher temperatures and significantly higher concentrations. However, in disposals with industrial waste fluids, temperature and concentration of the chemical components have to be taken into account and specific trials should be considered too.

Aggressive water that would damage cement concrete may have an effect on some type of aggregates like limestone, but they have in general no effect on the bitumen.

Many waste disposals have been sealed with impervious asphalt concrete facings placed with special machines in two to three layers.

In an already excavated and existing quarry, where the topography and natural terrain exists, an asphalt concrete core design can also be considered. The construction of the sealing element will be more or less the same as for dams described in this Bulletin, but the slope towards the deposit could be built steeper up to 1.3 vertical to 1 horizontal.

An asphalt concrete core for tailing dams can also be designed and built as described in this Bulletin, but the embankment slopes must be designed for the type and stability of the specific tailing that shall be deposited.

3.6 ENVIRONMENTAL ASPECTS

Asphalt concrete core dams are an attractive environmental solution.

The asphalt concrete contains no chemical material that will be dissolved or leaked to the environment. A great number of ACEDs are accordingly built for irrigation or drinking water reservoirs.

For earth fill embankment dams the availability, value and environmental aspect of clay borrow pits have increasingly become a matter of concern. In addition, truck transports from the clay borrow pits to the site can also be an environmental issue. This is not an issue with an ACED and the embankment fill for the dam can be taken from the area within the reservoir and as such not visible after the construction and impounding.

In mountainous areas a rock-fill dam can be designed to fit in naturally. And in urban or agricultural surrounding the embankment dam can be built with earth material on the downstream slope that can be sowed with grass or planted as on the Queens Valley dam for drinking water in Jersey, England.

4. DESIGN PRINCIPLES AND REQUIREMENTS

4.1 PRELIMINARY REMARKS – HISTORY

Asphalt concrete cores are especially used as impervious cores in embankment dams. They are mainly designed in areas where natural impermeable materials of sufficient good quality or quantity are not available, but have now also proved to be an economical alternative due to the fast rate of progress, even in some locations where natural impermeable material are available.

Asphalt concrete cores have been built by different methods.

A construction procedure which has been applied on some dams in some countries in the period before 1984 is the stone-bitumen-method (in situ mix). Metal sheet shuttering was used along the sides of the core wall, which was built in consecutive horizontal layers 0.2 - 0.3 m thick. The form was first filled with clean and dry stone material before hot bitumen was pumped in from a heated tank. The bitumen content is 30 - 40 % by weight. This method should not be considered as an asphalt concrete core and is not discussed further in this Bulletin.

A different technique has been used in Russia for large embankment dams up to 140 m high. The asphalt concrete mix produced in an asphalt mixing plant is made of coarser aggregates, has bitumen content 10 - 12 % and is poured between 1 m high steel shutters positioned on top of the previous layer. These shutters are removed as soon as the asphalt concrete has cooled down sufficiently and the filter zones are then placed on each side of the core. The asphalt concrete is supersaturated with bitumen and is termed “flowing” asphalt concrete. This technique is fairly similar to the machinery placed asphalt concrete discussed in this Bulletin, but not discussed here further. A report about asphalt concrete core construction at the Bouguchanskaya dam is attached in Appendix C, Bouguchanskaya Dam, Russia.

The first embankment dam with a machine-compacted dense asphalt concrete core was built in Germany in 1962. Since then more than 190 asphalt concrete cores, compacted in 20-25 cm layers, have been built. This procedure does not require the use of shutters, except for the first layers on top of the plinth and at the widening in the abutments, and the bitumen content is considerably lower than in the two methods described above, usually in the vicinity of 6.5 to 7.5 % by total weight. Furthermore, this technique allows the best quality assurance and control of the asphalt concrete core and is at present the most common technology.

The design principles described in the following apply to asphalt concrete cores which are installed in accordance with a construction method complying with the current state-of-the-art and these methods are described in greater detail in the following chapters. The asphalt concrete core is constructed at fairly simultaneous levels with the dam fill.

4.2 DESIGN PRINCIPLES

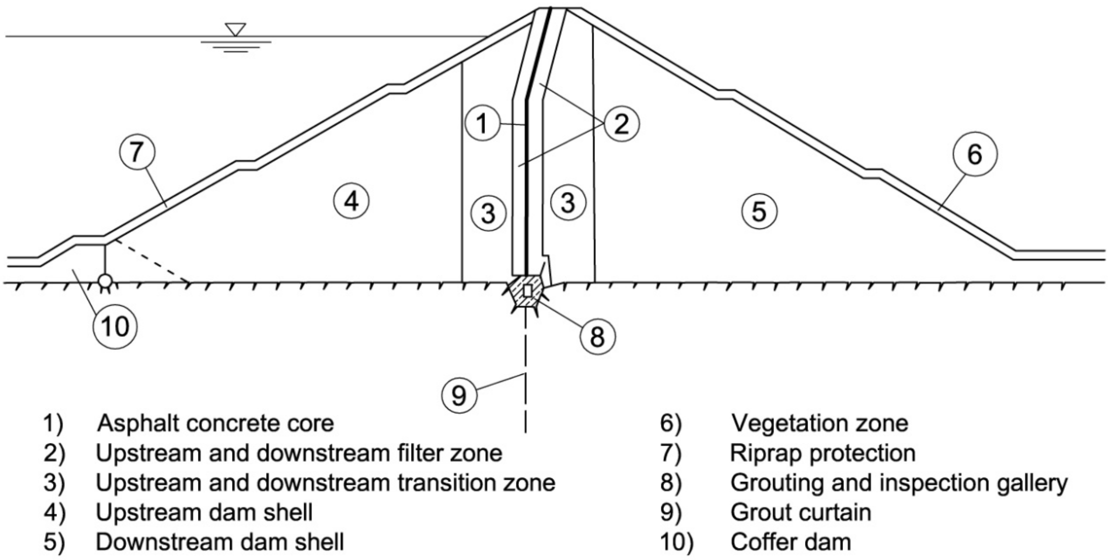


Figure 4.1 General layout and definition of zoning for AC dams

4.2.1 General design features for asphalt concrete core embankment dams

The thin asphalt concrete core has to adjust to the deformations in the embankment and to differential displacements in the dam foundation. Displacement accumulates during embankment construction, filling of the reservoir, time dependent consolidation and creep, fluctuations in reservoir level and earthquake actions. The essential function of the core is to remain impervious without any significant increase in permeability due to shear dilatation or cracking. Furthermore, should a crack occur, the asphalt concrete mix design should be such that viscous creep and plastic flow will gradually close these cracks (self-healing ability).

For a dam founded on bedrock the key to limiting the embankment deformation lies in the material properties and in the compaction of the transition zones and supporting shells. If the embankment is founded on compressible soil overburden, differential distortions due to unequal settlements under the embankment are likely to occur both across and along the valley. Some ACEDs have now been built on very challenging foundation conditions (see Appendix B, Yele Dam, China).

Comparison with and evaluation of field measurements from existing dams combined with finite element analyses, is the best way to predict deformations and distortions in new structures. The probable ranges for important parameters should be included in the analyses to study the sensitivity of numerical predictions to uncertainties in the embankment foundation properties.

The stress and strain levels in the asphalt concrete core based on finite element analyses are also used when modeling the behavior of the asphalt concrete in the laboratory. The laboratory specimens are subject to conditions approximating those that will exist in the field, and the behavior is studied with respect to degree of dilatancy and increase in permeability, ductility and cracking resistance, stiffness, strength and self-healing ability.

The properties of the asphalt concrete can, within fairly wide limits, be tailored to satisfy the specific design requirements.

The compaction of the filter zones and the hot asphalt concrete core result in a good interlocking of both construction elements. The asphalt concrete core can deform co-coordinately with the filter zones for the dams with a dam height of less than 100 m. For dams with a height of more than 100 m, the core may settle differentially by a few centimeters due to a higher unit density and lower deformation modulus of the adjacent zones. However, laboratory model tests have documented that such a differential deformation between the core and the transition zones has no detrimental effects on impermeability of the asphalt concrete core.

4.2.2 Supporting shell

For an embankment dam on a stiff foundation, the transition zone and supporting shell material, the degree of compaction and uniformity as well as the steepness of the slopes govern the deformations imposed on the thin asphalt concrete core. For dams on compressible foundations additional displacements and differential movement are imposed and must be estimated and accounted for.

It is recommended to place an especially well compacted zone on either side of filter zones. Water sluicing, in addition to vibratory compaction of layers with moderate thickness may be added. A trial field for the placing and compaction is recommended.

For a well compacted embankment of good rockfill resting on bedrock, the dam slopes may be as steep as 1:1.3 to 1:1.4 as demonstrated by for instance the Finstertal Dam, Austria (see Appendix B) and Storvatn Dam, Norway. Even so, the measured maximum displacements inside these two approximately 100 m high dams are very small (of the order 0.5 m) and the strains in the core far below allowable levels. The measurements agree quite well with the deformations computed by corresponding idealized finite element analyses.

In general, the embankment slopes for an ACED can be slightly steepened compared with a central earth fill dam with rock replacing most of the softer earth fill.

Case studies have demonstrated that ACEDs may successfully be constructed with much lower quality rockfill than used in previous dams of this type (Appendix B, Feistritzbach Dam, Austria and Storglomvatn Dam, Norway). ACEDs have also been built where rockfill is not available, and other materials have been used.

To accommodate potentially large core distortions for a given situation the designer may decide to use a particularly soft asphalt concrete mix, supersaturated with a high bitumen content (see Appendix B, Eberlaste Dam, Austria). The shear resistance of the asphalt concrete material will then be low. This must be considered when analyzing the stability of the slopes of the supporting shells, especially if the embankment is founded on a soil foundation (overburden) which may develop higher pore pressures, reduced effective stresses and strength during potential earthquake shaking.

4.2.3 Dimension and position of asphalt concrete cores, filter zones and filter zone materials

When determining the width of the asphalt concrete core the dam height, the dam geological foundation conditions and the seismicity at the dam site must be considered.

Under normal and good conditions, the asphalt concrete core width (cm) should be at least 0.7 x hydraulic head (m) with a minimum width of 50 cm. However, the Norwegian Regulatory Authority (NVE) has adapted a more conservative value: core width = 0.50 + [(0.7/100) x (H-50)]. The minimum width is 50 cm. All dimensions are in m.

Up to the end of the last century much more conservative design criteria have been used with 1/10 of the dam height.

Towards the abutments and for the connection to the concrete plinth the core should be increased to double core width. Only very few cases have a thinner core with approximately 40 cm.

The filter zones adjacent to the core are placed simultaneously with the asphalt concrete core and give this required lateral support. They must be stable to support the core paving machine and they play an important role for the deformation of the asphalt concrete core.

In general, the core should be placed centrally in the dam. However, when a parapet wall is installed on the dam crest, the vertical axis of the core can be located somewhat upstream of the dam axis in order to connect the core with the wave wall and to increase the cross section of the dam.

The asphalt concrete core is generally built vertically from the bottom to the dam crest. A completely inclined or partly inclined core has the advantage of providing a favorable and additional confining stress. However, a vertical core is subjected to smaller shear stresses. In the unlikely event that cracks should occur and repair work is required, the repair grouting can be performed more easily with a vertical core. Boreholes may then be drilled in the upstream filter zone and grout injected to seal the leakage once this is located.

However, on very high dams, the upper part of the core can be considered to be slightly inclined towards the downstream side in order to reduce the danger that the upstream embankment detaches from the core in the crest area. It will also help to have enough space to place the riprap and the underneath required zones.

The filter zones placed on the adjacent upstream and downstream sides of the asphalt concrete core and the supporting shells provide an immediate lateral support to the asphalt concrete core and for the core paving machine during the construction. The filter zones should consist of stable and well graded crushed aggregates or natural gravels with maximum grain size of approx. 63 mm. Experiences have shown that an important proportion of crushed or angular particles is needed to assure a good lateral support to the core. The grading should preferable comply with $d_{50} \geq 10$ mm and $d_{15} \leq 10$ mm and the total fines (0 - 0.063 mm or 0.074 mm) content shall not exceed 5% of total weight. The difference in grain size between aggregates in the asphalt concrete core, the filter zone and adjacent supporting shell should not be too large. The following guideline is given in the ICOLD Bulletin 84 (1992):

d_{100} core $\geq d_{10}$ trans. and d_{100} trans $\geq \frac{1}{4} d_{100}$ shell

The grading curve requirements for the filter zones in an ACED are fairly relaxed compared to the filter requirements of other embankment dams.

Filter zone produced from crushed aggregates gives usually more stable support to the asphalt concrete core and the core placing machine than natural gravel and is preferable. The filter material can be wetted in order to ease the compaction. If a significant portion of rounded gravel is used for the filter zones, a high horizontal stress will also be imposed on the asphalt concrete core. This can create a risk of reducing the core width.

It was previously frequently described to use a finer transition zone on the upstream side and a coarser free draining material on the downstream. The reasoning is that if a defect exists or a crack opens in the core, the transport of fine particles into the defect will reduce the leakage until the viscous, plastic flow of the asphalt material causes self-healing. It can be argued that the migration of fine particles into a potential crack will impair the self-healing and be detrimental in the long run (see chapter 4.3.1, General requirements, Self-healing). Due to this and the excellent experience with ACEDs, it is today generally accepted that the same filter zone material can be used both upstream and downstream of the asphalt concrete core. The leakage rate through the core will then depend on the width of the sheared zone, its depth below reservoir level, and the permeability of the filter/transition zones next to the core. For such an extreme event, it would be beneficial to have added fine-grained material to the filter zones to reduce the leakage rate until the reservoir level can be lowered and repairs executed.

Most standard core paving machines have a total width of 3.5 m, but the total width can be increased within practical limits. The total width includes the two filter zones on each side of the core and the asphalt concrete core. The filter zone of a dam up to 100 m height should have filter zone width of 1.3 to 2.0 m. For ACEDs more than 150 m in height and for dams located in earthquake areas, wider filter zones may be needed. In such cases, the filter zones will for practical reasons partly be placed with the core paving machine and the outer part with ordinary equipment.

The intensive compaction of the filter zones and the hot viscose asphalt concrete core result in a close interlocking of both construction elements. The asphalt concrete core can therefore not deform differentially from the filter and transition zones.

Figure 4.2 Test field for an asphalt concrete core after removing the filter zone (Nemiscau 1 dam, Canada)

4.2.4 Seepage control

Seepage control and measurement is an important issue for the dam design. The downstream filter zone works as a chimney drain for the controlled drainage of seepage through the core. The most common seepage control is a central measurement point at the dam toe but such a system will also include potential water coming from the valley sides and potential seepage through the foundation.

In a more advanced system the seepage passing the core and penetrating into the downstream filter zone is collected at the concrete plinth or in a gallery. A small longitudinal wall of asphalt concrete or concrete built on top of the concrete plinth or the gallery can lead the seepage to the gallery. The seepage can be drained with pipes into a gallery. On longer dams the collecting wall can be divided in sections in order to locate the seepage in a more specific part of the dam.

4.2.5 Concrete plinth and gallery requirements

The concrete plinth of an ACED is basically simple in design and construction and is mostly designed in the center of the dam. The plinth is shorter compared with upstream faced dams. The main purpose of the plinth is to serve as a cap for the contact and curtain grouting under the core. The concrete plinth should be anchored into the rock foundation by rock bolts. If a thick layer of overburden remains in the foundation and a plinth is designed on top of the diaphragm wall, the connecting structure between the asphalt concrete core and the cut-off wall must be carefully designed to ensure the stability and imperviousness of the structure.

Figure 4.3 Concrete plinth construction (Rennersdorf Dam, Germany, 2010)

The plinth or the gallery at the abutments in connection to the asphalt concrete core should generally be designed with no terrace steps being more than 45° in inclination. If the inclination in the abutments is steeper than about 60°, the surface of the plinth or gallery should be inclined towards the upstream to achieve a higher stress induced by the water pressure between the core and plinth. Inclined surfaces (maximum 10 V to 1 H) should also be designed for the connection between the asphalt concrete core and concrete structure (e.g. spillway or powerhouse).

The concrete plinth or gallery is usually built in 6 to 10 m long blocks with transverse water stops. The water stops are embedded in the asphalt material and must be heat resistant.

Figure 4.4 Plinth detail, La Romaine-2, Canada

A gallery can be constructed below the asphalt concrete core or as part of the dam and will result in a considerable cost increase. However, if a gallery is needed for additional grouting or repair work at a later stage or if a gallery is required to fulfill the construction schedule by separating core construction and grouting, a gallery should be considered.

The block joints in the plinth and the gallery must be properly designed to prevent later leakages through the joints.

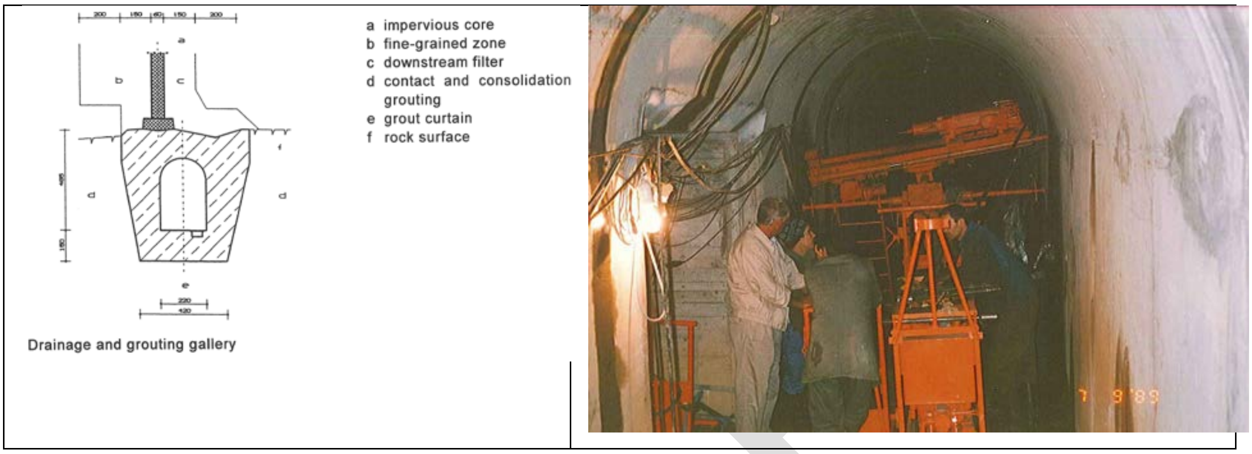


Figure 4.5 Drainage and grouting gallery, Feistritzbach Dam, Austria

4.2.6 Seismic Loading and Resistance

The slender asphalt concrete core has to be able to accommodate the cyclic and permanent strains imposed by the dam embankment during the earthquake without undergoing excessive cracking or material degradation. The core itself has little influence on the overall embankment behavior. As no existing asphalt concrete core dam has yet been exposed to significant earthquake loading, the design of new dams cannot rely on actual field experience. The design is based on the field performance of other types of embankment dams (e.g. earth core and concrete face dams) that have experienced earthquake loading, and on laboratory testing of asphalt concrete specimens subjected to cyclic loading and theoretical analyses and predictions of cyclic and permanent embankment deformations.

Compared to upstream facings, the position of a vertical asphalt concrete core, close to the central axis of the embankment, is favorable with respect to imposed static dam deformations and deformations caused by serious earthquake shaking.

The laboratory results presented by Wang and Hoeg (2011) and others show that the asphalt concrete core can withstand severe seismic shaking without significant material degradation and cracking. The earthquake resistance of the dam rather depends on proper design and zoning of the embankment itself.

Dynamic numerical analyses of embankment dams are performed by software that can handle non-linear elasto-plastic constitutive relationships for the embankment material (e.g. Plaxis, FLAC, SIGMA/W and Abaqus). The analyses are used to predict the dynamic stress-strain and displacement response during the earthquake loading and the permanent (residual) displacements resulting from the shaking. Equivalent linear approaches are not able to compute permanent deformations that occur during the earthquake shaking.

The largest dynamic amplifications and accelerations occur towards the top of the dam where the asphalt concrete core may experience tension and shear strains that could result in cracking. Numerical analyses of typical ACEDs demonstrate that the bending moments in the asphalt concrete core are the largest in the top part, but below about 1/5 of the dam height from the crest, the core is in compression only. The residual embankment settlements and displacements predicted by the numerical analyses should be compared against the displacements computed by the simpler Newmark approach for estimating permanent shear displacements. However, the Newmark approach only considers shear strains along specified slip planes and does not include volumetric plastic strains that occur in the embankment material. On the other hand, the results of the more complete and complex non-linear elasto-plastic analyses are very sensitive to the assumptions used in the material constitutive relationships.

When the computed results indicate that the top part of the asphalt concrete core may undergo excessive deformations and cracking during the Safety Evaluation Earthquake (SEE), special design measures are required to increase the dam's earthquake resistance:

- Use high-quality, well graded, well compacted rockfill/gravel in the top part of the dam. The effective stresses are low in the top part, and for low normal stresses friction angles above 50° may be achieved.
- Flatten the exterior slopes of the top part of the embankment to increase stability and reduce shear displacements.
- Use horizontal reinforcement (e.g. armoring with geogrids) in the top part of the dam.
- Increase the core thickness to allow for deeper tension cracks or larger shear displacements without causing critical damage to the core.
- Use an asphalt concrete mix with a softer bitumen type and/or higher bitumen content or introduce admixtures (e.g. SBS) to increase the core flexibility and ductility and the ability to sustain large shear and bending strains without excessive cracking. Reinforcing fibers of various types may also be added to the asphalt concrete mix to increase the core cracking resistance.
- In any case, if there is a possibility of cracking and local leakage through the top part of the core, the filter zone on the downstream side of the core should be designed as a wide filter. The purpose is to arrest any erosion from the upstream filter zone through the cracks and to transport particles downstream. Crack-stopper material in the upstream filter zone will then migrate into the cracks and reduce leakages and erosion that otherwise may occur during the period it takes to repair the core after the earthquake.

For a dam site where fault movements may occur in the dam foundation, special design and construction considerations are required. The best option is, if possible, to relocate the dam.

4.3 MIX DESIGN AND MATERIAL PROPERTIES

4.3.1 General requirements

Workability

A sufficiently high viscosity and deformability of the asphalt concrete mix are important properties to ensure a good workability especially for dams in cold and wet climatic environments. Crushed rock shall basically be used for aggregates and the addition of some natural sand or gravel in the asphalt concrete mix will improve the workability.

Limestone powder as filler material has a “lubricating” effect and will also improve the adhesion between bitumen and aggregates.

It is important to ensure that there is no clay, dirt, humus or other contaminations in the aggregates and - if necessary - the material should be washed.

Flexibility

An asphalt concrete core must be sufficiently flexible and ductile to follow the induced deformations of the embankment and the adjacent zones without cracking and leaking. The flexibility of the asphalt concrete mix can be adjusted and modified to the expected deformation of the dam shell and the adjacent zones. This means that the deformation of the asphalt concrete core depends on the induced deformation of the embankment. In general asphalt concrete mixes are very flexible and the grade and amount of the bitumen as well as the content of the fine aggregates influence the flexibility. The two possible mix designs of asphalt concrete (very flexible and relatively stiff) have been used in the past depending on the local conditions. One of the largest deformations which ever occurred on an ACED dam without any leakages was in a range of about 2.4 m (see Appendix B, Eberlaste Dam, Austria). On the other hand more stiff asphalt concrete mixes have been used for dams with stiff embankments in various countries.

Figure 4.6 Asphalt concrete cores are very flexible and ductile
(Trial test at Nemiscau 1 dam, Canada)

Permeability

The relationship between the air void content and permeability in compacted asphalt concrete samples is well documented in many studies and research reports. Permeability tests are fairly difficult and time consuming while void content measurements are fast and easy. Therefore, it is today generally accepted that the air void determination has to be part of the technical specifications and permeability tests only have to be used if there are concerns.

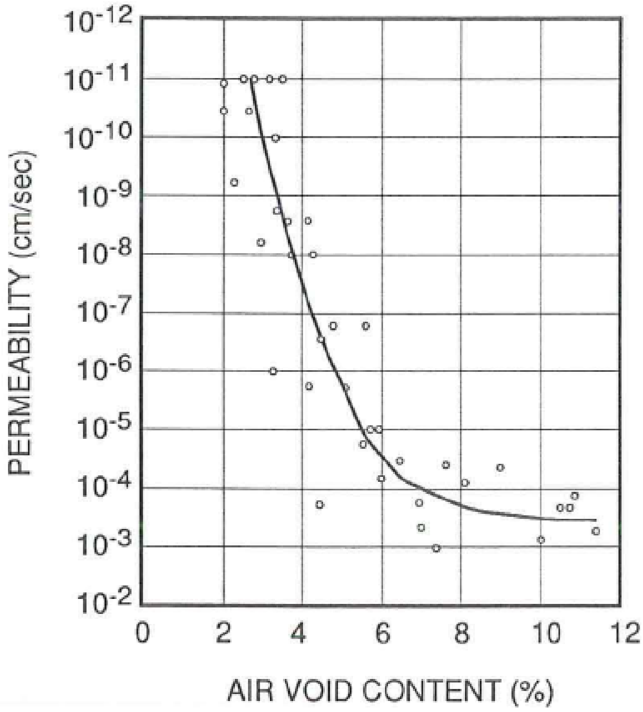


Figure 4.7 Permeability versus air void content of asphalt concrete mixes

Self-healing ability of asphalt concrete

Should a crack occur in the asphalt concrete core - which is highly unlikely, the viscoelastic-plastic and ductile properties of the asphalt concrete provide a self-healing ability. The degree and the time of the self-healing process depend primarily on the stress imposed on the crack, the temperature and the viscosity of the bitumen.

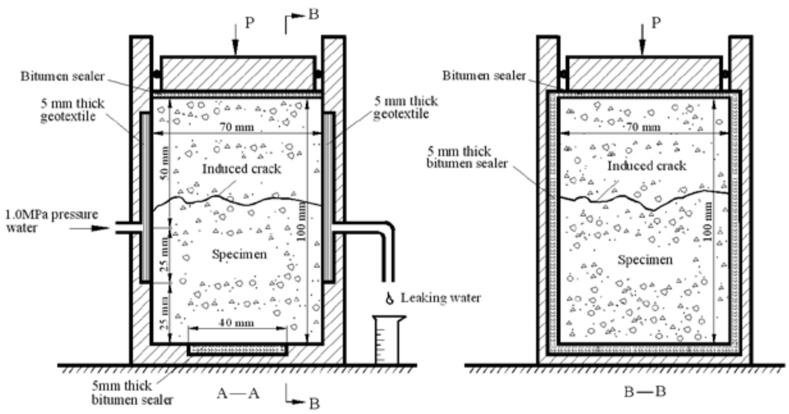


Figure 4.8 Self-healing of cracks in asphalt concrete material, test equipment

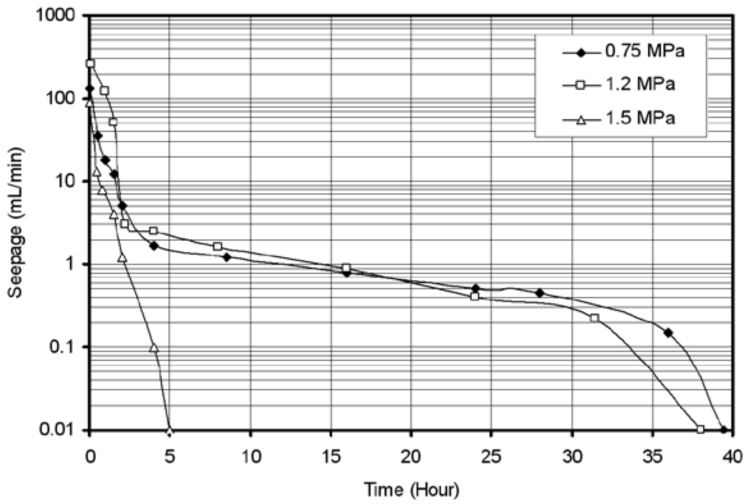


Figure 4.9 Results of self-healing tests

The regained tensile strength of the cracked specimen was found to be approximately 55% of the initial tensile strength after applying a vertical stress of 1.0 MPa for 24 hours at an ambient temperature of 7°C.

4.3.2 Aggregates and Filler

With the high content of bitumen and filler in asphalt mixes the bitumen/filler film around the aggregates is fairly thick when compared with ordinary road mixes. The coarser aggregates are “floating” (see Figure 4.10) in the mix of fines, filler and bitumen and even under very high hydraulic pressures there is no risk that the bitumen will be pressed out of the core.

Figure 4.10 Drilled and cut core sample with floating coarse aggregates

Aggregates for asphalt concrete cores should be sound and property-stable rock or a mixture of rock and sand or crushed gravel. In special cases, natural gravel can be used up to a certain amount to increase the workability. The quality requirements for the aggregates are fairly relaxed compared to the requirements for aggregates used for road asphalt concrete due to the severe tear and loads (see technical specifications, Chapter 6.2.2 Materials).

Differences in quality of the aggregates (strength parameters, etc.) have minor effects on the stress-strain behavior of asphalt concrete cores compared to other applications, like road construction. However, aggregate flakiness requires higher bitumen content in order to obtain the required void content (permeability) and it affects also the workability of the asphalt concrete.

Adhesion between aggregates and bitumen is a critical parameter for the asphalt concrete facing linings and road asphalt and an adhesion agent is normally required if the aggregates are acidic of origin. The bitumen/filler film around the aggregates for asphalt concrete cores is thicker and therefore, water cannot penetrate into the core and ensures imperviousness. Accordingly, both acidic and basic aggregates can be used for such asphalt concrete mixes without adding an adhesion agent.

The required filler in the asphalt mix will normally be a mixture of fillers retrieved from the aggregates and the added filler that is provided from an external source. The asphalt plant should therefore be equipped with an air bag filter system that retrieves the aggregate filler (see Chapter 5.3.1, Asphalt Mixing Plant, Requirements). Filler delivered from an external source will normally be expensive and it will be economical to produce aggregates with a high content of filler in order to reduce on the imported filler. The retrieved filler shall normally not exceed 50% of the total filler content in the asphalt concrete mix.

The surface area of filler will be the majority of the total surface of all aggregates in the asphalt concrete mix. Different fillers can have a great influence on the asphalt concrete mix workability.

Added filler can be cement or finely ground limestone.

4.3.3 Bitumen

Bitumen in this context is a product obtained from distillation of crude oil in a refinery. Various crude oils and the bitumen extracted through the refinery process have somewhat different characteristics. However most of the bitumen produced world-wide of the required penetration grade can be used for asphalt concrete cores.

Bitumen is a natural product and contains no additives that can pollute the environment or the water itself. Asphalt for concrete cores or asphalt concrete linings are therefore commonly used for irrigation or water storage structures.

Polymer modified bitumen in order to increase tensile strain of the asphalt concrete mix is becoming fairly common for many asphalt applications. However, the use of polymer modifier causes a considerable increase in the bitumen price and is generally not required for asphalt concrete cores.

Hardening and oxidation of the bitumen is a well-known phenomenon on road pavement and asphalt concrete facings. This is caused by radiation from the sun, variations in temperature and with air and moisture penetrating into the pavement. For asphalt concrete cores the material is well protected inside the dam with no sun radiation and in an environment where the temperature is moderate and fairly stable. Furthermore, the bitumen is very dense and neither air nor moisture can penetrate into the asphalt concrete core. If good bitumen is used, oxidation or hardening is no concern for asphalt concrete cores after the initial hardening during production at the asphalt concrete plant, transportation and placement.

Dams are built for a long lifetime and bitumen of a good quality will maintain the behavior of the core material for a very long time when protected inside the embankment dam. The aging properties of the selected bitumen must be controlled for all new asphalt concrete core projects.

The available various bitumen grades are commonly designated by a penetration value. The most common type is B 70/100 and B 50/70 is less commonly used. Bitumen type B 50/70 with an initial penetration value between 50/10 mm and 70/10 mm is fairly stiff while, for example, a bitumen B 160/220 is very soft.

The bitumen type and grade have a great influence on the asphalt concrete mix properties. These properties can be tailored to local conditions at the site and the design criteria for the dam. The local conditions to be evaluated are usually:

- Temperature at the site and the water temperature in the reservoir
- Potential earthquake shaking
- Potential foundation and embankment settlements

In locations where considerable earthquake shaking can occur or in locations with possible foundation settlements, a bitumen type with a higher penetration value is preferable.

Local climate conditions for road asphalt will often dictate the bitumen grade available in the particular country. In countries with a hot climate, the bitumen qualities available are general fairly stiff. However, special softeners are available and can be used to increase the penetration values if needed. Further, increasing the bitumen content in the asphalt concrete mix within certain limits will also produce a more ductile material even when based on a fairly stiff bitumen.

4.3.4 Mix design

General

The asphalt concrete mix design shall demonstrate the suitability of materials and that the mixture complies with the specific dam project and the local conditions. The local conditions can be described by:

- Foundation and estimated foundation settlements
- Estimated dam settlements during construction and impounding
- Earthquake hazard and potential impact at the dam site and in the region
- Climatic conditions.

The aggregates intended to be used for the asphalt concrete core shall be tested and evaluated in accordance with Chapter 4.3.2 Aggregates and Filler and Chapter 7 Quality Control during Construction. The following parameters should at least be evaluated:

- Origin and petrography of the aggregates
- Visual assessment
- Gradation
- Flakiness
- Water absorption

- Affinity to bitumen
- Strength according to Los Angeles abrasion and impact method
- Heat resistance

Filler material in the asphalt concrete mix will consist of retrieved aggregate filler and the external filler e.g. ground limestone, cement or other approved filler material.

- Gradation of material less than 0.063 mm (0.075 mm US Standard)
- Water absorption

The bitumen intended to be used shall be tested for (see Chapter 4.3.3 Bitumen and Chapter 7 Quality Control during Construction):

- Penetration (before and after heating)
- Ring & Ball (before and after heating)
- Fraaß fracture point
- Long term aging properties
- Elastic recovery (only for polymer modified bitumen)

The aggregates including the filler shall be combined is such a way that the grading follows the Fuller's gradation curve within reasonable limits. If this cannot be achieved, further adjustments must be performed to produce more adequate aggregates. In order to increase the workability of the asphalt concrete mix, natural sand or gravel with a certain amount of surface rounded particles can be added.

Normally the bitumen content will be between 6.5 and 7.5 % measured as percentage of total weight. To a great extent the bitumen content depends on the gradation curve, the specific density of the aggregates and the filler content. A slightly higher bitumen content than the bitumen content which is theoretically sufficient to fill the voids in the aggregate mix is recommended.

Such asphalt concrete mix can easily be compacted to obtain a void content of less than 3% in the field and will definitely be impermeable.

Fuller curve

The mineral grain composition shall comply with Fuller's gradation curve n = 0.45 (Figures 4.11 and 4.12) within reasonable limits and must be improved by adding a higher content of fine grained material (filler material smaller 0.063 mm European Standard and smaller than 0.075 mm US Standard).

Asphalt concrete mixes considering the Fuller gradation curve have the highest strength, are ductile and will have the ability to sustain great tensile and shear stresses before cracking. The maximum aggregate size should generally not exceed 18 mm due to segregation concerns.

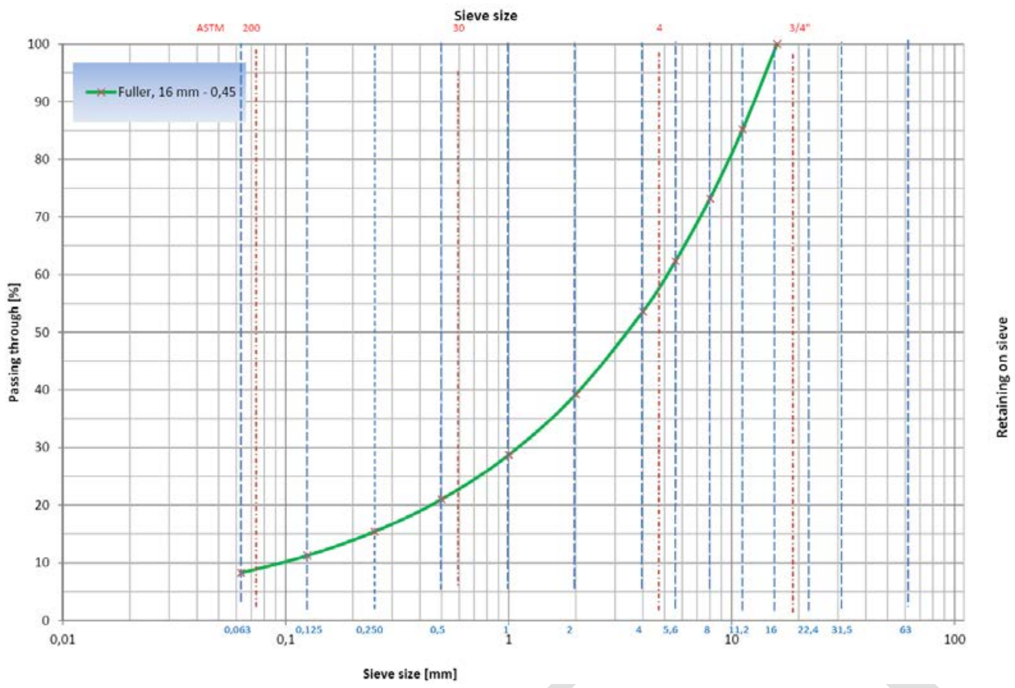


Figure 4.11 Theoretical Fuller curve, maximum grain size 16 mm, n = 0.45, metric sieves

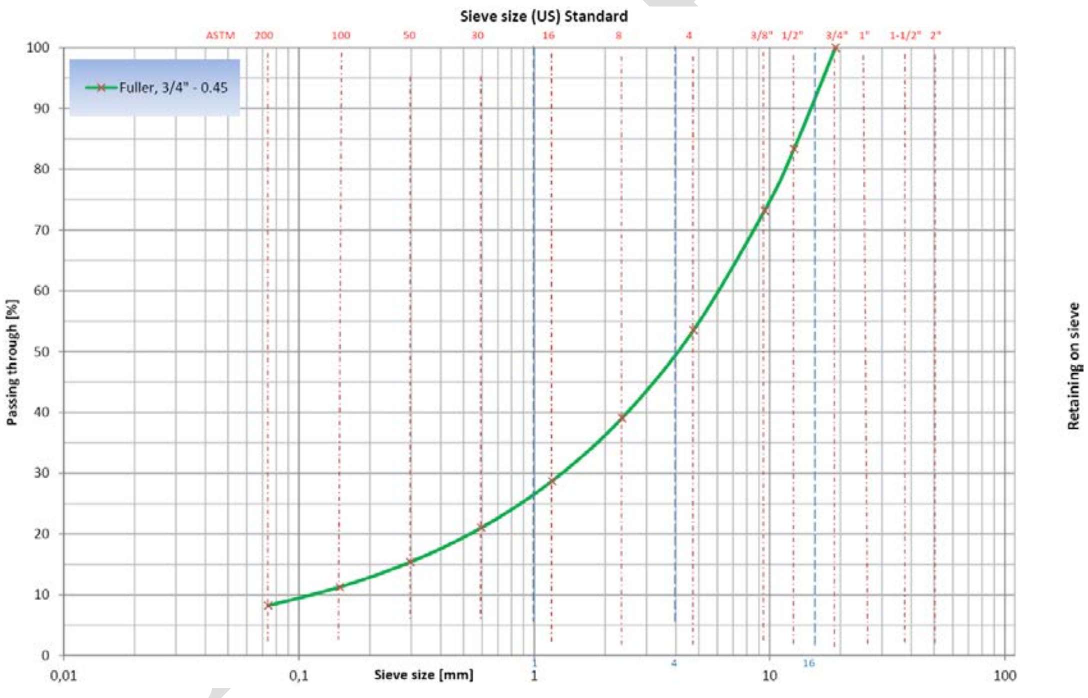


Figure 4.12 Theoretical Fuller curve, maximum grain size ¾-inch, n = 0.45, ASTM sieves

Figures 4.11 and 4.12 are only showing the theoretical Fuller curves to achieve the maximum density of aggregates. The content of fines must be increased for the production of AC material.

Suitability test

The contractor shall prepare at least three Marshall-samples with different bitumen and filler contents in his laboratory for the air void optimization. The bitumen content for the initial tests is usually in a range between 6.5% and 7.5% of the total weight with maximum increments of 0.5%.

The Marshall samples are usually compacted with 30 blows on both sides. This compaction corresponds approximately to the compaction achieved by adequate pavers in the field. If the client or the contractor wants to evaluate the workability of the asphalt concrete mix, further tests can be performed with 10 and/or 20 blows in addition to the normal 30 blows on the samples.

The asphalt concrete mix production and the compaction temperature depend on the grade of the bitumen to be used. For bitumen with grade B70/100 penetration, the compaction temperature shall be between 130° and 170° C. For the final decision on the bitumen and filler content the achieved air void content and the workability of the Marshall samples have to be considered.

After the preliminary asphalt concrete mix design is finished, a triaxial test should be performed for higher dams. Such tests shall be carried out and evaluated by an experienced laboratory and the consequences of the triaxial test results must comply with local conditions of the dam.

In order to define the final bitumen content, it is also important to consider the accuracy of the bitumen dosage (in-weighing) at the asphalt plant. The accuracy is normally required to be ± 0.3% measured on a single item test or less than ± 0.2% in average.

The optimized bitumen and filler content tested on Marshall samples in the laboratory shall have a maximum void content of 2.0 %

After the trial section is performed at the construction site the final bitumen content for the regular production can be evaluated based on the results and - if required - adjusted accordingly.

If major changes of the material properties, the material mix or paving conditions occur, the suitability test has to be repeated.

The final bitumen content and the properties of the asphalt concrete mix for the regular production have to meet the design requirements which take into consideration the actual dam conditions such as dam height, dam fill materials, foundation conditions, seismicity of the dam site, etc.

4.4 LABORATORY TESTING OF ASPHALT CONCRETE MIXES

4.4.1 Preparation of Marshall test specimen

Testing of Marshall specimen (EN 12697) is a common way to control the void content and the workability of mixes. For asphalt concrete cores and placed layers with height of 20 to 25 cm, it is recommended that the Marshall samples should be compacted with 30 blows on both sides. Such compaction usually corresponds approximately to the compaction achieved at the dam. The compaction temperature of Marshall-Specimen depends on the bitumen grade which is used for the specific application (for example 135±5 °C for regular bitumen B 70/100). The Marshall hammer shall have a steel anvil. Marshall compaction tests should be used for the initial asphalt concrete mix design and for daily control at site.

4.4.2 Tests on Marshall samples

Marshall samples with different compaction efforts can be used for the determination of the void content during mix design work. However, the daily quality control on Marshall samples must be done on specimen compacted with 30 blows on each side.

4.4.3 Tri-axial compression test

C-D Tri-axial tests are often used for evaluating the asphalt concrete mix intended for any project. The results can be compared to expected stress conditions and assumed core displacements. For higher dams, this should be performed as a standard.

Cylindrical specimens of diameter 100 mm (150 mm) and height 200 mm (300 mm) are prepared in the laboratory. Compaction of the tri-axial specimens should normally follow the below described procedure. A standard Marshall tamping hammer is used with 30 blows per layer. The specimens are built up in 4 layers of equal thickness. This compaction process produces samples that have approximately the same parameters as from drilled core samples from a dam. The specimens are enclosed in an impervious rubber membrane during the test.

Test conditions normally used are:

- Test temperature: 5, 10 or 20°C, depends on the local conditions and water temperature in the reservoir
- Rate of strain: 0.03%/min. - 0.1%/min.
- Lateral stress: 0.2 MPa to 1.5 MPa

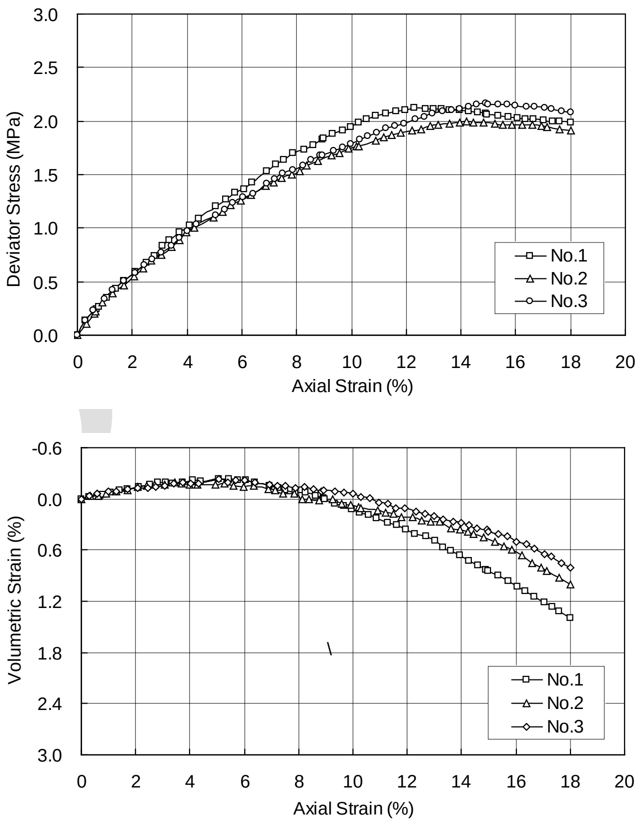


Figure 4.13 Example of tri-axial test for asphalt concrete core, sample with diameter 100 mm, height = 200 mm.

The test temperature for the samples shown in Figure 4.13 was 15°C and the lateral confining stress was 0.4 MPa. The specimens had a bitumen content of 6.5% and bitumen grade B70 was used. In the figure positive values for volumetric strain indicate volumetric expansion, i.e dilatation. The test results showed volumetric compression (reduction) up to an axial strain of about 6% and then dilation that amounted to 0.1-0.4% at an axial strain of 12%. In general, dilation decreases with increasing confining stress and bitumen content.

4.4.4 Bending test

A two-point bending test of a prismatic specimen can be applied to determine the flexibility of asphalt concrete layers under the deformation yielding bases. This is a simple test and can be carried out in room temperature (20 °C ± 5 °C).

4.4.5 Cyclic loading Tri-axial test

This test can be considered in areas with a probability of earthquakes with high intensity. Such test requires very special equipment and highly experienced personnel to measure the combining and axial stresses as well as the creeping of the material.

4.4.6 Other tests

Other tests than the above mentioned can be considered under special circumstances and conditions.

4.5 NUMERICAL ANALYSES OF DAMS WITH ASPHALT CONCRETE CORES

An asphalt concrete core is like a very thin diaphragm embedded in the embankment. The deformations and stress-strain conditions of the asphalt concrete core for the dam are induced by the embankments and the foundation. It is fairly difficult to perform an accurate calculation of the deformations after impoundment of an embankment dam made of rock and gravel materials (see also ICOLD Bulletin no 150). The stress calculations of the embankment have proved to be more reliable but some uncertainties for the ACED remains.

4.5.1 Implementation of material properties

Asphalt concrete materials have a strongly strain rate-dependent behavior and the properties depend on long-term creep test results (see References). The stress-strain curve of asphalt concrete at creep-stable states presents a nearly linear relation in a certain strain range and the confining stress has insignificant effects on the modulus because the coarse aggregates are floating in the mortar. When the stress-strain curve is beyond the linear relation the coarser aggregates will come in contact and a non-linear relation will result.

The Poisson’s ratio depends to a great extent on the asphalt concrete mix design and can normally be in a wider range.

5. CONSTRUCTION METHODS AND GUIDELINES

5.1 GENERAL OBJECTIVES AND COMMENTS

An asphalt concrete core construction is generally easy and fast to build and the construction site is tidy with a good overview, however, quality control must always be implemented at 100 % due to the fairly thin asphalt concrete wall built inside the dam. The machinery and equipment used for the ACED construction as well as the employed personnel must fulfill the highest standards.

ACEDs are nowadays built under all various climatic conditions - from cold and wet to very dry and hot climates. Wet and cold conditions can be challenging and require special considerations. In hot and arid climatic conditions the asphalt concrete core will remain hot and viscous for a long time. The asphalt concrete is normally placed in horizontal layers with a thickness of 20 to 25 cm after compaction. Each layer is placed on top of the previous one symmetrically to the centerline of the appropriate level of the dam. As the specified width is a minimum requirement, the actually placed width will be somewhat wider than the theoretical one, depending on the machinery and the contractor's experience.

When hot, the asphalt is viscous and fluid in consistency and the fine filter zone adjacent to the asphalt concrete core must be placed simultaneously with the asphalt concrete in order to provide the core with an immediate lateral support. There must be no contamination from the filter zone material on or in the asphalt concrete placed.

The asphalt concrete layers melt together to form a continuous and homogeneous wall within the dam with no detectable joints between the layers. Generally, no tack coat is required between the layers. If the surface of the asphalt concrete core is to a great extent contaminated with sticking fines a tack coat can be considered.

Asphalt concrete contains heat for a considerable time and is thus a quite forgiving material. Even so, it is important that moisture is not trapped between the layers since trapped moisture may result in a weakened joint.

Nowadays, any modern paving equipment is made with infrared heating equipment in front of the paving machine. Its main objective is to ensure that no moisture remains on the previously placed asphalt concrete layer. A secondary objective is to warm up the top of the previously placed asphalt concrete layer. The heat contained in the newly placed 20 - 25 cm layer will warm up the top surface of the previous layer sufficiently for the layers to melt together. The minimum temperature requirement for the previous layer and the minimum temperature requirement for compaction of the new layer must be strictly respected. The situation is very different when placing thin asphalt concrete overlays on road and airfields. In these cases, the thin overlay will fairly soon be cooled down if the underlying surface is cold and the air temperature is low.

With good machinery and placement procedures it is possible to perform core placement during moderate rainy conditions and at low temperatures down to 0˚C.

The asphalt concrete to be placed is very dense with a high content of bitumen, fine aggregates and filler. Its compaction differs from the asphalt concrete compaction for thinner road pavements as the aggregates are moved into their ideal configuration through vibration – thus achieving the main requirement of less than 3% void content.

Some core paving machines are equipped with vibratory plates for the initial compaction, however, even with vibratory plates fixed to the core paving machine, additional hand-held vibratory rammers or vibratory rollers will be required in order to achieve the required void content.

In cold, windy and/or wet conditions, it is important that the initial compaction of the asphalt concrete core is performed in fast succession of the core placement.

The compaction equipment for the asphalt concrete core will depend on the width of the core. The first compaction behind the paver can either be done with vibratory rammers or vibratory rollers. The roller is normally 15 - 20 cm wider than the placed core and will therefore also partly compact the edges of the adjacent filter zone. The filter zone will require more compaction than the dense asphalt concrete and is accordingly placed in thicker layers than the asphalt concrete. The amount of over-height depends greatly on the type of filter zone material to be used. When specifying the over-height, it is highly important that the roller is not just "riding" on the filter zone – but providing sufficient compaction to the asphalt concrete core.

For higher dams with a varying width of the asphalt concrete core, several rollers with different roller widths may be required for the compaction as the core width decreases with the height.

The compaction of the filter zones on each side of the asphalt concrete core should be performed with two rollers working in parallel. This parallel movement is necessary as the soft and flexible asphalt concrete core can easily be distorted horizontally.

During compaction of the filter zones, a horizontal force will be imposed on the asphalt concrete core. The degree of horizontal pressure depends greatly on the type of the filter zone material. A significant proportion of rounded gravel material will generally induce more horizontal pressure than crushed rock. It must be ensured that the core maintains the minimum designed width.

Due to the compaction of the filter zone material and the horizontal stress imposed on the asphalt concrete core, the asphalt concrete surface may be slightly convex after compaction of the core and the filter zones. If this is the case, minor small longitudinal cracks will occur on the surface of the asphalt concrete. This phenomenon has been studied in detail and is no reason for concern. The small cracks will disappear when a new layer is placed on top, heating up the previous surface and melting them together.

The top surface of the asphalt concrete core will cool down fairly quickly but the inside of the core will remain warm for a very long time. It must be ensured that the asphalt concrete core is not exposed to any horizontal or vertical loading or stress. If local conditions require that transportation is necessary across the asphalt concrete core, special movable bridges have to be built for such purposes.

Hand placement of the asphalt concrete core and filter zones will always be required at the low point of the dam, near the connection to the plinth and towards the abutments. In such an area, the asphalt concrete is placed inside a pre-arranged formwork and between the filter zones. The formwork is lifted as the zones are placed and compaction commences. The same quality requirements apply for hand placed and for machinery placed areas. Under cold and or wet conditions, hand placement and compaction must be performed in quick succession in order to maintain the minimum required temperature for compaction.

Before asphalt work commences, the concrete plinth must be properly treated in order to achieve a good bond between the concrete plinth and the asphalt concrete core. First, all grouting spills must be removed; thereafter, the thin cement film covering the concrete aggregates at the surface must be removed. This can be achieved by various methods but jet blasting or sand blasting is considered preferable as it also leaves a fairly rough surface and it is environmentally friendly.

The prepared concrete plinth must be covered with a thin layer of asphalt mastic to ensure a good bond between the concrete and the asphalt concrete core. The concrete must be fully cured before this procedure commences. The surface must be cleaned, completely dry and heated by propane burners before the asphalt mastic is applied. Therefore, this type of work cannot be performed during precipitation.

To secure a good bond (adhesion) to the concrete, dilute bitumen is commonly sprayed on the surface of the concrete. After the solvent in the dilute bitumen is fully volatilized a layer of 1 to 2 cm thick asphalt mastic is placed. An additive to the asphalt mastic or treatment of the concrete surface may be required.

When the hot asphalt concrete is placed on top, the asphalt mastic will be liquefied and melt into the asphalt concrete placed on top. The asphalt concrete in the joint area will therefore be richer in bitumen and fines and act as a stress relieving layer.

5.2 HISTORY OF ASPHALT CONCRETE CORE CONSTRUCTION TECHNOLOGY

The first embankment dam with machine placed and compacted asphalt concrete, the Kleine Dhünn Dam, was built in Germany in 1962. The asphalt concrete core design was chosen after extensive research and practice tests - most of them performed by Strabag Bau-AG. Based on the very good results obtained, additional dams with central asphalt concrete cores followed in quick succession such as the Bremge Dam (1962) and Bigge Outer Dam (1963) in Germany and the Eberlaste Dam (1968) in Austria. With regards to the Eberlaste Dam, it should be mentioned that the total settlement of the dam was 2.40 m due to significant subsoil deformations. However, the water tightness of the asphalt concrete core was unaffected.

All bituminous cores so far were of minor to medium size. The breakthrough for high dams with asphalt concrete cores came in Hong Kong in 1973 with the 100 m high dams of the High Island Water Scheme. After this breakthrough other high dams in Austria and Germany were constructed with an aspahlt concrete core such as the Finstertal Dam (1979), the Grosse Dhuenn Dam (1980) and the Schmalwasser Dam (1991).

Danghe Dam, the first asphalt concrete core dam in China, was built in 1973 by a local construction company. The first ACRD in Norway, the Vestredal Dam, was built in 1980. Other dams were built during the same period in Hong Kong, Chile and Japan.

During the second part of the 1990s, there has been a considerable increase in asphalt concrete core dams being built. A very large part of this increase was due to the construction activity in China. In Quebec, Canada, the first ACED was built in 2008 and Brazil followed with their first ACRD in 2010.

Due to the good experiences and performance of these dams, the height of AC dams also increased. Major milestones were the 100 m high asphalt concrete core at Finstertal Dam in Austria, completed in 1980, the 128 m high Storglomvatn Dam in Norway and the 125 m high Yele Dam in China. Today, new projects approaching a height of 200 m are under design and construction.

The advantages and economic reasons for choosing an ACED design vary considerably from location to location.

The majority of the German rockfill dams built before the 1960s had an impervious clay core. After the successful attempts with asphalt concrete cores at the Dhünn Dam and the Bremge Dam this construction method was increasingly used as its benefits are evident:

- Short construction period
- More or less weather independent
- Independent from local natural clay sources
- Possible impoundment during construction

Several dams in Austria have been built as embankment dams with moraine or silty clay cores on lower elevations. Some of the main reasons for selecting asphalt concrete cores were the short construction season on high elevations in the Alps, the limited quantity of suitable and less permeable materials for classic dam types, the weather conditions in mountainous regions together with heavy rainfall and difficult random conditions for placing impervious materials like moraine and other fine grained materials as a core.

In Norway, the big majority of dams were embankment dams with a moraine core. With new dams in the mountainous regions where moraine was not available, alternative design had to be evaluated and ACED design was chosen. Some of the major proven benefits are:

- The construction season in the mountainous regions is short and the climate often wet and cold. ACEDs can be constructed under such conditions and the construction schedule can be shortened and the construction season can be prolonged.
- The reservoir can be filled as the construction proceeds.

In Quebec, Canada, the majority of dams previously built were embankment dams with a moraine core. In new areas were moraine was not available, asphalt concrete core design was chosen for much of the same reasons as in Norway.

Dams in Brazil were mostly earth fill embankment dams or CFRDs. The construction time period from the time the contract is awarded to power generation commences is of major importance due to the high investment cost incurred by the investor group as most of the hydropower projects are BOT projects. Therefore, a certain approach has been developed whereby construction is very fast with work being performed on two or three shifts. Many parts of Brazil are also characterized by high precipitation that causes delay for some dam types. Although there is earth fill material available, ACEDs have proven to be an economical alternative in Brazil because of the fast rate of construction even in areas with high precipitation.

The initially used basic placement technique has been generally maintained, though the machinery has undergone considerable improvements over the years.

5.3 EQUIPMENT

5.3.1 Asphalt mixing plant

General

Asphalt concrete for ACEDs must be produced at the highest possible standards and any variations must always be within the specified tolerances. This entails strict criteria for the type and accuracy of the asphalt mixing plant itself and the variations in the aggregates for asphalt production as well as the temperature control and the temperature limits related to the bitumen grade also considering the climatic conditions. Furthermore, asphalt produced for and placed on a road or airfield can quite easily be removed if there has been a fault in production. Potential removal and repair is considerably more troublesome on an ACED if the faulty production is not noticed immediately after the asphalt concrete was placed.

There are in principle two major types of asphalt mixing plants. Asphalt batch plants where the various aggregates are re-screened after heating and weighed separately into the mixer together with the required bitumen and filler. The other types are continuous asphalt mixing plants or drum mixers where the various aggregates are loaded by weight or volume directly into the heating and mixing drum. There is no screening at the asphalt mixing plant and the weighing is done before the aggregates are heated. Continuous drum mixers are mostly used for large continuous productions and the mix accuracy depends on aggregates that are within strict tolerances.

On ACEDs, daily production will be low with frequent start and stops when work commences at the bottom of the dam. As the dam rises, production will gradually be more continuous with increased production.

For ACEDs, asphalt batch mixing plants should be specified in order to have sufficient control of the produced asphalt concrete. Continuous mixing plants deliver asphalt concrete products in a wider range compared to batch mixing plants and they are not as suitable as batch plants.

Asphalt concrete for ACEDs is rich in bitumen, fine aggregates and filler. Therefore, the mixing time must be increased compared to the regular mixing time for road asphalt. Company leaflets from various asphalt batch mixing plant suppliers usually base the production capacity on a mixing cycle of 45 seconds. For this sort of asphalt concrete, it is recommended that the cycle is increased, for example to 60 seconds, depending on local conditions. This could reduce the capacity by approximately 33%.

Due to the very high quantity of fine aggregates (approximately 50% ≤ 4 mm), the screening capacity at the asphalt mixing plant often becomes the critical production factor. Asphalt mixing plants for ACEDs should have a higher screening capacity than those used for road works.

Requirements of asphalt mixing plant

Asphalt mixing plant capacity:

The asphalt mixing plant should normally have a capacity of placing at least three layers per day at any level of the dam. The number of working hours per day should be considered carefully as production will not be continuous.

The production capacity of the heating drum depends to a great extent on the moisture content in the aggregates. The fine fraction (less than 4 mm) especially absorbs a high quantity of moisture if unprotected towards rain and should be covered on locations where precipitation is frequent.

Cold feed silos for asphalt concrete aggregates:

Aggregates are normally crushed or a mixture of crushed and natural sand/gravel is used. The crushed aggregates should be prepared at a minimum of four fractions and loaded in separate silos. If natural sand is added, an additional silo is required.

The crushing and screening process should be subjected to close quality control. The grading curve for the various fractions produced will depend on the crushers and their wear and especially if screening has been performed in dry or rainy conditions. Variations in the gradation curves will cause difficulties and necessitate adjustment during production at the asphalt plant.

Dust and Micro Filter:

The asphalt concrete mix for ACED dams contains approximately 10 - 15 % filler (material ≤ 0.063 mm – European Standards or ≤ 0,075mm, sieve #200 – US Standards). This is provided by the filler in the aggregates and filler supplied from an outside source. To extract the filler from the aggregates, the asphalt mixing plant will need to be equipped with an airbag filter through which the filler is exhausted from the heating drum. A good airbag filter system is economical as it reduces the purchase of filler from an outside source, and it is beneficial to the environment.

Filler silos:

The asphalt plant should be equipped with two filler silos, one for filler extracted from the airbag filter and one for external filler. The asphalt concrete mix is sensitive to the type of filler used, and accordingly there should be separate in-weighting from each silo.

Screens and hot storage silos for the heated aggregates:

The aggregates are screened after heating in the heating drum. It is recommended that the screens at least produce the following aggregate fractions:

- 0 – 3 mm (0 – 4 mm)
- 3 (4) - 8 mm
- 8 - 11 mm
- 11 – 16 (18 mm)

Screening dimensions may vary with national standards.

An additional fraction of less than 2 mm will achieve better gradation control of the asphalt concrete. But smaller fine fraction will require a bigger screen surface at the asphalt plant.

Mixer unit:

The mixer unit selection depends on the amount of weight (kg) it is capable of mixing. The mixing capacity per hour is a multiple of the mixer size multiplied with the number of cycles per hour.

Hot storage asphalt mix silo:

In order to have a continuous supply when required at the dam, the asphalt plant should be equipped with a small hot storage silo. The silo will also reduce the number of "starts and stops" at the asphalt plant, reduce production waste and secure a more homogeneous asphalt concrete mix.

Quality control:

A computer printout for all components of each batch produced is recommended. This enables the operator to control all quantities for each batch and to check whether a mix has been faulty. Further, the accuracy of the asphalt plant can be daily monitored.

Modern asphalt mixing plants are equipped with an alarm or warning signal for any fault in the weighing to the mixer.

Special operating procedures for the asphalt plant should be taken in cold and/or humid regions.

5.3.2 Core paving equipment

A) German equipment (STRABAG International GmbH)

Initial experience was gained in the early 1960's using a towing box pulled by a bulldozer with a crane supplying the hot mix. Compaction was carried out subsequently by means of vibratory plates with small rollers for the final compaction (1^{st} generation).

The equipment used to place the earlier constructed asphalt concrete cores was developed shortly afterwards (2^{nd} generation). The transition material was placed before the asphalt concrete by being tipped onto a roof-shaped nose mounted at the front end of the core placing machine. From there it is laterally distributed to the left and right and leveled by a screed following behind. A hopper for the asphalt concrete is located behind the screed. From this hopper the asphalt concrete then reaches the free space formed by the above mentioned nose. The nose formwork ends behind the feed shaft for the asphalt concrete to allow the asphalt concrete to interlock with the transition zone material. Both transition zone material and the asphalt concrete core are compacted by a group of vibratory plates at the rear end of the core placing unit. With the repeated development of the placing and finishing equipment described in the previous paragraph, experience could be gained both with the various geometrical shapes of the cores and placing conditions. A new core placing machine representing the current state of the art has been developed on the basis of this knowledge (see Figures 5.1 and 5.2, 3^{rd} generation paving equipment).

There is a height-adjustable, covered infrared heating device on the front of the paver. The core placing unit runs on steerable crawlers in the front and on wheels in the rear. The hopper for the asphalt concrete mix is situated between the front crawlers of the paver and the formwork of the core starts just underneath the hopper. The equipment axis layout ensures that each layer is placed on the core axis.

The hopper for the filter zone material is situated directly behind the asphalt concrete hopper and supported at the back by two steerable rubber wheels. The wheels run on the newly placed filter zone and effect a light initial compaction.

The asphalt concrete is dropped out of the hopper between the formwork and is leveled to placing thickness. A pre-compaction of the asphalt concrete core is achieved by using the tamping bar with adjustable frequency and amplitude. Material from the filter material hopper flows to the right and left of the installed core. The surface of the core is protected by a steel plate. A dividing wall in the bucket enables different filter materials to be placed on the upstream and downstream faces of the core, if required.

There is a slide gate at the end of the filter zone material hopper. An electronic control unit ensures that the filter zone material is placed with the correct height.

A group of vibratory plates in the rear of the core paving machine provides the initial compaction to the core and the adjacent filter zones. The final compaction is achieved with double vibratory rollers for both asphalt concrete core and filter zones.

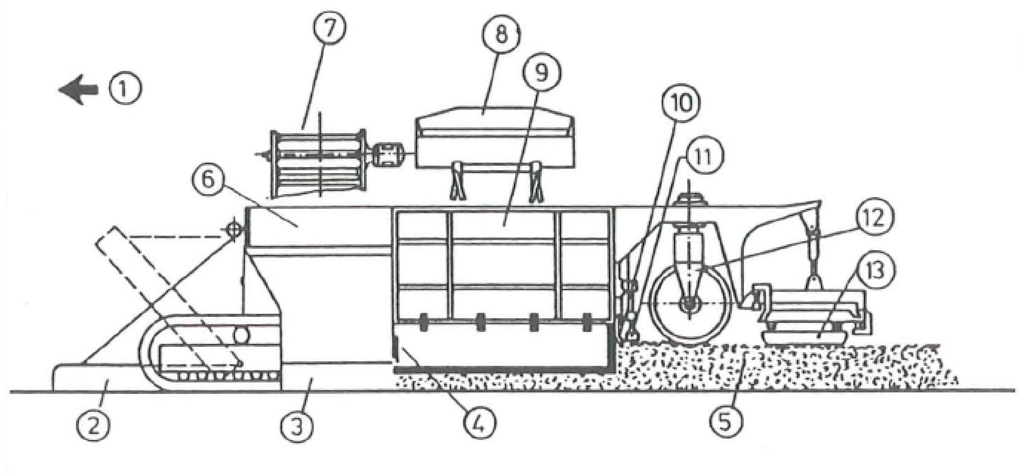


Figure 5.1 Core Placing Unit, 3rd Generation, Strabag System

(1) Placing direction.

(2) Heating channel.

(3) Steel plate formwork.

(4) Adjustable leveller for asphalt concrete placing thickness.

(5) Filter zone material.

(6) Bituminous mix hopper.

(7) Chain drag conveyor belt for the bituminous mix.

(8) Loading equipment for filter material.

(9) Hopper for filter material.

(10) Leveling bar for filter material.

(11) Pre-compaction unit for asphalt concrete.

(12) Rubber tire wheels.

(13) 3 vibratory plates (middle plate heated).

Figure 5.2 STRABAG Placing unit 3rd generation with pre-compacting plates at paving works

B) Norwegian equipment (Veidekke Industri A.S.)

The equipment has been in use since 1983 and undergone improvements as experience has been gained. Over the years it has been proven to be very simple and robust.

The Veidekke equipment is shown in principle in Figures 5.3 and 5.4.

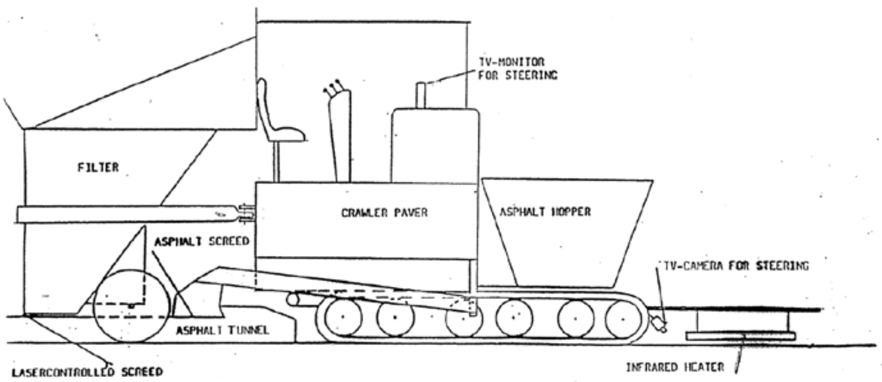


Figure 5.3 Principle of Veidekke Core paving machine

The core paving machine consists of two separate parts which are connected to each other - the asphalt concrete core unit and the unit for placing the filter zones on each side of the core. Both units run on the previously placed filter zone layers.

The asphalt concrete core unit is a modified standard asphalt concrete paver placing the asphalt concrete and filters zones simultaneously. The core paving machine is able to place asphalt concrete and filter zone up to 30 cm after compaction.

In the front, the machine is equipped with an infrared propane heater that can be adjusted in width according to the core width.

A steel string is placed in the center line for each layer. The TV camera mounted in front of the machine and a TV monitor inside the cabin enables the operator to steer the machine with precision following the course of the string.

The hot asphalt concrete from the asphalt mixing plant is loaded into the asphalt concrete hopper by a wheel loader fitted with a hydraulic operated silo. The asphalt concrete is placed by the asphalt concrete screed to the correct width and led through a tunnel where the filter zone is placed on each side. The filter zone material is loaded into that unit by an excavator. The level is automatically controlled by laser.

The width of screed placing the asphalt concrete core can be either fixed or on higher dams flexible from a width of 1.3 m (or more) to 0.5 m. In the latter case, the width of the asphalt concrete core can gradually be adjusted according to the design. The width of the filter zones can be adjusted together with the width of the asphalt concrete core.

In cold areas and/or in areas with high precipitation, the machine is equipped with a moveable roof over the asphalt concrete hopper.

Figure 5.4 Veidekke core paving machine in work, Jirau Dam, Brazil, 2012

C) Chinese equipment

China started to build asphalt concrete cores for embankment dams early in 1970. The asphalt concrete cores for earlier dams were built by hand work placing the asphalt concrete manually inside formwork. Modern machinery placement commenced in 1997 with Chinese made equipment. The first fairly simple core paver was pulled by a separate unit and the filter zone material was loaded manually into the formwork that was part of the core paving machine.

Later on a more modern core paving machine was developed however the Chinese asphalt concrete core unit runs on wheels, not on crawler chains. Further modifications have later been performed, for example with combined asphalt concrete core and filter zone units.

In 2009 a new type of core paver was developed which runs on three rows of wheels. In 2010 the next modification of a core paver was developed where the asphalt concrete hopper and main machine are supported by one row of wheels in front and a pair of caterpillar treads. The latest core paver consists of only one unit. The machine is supported by three rows of wheels and the filter material hopper is fixed on the machine.

Figure 5.5 Xi’an Huize latest core paving machine in work, Huangjinping Dam, 2015

D) Swiss equipment (WALO International AG)

After several projects in China, Spain and Germany with conventional core-paving equipment, WALO inaugurated a completely new paver type in the year 2015. The machine combines all of the important parts in one compact unit. A solid carriage supports a covered and heated asphalt concrete bin, spacious hoppers for filter material, a high-performance infrared-heating device and heavy-duty compaction units.

The paver is GPS controlled in three dimensions. In combination with the four independent crawlers, the steering mechanism allows to follow the central line precisely even for curved dam axis with low-radius curves. Due to the 3-dimensional GPS control, the actual paving height can be controlled precisely and permanently.

The combination of compressed air and the infrared heating device in front of the paver allows a permanent construction progress, even under difficult weather conditions.

Several sensors and their recorded data enable a consistently and traceable quality control.

Figure 5.6 WALO's latest core paving machine in work

5.3.3 Compaction equipment

This chapter covers the compaction of the asphalt concrete core as well as the compaction of the adjacent filter zones.

The filter zones will settle more during the compaction than the asphalt concrete core and will therefore need to be placed at a thicker layer than the asphalt concrete to ensure that both zones are at the same level after compaction.

As generally described in Chapter 5.1, the compaction on asphalt concrete cores differs from the compaction on roads or airfields. For roads the overlays are generally thin and the asphalt concrete mix contains less fines, filler and bitumen. The material delivered for an asphalt concrete core dam is much more viscous and dense and during the compaction process the asphalt concrete is vibrated in depth to ensure that the contained aggregates minimize the void content to achieve the void content criteria.

In addition to the required void content (< 3 Vol %), the asphalt concrete core shall have a good interlocking with the adjacent filter zone (see Figure 4.2, Test field). Nevertheless, the minimum width of the core has to be achieved (see Figures 5.7 and 5.8).

The width of the core roller drums must be wider than the actual placed width of the asphalt concrete core as the soft asphalt concrete material normally cannot support the roller alone without “sinking in” and thereby stopping. The roller will accordingly need to run partly on the filter zones at each side of the core for compaction of the asphalt concrete core. In addition, the use of hand held vibratory rammers is also feasible for the compaction; however, the final compaction should be done with a roller.

There is a general concern that if the core roller is too wide, the whole roller will “ride” on the filter zones giving the core insufficient compaction and vibration. At the same time, if the contact area on the filter zone is too small, the top of the asphalt concrete core will be pressed outwards due to the weight of the roller and thus unnecessarily increase the overconsumption of asphalt material.

The required additional height of the filter zone during placement is an issue that needs to be observed throughout the core paving operation.

It is today a common practice that the roller drums should not exceed the width of the asphalt concrete core by more than 10 – 20 cm. However, this should not be considered as an absolute rule. For wider asphalt concrete cores the extra width has to be considered together with the weight of the roller to be used. Standard rollers with two roller drums for thin asphalt concrete cores (0.5 - 0.6 m) have a weight from 750 to 1200 kg. Standard asphalt rollers for roads with a drum width of 100 cm or more have a weight of more than 2000 kg.

In order to vibrate the placed asphalt concrete core to full depth, the vibration should be at a high amplitude and low frequency. It is necessary to have rollers with synchronized operation drives on both roller drums. It is also beneficial to have rollers with a big roller drum diameter. Rollers with a smaller drum diameter get stuck more easily and have a tendency to “push” the asphalt concrete forward rather than driving and vibrating on top of the core. To prevent asphalt to stick to the roller drums, water spray on each roller drum will be required.

Before any placement commences on the dam, a full scale trial section with the machinery, the asphalt concrete and the filter zone material for the dam work should be performed on site. One of the major issues here is to test out the compaction equipment, the sequence of compaction and the number of passes required in order to comply with the specification requirements.

The number of passes required for compaction of the asphalt concrete core depends and varies with the asphalt concrete mix design and its compactibility. Three to five passes of vibration are normally required. Increasing the number of roller passes may not decrease the void content any further, but rather make the asphalt concrete core surface black and shiny by vibrating the bitumen and filler rich mix towards the top.

The filter zone on each side of the asphalt concrete core is normally 1.3 to 1.5 m wide. Normal vibratory rollers with a width of 100 - 120 cm and with a drive on each drum are sufficient for this purpose.

The compactibility of different filter zone materials depends on its composition. While it is desired to achieve a sufficient high density of the filter zone, care must be taken not to squeeze the asphalt concrete core in such a way that the cross section of each layer becomes concave and thereby reducing the core width below the minimum requirement. Filter zone with a significant proportion of natural rounded gravel compared with that from crushed rock will more easily impose a horizontal stress on the asphalt concrete core during construction.

In order to achieve sufficient compaction, the filter zone material could be wetted, if it is too dry. It has to be wetted before putting it in the hopper to avoid some water on the asphalt concrete layer.

The placed asphalt concrete core while it is not yet cooled down can easily be displaced. To prevent that, all compaction of the filter zone should be performed with the two filter zone rollers working in parallel.

Figure 5.7 Compaction work at Murwani Saddle Dam, Saudi Arabia 2007

Figure 5.8 Final compaction of the asphalt concrete core

5.3.4 Site laboratory

A fully equipped site laboratory with trained personnel including necessary materials for a continuous QC/QA control must be established prior to the commencement of the asphalt works.

Good daily quality control on site is of utmost importance. It is however fairly easy to perform and it is - for the most part - similar to the quality control required for ordinary asphalt works for roads. The frequency of the tests will be specified in the technical specification but should be expanded whenever there are any doubts about the quality obtained either due to variations in the aggregates, operation of the asphalt mixing plant or due to the quality of the work performed during the placement operation.

In the event that some of the daily results are unacceptable, removal of the faulty asphalt concrete material may be required. If the asphalt concrete material is still hot, this can easily be done by an excavator, but if the asphalt concrete material has cooled down, removal is a major undertaking. It is therefore strongly recommended that all daily results should be available at the end of the day productions and before work resumes the following day.

The main quality concern at site is to be confident that the placed material has a void content less than 3% at all times. The real value of the in situ void content can primarily be determined by core drilling and testing of the extracted cores. However, core drilling by ordinary equipment can only be performed to a depth of approximately 45 cm, generally through two placed layers. The core needs to cool down for several days before core drilling can be performed successfully. In order to achieve a reasonable construction progress, core drilling is therefore only performed as a spot check. The frequency of core drillings will depend on the results achieved from previous tests, results from other daily quality controls and the workmanship on the asphalt concrete core placing.

With today's good experience on ACEDs, it is sufficient to perform core drilling frequently depending on the work progress or after core height increases of 5 to 10 m provided that previous results and other quality controls are satisfactory. However, the first core drilling should be performed at the latest within two weeks after commencement of the asphalt concrete work. It may be desirable to perform the initial core drilling as soon after start of work when there is an opportunity to do so.

Void content control has also been supplemented with nuclear density measurements, but it is absolutely necessary to calibrate the nuclear reading on at least 5 cores, which may be from the test section, and to use the appropriate equipment for deep density measurements. Such tests can be used as additional information to the daily quality control. The nuclear testing does not eliminate the core drilling and testing.

Daily void content measurements on compacted Marshall samples in the laboratory and extraction analyses of the asphalt concrete material placed on the dam are the main daily quality control measures. If these results are consistent and good and if the climatic conditions and workmanship are satisfactory, it can be ensured that satisfactory void content measurements are obtained. However, should there be any doubt about the quality achieved, further work should be stopped immediately and the placed asphalt concrete material should be further tested and/or removed while still hot.

Laboratory testing of the asphalt concrete core is performed in two parts:

a) Initial testing on aggregate and bitumen including asphalt concrete mix development

b) Daily testing program during construction period

The preliminary testing (a) to be carried out is described in Chapter 4.4, Laboratory Testing of Asphalt Concrete Mixes.

The day to day work (b) to be controlled at the construction site is summarized in Chapter 7, Quality Control During Construction.

The quality and variations of the produced asphalt concrete depend on the asphalt concrete aggregates and their variation. The screening at the asphalt mixing plant will to some extent reduce variations in the stockpiles, but variations in the fine aggregate fraction, normally 0 – 4 mm (0 - 2), will not be corrected unless the finest screen corresponds to the nominal maximum size of the fine aggregate fraction (0 - 4/0 – 2 mm). The aggregates produced should therefore regularly be sampled and tested during production. The grading curve and flakiness will further vary with the degree of wear of the crushers and if the screening of the materials has been performed in dry or during rainy conditions. The aggregates should be stored separately and in a way to minimize segregation.

The type and requirements of the bitumen to be used shall be described in the technical specifications. The bitumen supplier or producer will normally perform regular controls of the bitumen qualities that he has available. Unless in very special circumstances, the site controls can consist of:

– A quality certificate on each delivery from the supplier.
– Penetration tests and - if required - additional Ring and Ball tests on each delivery to make sure that the correct bitumen quality has been delivered.

Asphalt mixing plant requirements are discussed in section 5.3.1. The plant will require regular maintenance and all weighing scales will need to be calibrated at least each time it is established. In case of any concern about the weighing accuracy, a new calibration shall be performed. The screeds must be regularly controlled.

The asphalt concrete composition shall be controlled at least once daily and further tests will also depend on the quantity produced per day. The extraction analyses shall include:

– Grading curve of the combined aggregates

– Bitumen content

The asphalt concrete samples should be taken from the placed core to include possible segregation after transportation and placement or directly from the asphalt mixing plant. A high degree of accuracy is necessary for taking and preparing the laboratory samples and the personnel should have previous experience or necessary training.

In order to reduce the frequency of the core drilling and void content measurement from the dam it has now become normal to specify daily compaction tests and void content measurements of Marshall samples compacted in the laboratory based on asphalt concrete taken directly from the asphalt plant. The compaction of the Marshall samples at the laboratory (number of blows) should be performed in a way that the degree of compaction from the Marshall samples corresponds to the core compaction on the dam. The compaction temperature must correspond to the grade of bitumen.

Filter zone material is usually specified as a well graded material between 0 mm and maximal 60 mm (or 0 – 80 mm) natural gravel with a certain amount of crushed material and/or crushed rock. Different materials compact quite differently. While it is desired to achieve the best degree of compaction, compaction criteria according to CBR (California Bearing Ratio) or similar methods are normally not included in the technical specification. The reason being that over-compaction of the filter zone may squeeze the asphalt concrete core and make it thinner or concave in form. In order to obtain the best possible compaction, wetting of the material is recommended before placement. The grading curve should be regularly controlled and checked with the specifications. It is important that the material is well graded to minimize segregation.

Core drilling of the asphalt concrete core is performed with special core bits. It is important to use a core drilling equipment equipped with water to eliminate a temperature raise during core drilling. The core drilling is possible after the core has cooled down sufficiently. Dense asphalt concrete maintains its temperature for a long time and even though the top cools down and is stable, it is still soft and warm some centimeters down. In warm climates it has proven to be beneficial to cover the spots with cloth which is kept wet for several days in order to minimize stoppage time related to the core drilling. With the appropriate equipment, the core drilling can be performed deeper than to the normal depth of 45 cm. The difficulty is not the actual drilling but being able to extract the core and to disconnect it at the bottom of the drilled core. Drilling of the core before it has cooled down sufficiently will result in deformation of the extracted core. The top and bottom 2 - 3 cm of each extracted core must be cut off before the remaining core is cut in about 5 cm thick slices. After weighing the slices in air and water, the density is easily calculated. When compared with the calculated maximum density (zero void), the actual void content of the particular sample (slice) will be easily calculated. If the asphalt concrete has segregated during transportation and placement, it may be necessary to calculate the maximum density based on the composition of the drilled core slice.

Figure 5.9 Drilled and sliced samples from the AC core

Drilled holes in the asphalt concrete core must be cleaned and carefully filled with hot asphalt concrete material in 50 mm thick layers and properly compacted.

The width of the placed core shall be controlled regularly. The filter zone on each side of the core is carefully removed after about one day and the total width and distribution on each side of the center line is measured. The core width control shall be carried out periodically and when the filter material is replaced with new material.

5.4 CURRENT STATE-OF-THE-ART

5.4.1 General

The placing temperature for the asphalt concrete core material shall in general be between 140° and 170° Celsius and the compaction temperature always above 130° Celsius considering the bitumen grade and the climatic conditions. The core will be placed and compacted simultaneously with the adjacent zones. The thickness of each compacted asphalt concrete layer will in general be between 20 cm and 25 cm. To achieve highest quality standards, the asphalt concrete core material shall be placed with special core paving machines and experienced staff. In areas with limited space to operate the core paving machine or in connection to concrete structures manual placing is necessary (e.g. for the first layers above the concrete plinth and the widening of the core towards the abutments). Manual placing requires the same quality as machine placing.

Figure 5.10 Hatta Dam, UAE, under construction, 2003

5.4.2 Preparation of the concrete surface and mastic application

The surface of all concrete structures shall, before the mastic is applied, be prepared by removing all loose debris, grouting residue and cement film. The preparation shall be done by one of the following methods:

- Sand blasting
- Hydro-jet blasting
- Cleaning with hydrochloric acid followed by water washing

The concrete must be properly cured and the surface has to be thoroughly cleaned and dried. To ensure the bonding and adhesion between the concrete and the mastic, the following methods can be performed:

- Application of a thin film of bituminous primer
- Using a bonding additive to the mastic

Figure 5.11 Tack coat spraying on concrete plinth prior to mastic application

To ensure an adequate bond and a flexible connection between the concrete structure and the asphalt concrete core, a mastic layer must be applied. Mastic consists of bitumen, filler and sand and must be mixed in a temperature controlled mastic boiler. The mastic application will be done manually with a total thickness of approximately 1 to 2 cm.

Figure 5.12 Mastic application on concrete plinth

5.4.3 Manual placement

The first layers immediately above the concrete plinth will be placed manually and will be extended on each side to ensure a tight connection. It is very common to widen the first two layers above the plinth by doubling the core width followed by two layers with a factor of 1.5 of the core width. Thus, the regular asphalt concrete core will start 0.80 m above the concrete plinth. However, the manual placement may also be limited to the first two or three layers above the plinth which allows the utilization of the paver more rapidly.

This so called “foot” of the asphalt concrete core will be placed manually by using steel formwork which is placed symmetrically along the centerline (axis) of the core. The formwork is braced with steel frames and stabilized from the outer side with filter material. The gap inside the shuttering will be filled with asphalt concrete and compacted with vibratory rammers or vibratory plates. After this pre-compaction is finished, the steel frame is removed and the asphalt concrete core plus the filter material is compacted with rollers. Thus, the required interlocking between asphalt concrete core and filter material will be achieved.

Figure 5.13 Manual placement and core widening adjacent to the abutments

5.4.4 Machine placement

After having finished the manual placing, the following layers are placed with the core paving machine. The asphalt concrete is fed into the central bin of the core paver and the filter material for the up- and downstream is loaded into the side-buckets of the core placing machine.

The asphalt concrete flows out of the hopper directly into a slip form while the filter material is placed on the outsides of the shuttering. Asphalt concrete and filter material are compacted simultaneously by a group of vibratory plates mounted at the back of the placing unit or by rollers according to the type of equipment. Finally, a set of light vibratory rollers follows to compact the crushed stone and the asphalt concrete layer to the required values. The core is compacted with rollers of a static weight of 1 to 1.5 tons, the filter zone is compacted with rollers of 2 to 2.5 tons static weight. The thickness of one compacted layer ranges between 20 cm and 25 cm.

Figure 5.14 STRABAG Pre-compaction with vibratory plates

Figure 5.15 Veidekke paving equipment without pre-compaction

Figure 5.16 Compaction of the AC core and the adjacent zones by vibratory rollers

5.4.5 Water stops

Water stops are usually included between the construction sections of the concrete plinth. In such a case heat-resistant rubber water stops or metal water stops in the concrete plinth have to be used and connected to the asphalt concrete core. For this reason, they are coffered with a formwork on top of the plinth or the plinth itself can locally be grooved. After the asphalt concrete placing outside of the formwork, the steel frame is removed and the coffered part is filled with mastic.

Figure 5.17 Typical detail of plinth with water stop and formwork

Figure 5.18 Typical detail of water stop and groove on a gallery

5.4.6 Preparation of the asphalt concrete surfaces

To achieve a proper bond between the individual layers, the previous layer shall be re-heated with an infrared heater to remove moisture. Additionally, the pre-heating shall be done at least before placing the first layer of each working day and always when climatic conditions or minor and short precipitation require this. If dust or water contaminates the surface, the dust or water must be removed using an industrial vacuum cleaner and/or compressed air. If necessary, tack coat has to be applied to cover remaining dust and sand particles.

Figure 5.19 Infrared heater in front of core paving machine

5.4.7 Additional requirements

The embankment and the core shall basically be constructed simultaneously. The height of the embankment outside of the asphalt concrete and transition (filter) zone shall never be more than two asphalt concrete layers below or above. If the asphalt concrete core needs to be crossed with equipment or machinery, specially fitted temporary portable bridges must be used. Those bridges fully support the construction equipment and prevent the asphalt concrete core and the filters from loading. The center line of the core is to be marked or a steel wire fixed on the previous layer by surveyors.

Figure 5.20 Temporary bridge for crossing the asphalt concrete core when required

6. TECHNICAL SPECIFICATIONS FOR CONSTRUCTION OF AC CORES

6.1 REFERENCES FOR STANDARDS

The standards proposed in this bulletin are specified according to European Standards and need to be adapted and compared with the local standards in many other countries.

6.2 TECHNICAL SPECIFICATIONS

This specification shall be seen as a recommendation and guideline for the minimum requirements for the construction of an ACED. Additional and special controls may be considered necessary depending on the dam to be built, local conditions and special features and challenges.

6.2.1 Specialized asphalt concrete core contractor's qualifications

For all works in connection with the asphalt concrete mix design and construction of the asphalt concrete core, a contractor with confirmed experience or if necessary a specialist subcontractor in the same field must be engaged. The specialized contractor is hereafter nominated as the Specialist Contractor and shall take full responsibility of the quality of placed asphalt concrete core as specified in this technical specification. The Specialist Contractor (or subcontractor) shall have:

- The qualifications to design the asphalt concrete mix to meet specific requirements to water tightness, stress-strain behavior and ductility.
- The necessary experience in planning, organizing, laying and compacting of the asphalt concrete core and the adjacent filter zones.
- The necessary asphalt concrete core paving equipment available to perform this work.
- The necessary experienced personnel to execute, train and supervise all the work related to asphalt concrete core construction.
- The required expertise to control and approve all the laboratory work on site related to daily asphalt concrete production, asphalt concrete placement and the testing program.

The placement of the asphalt concrete core material and filter zone material as well as the quality of the work performed must at all times be supervised and controlled by the Specialist Contractor.

Prior to construction, the Specialist Contractor must document the suitability of the asphalt concrete mix design, the equipment, experienced personnel and skills for executing a trial section and construction of the AC core including all necessary details.

6.2.2 Materials

6.2.2.1 Asphalt concrete core

BITUMEN (see Chapter 4.3.3 Bitumen)

The bitumen content in the asphalt concrete core will normally be between 6.0 and 7.5% by total weight of asphalt concrete. The final bitumen content will depend on the grade of the bitumen available, the final grading curve for the aggregates, the specific weight of the aggregates, the bitumen absorption into the aggregates and the ductile properties required for the asphalt concrete.

The bitumen shall comply with standard European specifications according to EN.

The Specialist Contractor shall report the results of the following initial tests:

- Penetration, EN 1426,
- Ring and Ball, EN 1427
- Fraaß fracture point (EN 12593)
- Loss on Heating, (EN 12607) max. 1.0 %
- Determination of the limits of penetration loss and softening point increase after heating (at least 70% remaining for penetration and 5 °C increase for softening point for B 50/70 or B 80/100). Limits for other bitumen grades have to be determined independently.

AGGREGATES (see Chapter 4.3.2 Aggregates and Filler)

The aggregates shall be produced from solid crushed rock or natural gravel or from a mixture of both.

The aggregates shall be produced in a minimum of four fractions:

For example,

0 - 4 mm

4 - 8 mm

8 - 11 mm

11 - 16 mm

Other classifications are also possible.

The aggregates in the various fractions shall be stored separately under conditions to protect against contamination, to minimize segregation and if necessary against moisture.

The aggregates shall comply with:

- Strength according to Los Angeles (LA) for coarse aggregates - less than 40 % loss according to EN 1097-2 for 500 rotations
- Flakiness Index - less than 35%

The Specialist Contractor shall report the results of the following initial tests:

- Petrography

- Grading curves
- Water absorption in aggregates (EN 1097-6)
- Adhesion to bitumen

Several test types are known to determine the adhesion of bitumen to aggregates. All tests are very subjective and thus the results are difficult to interpret. There is no general percentage that can be given as a reference but the affinity should be optimized. Usually, this type of tests is used for ordinary asphalt concrete subjected to the influence of air and water. The application of these tests for ACEDs is therefore debatable.

Bonding agents can be used to improve the adhesiveness as shown below.

Figure 6.1 Adhesiveness after 72 h water storage without bonding agent

Figure 6.2 Adhesiveness after 72h water storage with bonding agent

FILLER (see Chapter 4.3.2 Aggregates and Filler)

Filler materials are particles between 0 - 0.063 mm (0 - 0.075 mm) and will be a combination of fines from the aggregates retained at the asphalt plant (from the bag filter), and added fines from other sources. The added fines can be crushed limestone, Portland cement or other material approved by the Client. The quantity of filler obtained from the aggregates will depend on the aggregate type and the crushing process, but shall not exceed 50% of the total filler content in the asphalt concrete mix.

The workability and voids content in the mix will, to a great extent, depend on the amount of and composition of the filler in the asphalt concrete. These parameters shall be tested and documented as part of the initial asphalt concrete mix design.

For a comparison and the assessment of alternative filler sources the Ridgen Test (BS) can be useful. The Ridgen Test determines the void content of dry and compacted filler and can be used to interpret stiffening features of asphalt concrete.

6.2.2.2 Adjacent filter zone

The filter zone material shall preferably be produced from crushed rock, maximum grain size 63 mm with $d_{50} > 10$ mm and $d_{15} < 10$ mm. The total fines content shall not exceed 5% of the total weight.

The filter zone material can be wetted before being placed on the dam in order to ease compaction.

As the adjacent filter zones are normally either placed above or below the zone outside, a fair amount of surplus filter zone material will be required for production, transportation and placement.

6.2.2.3 Mastic and preparation for application

Mastic shall be applied to the concrete plinth underneath the asphalt concrete core in order to provide a good bond between the concrete and core.

The easiest method to produce mastic in a mixing plant includes the following two steps:

In the first step aggregates of 0 to 2 (4) mm grain size will be covered with approximately 2% of bitumen (of the total weight) at the asphalt plant. This “semi dry” mix shall be stored under cover. In a second step, additional bitumen in the required amount shall be added in the mastic boiler.

The composition of the mastic shall approximately consist of:

- Bitumen 20 %
- Filler 15%
- Aggregates 65 %

The mastic must be produced at a temperature depending on the bitumen grade and shall be transported to the site in a mobile mastic boiler where the temperature is thermostatically controlled.

Stearic Acid (1.5 % of the bitumen weight) shall be added to the mastic to improve the adhesion to the concrete plinth if necessary.

Before the mastic is applied, the concrete plinth shall be prepared by removing all loose debris and grouting residue.

The surface shall then be prepared by one of following methods:

- Washing with hydrochloric acid followed by washing with water
- Sandblasting of the concrete surface
- Jet blasting by high pressure water

After cleaning of the concrete tack coating with a polymer primer or emulsion must be sprayed on the surface to provide a suitable bond.

When the concrete plinth is completely clean and dry, the mastic shall be applied in one layer of approximately 10 mm thickness. A thicker layer or an additional layer shall be considered on steep abutments where high stresses are expected between the concrete plinth and the asphalt concrete core.

The mastic shall have a width equal to the widened asphalt concrete core towards the concrete plinth plus 0.25 m on either side.

6.2.3 Mix design of the asphalt concrete material for the core

The asphalt concrete mix design shall be based on these specifications and best practice (see chapter 4.3.4 Mix Design).

Based on the special dam design and requirements, the asphalt concrete mix design shall be established by the Specialist Contractor in his laboratory. After testing aggregates from the crushing plant, bitumen and filler, the various materials shall be mixed according to this specification in order to establish an appropriate asphalt concrete mix.

The combined aggregate size distribution shall satisfy the Fuller gradation curve and the grading curve shall be within the margins specified below. The component weights add up to 100% - not including bitumen.

If necessary, the crushing and sieving operations have to be adjusted to be in the margins in order to achieve the gradation criteria.

The grain size distribution of the mix design must be within the following limits (envelope).

Table 6.1 Grain Size Distribution

Sieve Size, mm	Range passing %
19	100
16	90 - 100
11.2	80 - 93
8	65 - 82
4	45 - 62
2	35 - 45
1	25 - 35
0.5	19 - 28
0.25	15 - 21
0.125	12 - 18
0.063	11 - 15

In the mix design report the following results must be compiled and presented for approval:

- Aggregates
- Grading curves
- Los Angeles value for the aggregate
- Water absorption in aggregates
- Flakiness
- Bitumen brand
- Penetration
- Ball & Ring
- Loss on Heating

Based on the selected materials, a provisional asphalt concrete mix shall be prepared with a minimum of three different bitumen contents, 6.5 %, 7.0 % and 7.5 % (bitumen content in percentage of total weight).

The void content shall be calculated on the prepared samples after they have been compacted with 30 blows on each side according to the Marshall method and at the appropriate temperature, which will depend on the bitumen grade and the temperature specified for compaction on the dam. Based on the results for the void content and workability, the preliminary bitumen content shall be decided.

The properties of the asphalt concrete mix from the initial mix design shall (for all major dams) further be documented through a triaxial test. The triaxial test shall be performed at an experienced laboratory with previous knowledge in performing the test and the evaluation of the results shall be performed by an experienced professional and be a part of the mix design report. If the results of the triaxial tests are not appropriate for the dam design, the mix design shall be modified and new triaxial tests shall be performed.

6.2.4 Production of the asphalt concrete material

The asphalt concrete material shall be produced in an asphalt batch mixing plant with the capacity to produce a volume which is sufficient for laying up to three layers per day at any level of the dam. The proportions of aggregates, fillers and bitumen shall be added automatically and by weight after hot screening of the various components. The plant shall have an automatic warning or stop by any faulty operation or in-weighing and have an automatic log and print-out possibility for each batch also showing the actual mixing temperature. Mixing temperatures will depend on the bitumen grade being used for the mix.

The asphalt mixing plant shall have:

- Minimum of 4 cold feeding bins
- Minimum of 4 hot storage silos under the sieves at the plant
- Two filler silos, one for retrieved aggregate filler and one for imported filler
- A bag-filter system for collecting fines to be used as filler from the aggregates
- One hot storage silo of minimum 40 tons

The batch mixing plant shall have a production accuracy in accordance with the specifications given below:

± 5% for grain size 2 mm and coarser

± 3% for grain size 0.125 - 1 mm

± 2% for grain size 0.063 mm

The allowable maximum deviation of the bitumen content is ± 0.3% on any single test. The Contractor has to maintain a file of the production record for each day and for each layer.

6.2.5 Transport, placing and compaction of the asphalt concrete material

Transportation of asphalt concrete material to the dam varies with the specialized contractor’s equipment. If the asphalt concrete material is transported by trucks, it must be covered by a “roof” or a blanket to prevent temperature loss, oxidation or to protect from precipitation. For long distance transports and in cold climates insulated truck beds are recommended. Segregation during the transport must be minimized.

The asphalt concrete core and the adjacent upstream and downstream filter zones must be built simultaneously in horizontal layers of 20 to 25 cm compacted thickness. This shall be done in close co-production with the rest of the dam works.

The asphalt concrete core and the two above mentioned filter zones shall normally not be more than two layers ahead or behind the adjacent shell. The reason for that is the safety of the roller operators, the lateral support of the asphalt concrete core as well as a minimized amount of surplus filter zone material.

Each asphalt concrete layer shall be laid in the correct position on top of the previous layer based on markings of the center line provided by the surveyors. The previous layer must be cleaned of any dust or debris before any new layer is placed. If the previous layer is cold or wet, it must be dried and heated by means of an infrared heater. Compressed air shall be used whenever required to clean the surface. The use of direct propane burners must be done with care to prevent any oxidation of the placed asphalt concrete core. Asphalt concrete placement shall not be performed during heavy rain fall.

The temperature for placement and compaction of the asphalt concrete material depends on the bitumen grade and local conditions.

If the core paving machine is equipped with vibratory plates, a pre-compaction of the asphalt concrete core will be done by the paver itself.

The main compaction of the asphalt concrete core and the filter zones can be performed with vibratory rollers (Veidekke system). The asphalt concrete core shall be compacted by a roller with a width equal to the asphalt concrete core plus 15 to 20 cm or by means of vibratory rammers or plates. The filter zones shall be compacted by two rollers operating in parallel, one on each side of the core, with a width of 100 to 120 cm, and weight in the range of 1,500 to 2,500 kg. The number of passes and the compaction for the asphalt concrete core and the filter zones shall be established during the trial section and the asphalt concrete core shall be inspected to ensure that no lateral displacement of the core has occurred.

The asphalt concrete core is compacted by means of careful vibration to obtain an air void content of less than 3% which corresponds to a k-value (permeability) of approximately 10^{-9} to 10^{-10} cm/sec (see chapter 4.3.1 General Requirements).

The width of the core should be periodically controlled after careful removal of the filter zones on each side. The width shall at all times be equal to or more than the specified theoretical width and with minimum half of the specified width on each side of the dam's center line. Therefore, a certain amount of overconsumption of asphalt concrete material will be necessary.

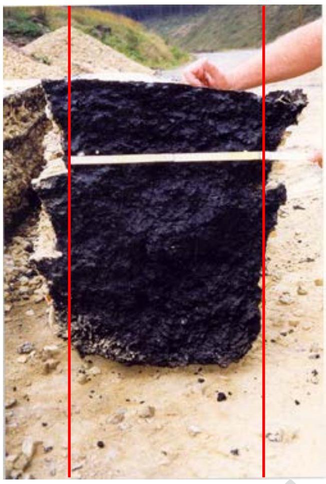


Figure 6.3 Typical cross section of an asphalt concrete core taken from trial field with minimum core thickness (red lines)

The main contractor in cooperation with the specialist contractor shall organize the work, the materials and the transportation in such a way that no delay is caused for the placing of the dam fill material and the asphalt concrete core. Furthermore, it must be ensured that the asphalt concrete material does not cool down below the required temperature for the placement prior to compaction. The temperature of the asphalt concrete shall be recorded and controlled for each delivery to the dam. Asphalt concrete material with a temperature below the specified limit or asphalt concrete material that has been produced at too high temperatures must be rejected.

Generally, it is not allowed to cross the asphalt concrete core with any kind of equipment while being hot or cold. If this is needed for practical reasons, portable bridge structures, capable of fully supporting the weight of construction equipment needs to be built. No part of the bridge structure shall touch the core (see Chapter 5.4.7, Figure 5.19 Temporary bridge).

The asphalt concrete core is widened (flared) towards the concrete plinth at the abutments (see Chapter 5.4.3, Figure 5.12 Manual placement). For this kind of work, hand placement of the materials is necessary and the same quality requirements as for machine placing must be met.

6.2.6 Pre-construction trial section

Prior to commencement of the asphalt concrete work on the dam, the specialist contractor in cooperation with the main contractor shall carry out a trial section. This trial shall demonstrate that the asphalt mixing plant, the asphalt concrete mix, the construction methods together with the number of passes for the compaction, the personnel and equipment can perform the various tasks and fulfill the requirements of the technical specification.

The trial section shall be conducted in the specified core width over a minimum length of 25 m and shall include:

- Construction of a concrete plinth 25 m long, 4 m wide and 0.2 m thick, including water stops if required.

- Demonstration of the method proposed to clean and to prepare the surface of the concrete plinth.
- Application of mastic over 25 m length with a width according to design.
- Construction of one layer of asphalt concrete with a width according to design and filter zones hand-placed over the full 25 m.
- Construction of two layers of asphalt concrete core with a width according to the design and filter zones placed with the core paving machine.

If the contractor intends to place 3 asphalt concrete layers in one day, he has to demonstrate this in the trial section.

The following parameters must be determined in the trial test field:

- Measurement of placing temperature of asphalt concrete material
- Visual evaluation of the work
- Check batch mixing plant records
- Laboratory analyses per layer which includes Marshall samples, core drilling and extraction analyses
- Gradation analyses of the filter materials

After the asphalt concrete core material in the trial section has cooled down, drilled cores shall be recovered at least at three locations with two cores each. The cores shall be drilled to the depth of at least 0.45 m at a minimum of two locations. At one location two cores shall be drilled into the concrete plinth in order to confirm the bond between the asphalt concrete core and the concrete structure.

Each core shall be logged, inspected and tested as follows:

- Void content
- Gradation
- Bitumen amount
- Ring and Ball test
- Penetration

If results from the trial section are unsatisfactory, a new trial section shall be conducted.

A comprehensive report on the trial section including all results obtained and the specialist contractor's recommendations shall be submitted for approval before any work commences on the dam.

7. QUALITY CONTROL DURING CONSTRUCTION

7.1 QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC PROGRAM)

The QA/ QC program recommended covers the following items:

- General specifications required for the specialized contractor
- Material requirements for the asphalt concrete core and the adjacent filter zone material
- Design of the asphalt concrete core
- Asphalt mastic preparation and placement
- Production of the asphalt concrete material
- Transportation, placement and compaction of the asphalt concrete material
- Performance of the pre-construction trial section
- Test program for the quality control to be performed during construction
- Requirements of the laboratory at the construction site

7.2 TEST PROGRAM FOR THE ASPHALT CONCRETE CORE

During the asphalt concrete core construction, the specialized contractor shall carry out at least the following tests and shall submit the results on a daily basis.

Table 7.1 Checklist Quality Control

	Description	Amount
At the mixing plant	control of weighting units	1 at the start, at least annually
	control of the thermometer of mixer of bitumen tanks	1 at the start, at least annually
	control of pre-dosing outlets	1 per month
	aggregates plus filler, visual control, gradation analyses	1 per week
	bitumen quality, penetration	1 per delivery
	density and voids content on Marshall specimens asphalt concrete analyses including gradation, bitumen content	1 per 150 tons, minimum 1 per working day
During the transport	cover asphalt concrete on trucks	each truck
	diesel cleaner forbidden	each truck
	temperature measurement	1 at start of transport, 1 at the end of the transport
	visual check of segregation	each truck
At the placing unit	temperature measurement	each delivery
	visual inspection of asphalt concrete	each delivery
	control of core axis	continuously
	control of underlying surface	continuously
	equipment control	daily
	asphalt concrete analysis	1 per 150 tons, minimum 1 per day
	gradation of filter zones	weekly
	weather conditions record	daily
At the asphalt concrete core	surveying at core, width, height, level	per layer
	drilling 3 core samples to measure the density and voids content of the core samples	1 per 4-6 m height of the core
	drilling 15 - 20 core samples to test the triaxial, bending and other mechanical behaviors according to the design requirements	1 per 12-15 m height of the core
	non-destructive method (Troxler or similar)*	daily
	dry density, voids content and gradation of filter zones	1 per 5 working days
	weather conditions record	daily

8. CONTROL OF DAMS IN OPERATION

8.1 SEEPAGE CONTROL

Basically, the seepage control is the most sensitive and important criteria to assess the behavior of a dam and the asphalt concrete core.

The seepage control is often installed at the dam toe but the results will include potential leakages through the asphalt concrete core, through and under the foundation and from the abutments on the downstream side.

A more precise seepage control only through the asphalt concrete core is related to a special design including a concrete plinth with a pipe collecting system or a gallery. Such a design includes, for example, a low watertight wall on the concrete plinth approximately 1.5 m to 2 m downstream of the asphalt concrete core and pipes. Galleries can be of advantage if foundation grouting should be done in a later stage and independently from the dam construction. In such a case the seepage control system is embedded in the gallery and allows a controlled observation of a leakage if there is any.

The seepage related to asphalt concrete cores and independently of the foundation or abutment seepage for existing dams is extremely low and never causes any problem for the safety assessment of the structure.

8.2 DEFORMATION CONTROL

The deformation control of an ACED is of secondary importance for the assessment of the safety and the behavior of the dam compared to the information about seepage loss and/or the pore water pressure in the foundation and the dam body. The most important criteria for the safety assessment of embankment dams are seepage rates and pore water distribution. The instrumentation level depends basically on the dam height and the foundation conditions as well as other requirements like research activities, experience with such dam types in the country, etc.

The basic instrumentation for the deformation control shall at least include geodetic surface monitoring devices and inclinometers. Additionally, earth pressure cells (horizontal and vertical plates) in the dam body and near the asphalt concrete core or pressure cells on top of the plinth or the gallery and in base of the asphalt concrete core can be installed to allow a more sophisticated assessment of the dam performance.

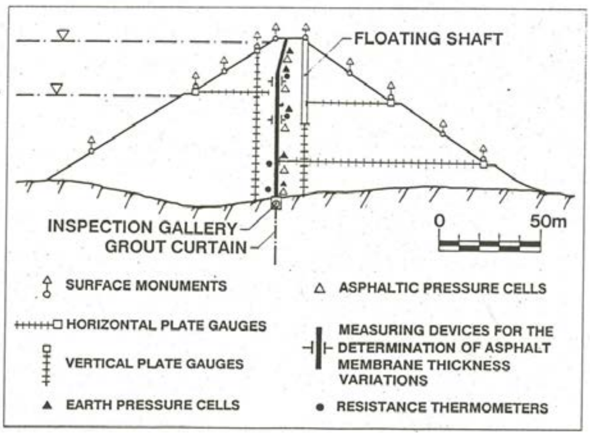


Figure 8.2.1 Example of a highly sophisticated instrumentation for a 90 m high dam for basic research activities

APPENDICES

APPENDIX A

CHRONOLOGICAL OVERVIEW OF EXISTING, UNDERCONSTRUCTION (U/C) OR UNDERDESIGNED (U/D) DAMS

	Name	Country	Height (m)	Crest (m)	Year completed	Average slope; upstream	Average slope; downstream	Volume 10^3 (m^3)	Asphalt volume (m^3)	Asphalt core thickness (m)
1	Kleine Dhuenn	Germany	35	265	1962	1:1.7/1:2.25	1:1.65/1.75	350	4500	0.7/0.6/0.5
2	Bremge	Germany	20	125	1962	1:2	1:2	50	1050	0.6
3	Eberlaste	Austria	28	475	1968	1:1.75/1:2.5	1:2	850	8750	0.6/0.4
4	Koedel	Germany	17	90	1969	1:2.2	1:2.2	60	850	0.4
5	Legadadi	Ethiopia	26	35	1969	1:1.4	1:2	-	550	0.6
6	Wiehl	Germany	53	360	1971	1:2.4	1:1.6/1:2.2	900	6250	0.6/0.6/0.4
7	Meiswinkel	Germany	22	190	1971	1:2	1:2	90	1420	0.5/0.4
8	Finkenrath	Germany	14	130	1972	1:2	1:2	80	710	0.4
9	Wiehl (main dam)	Germany	18	255	1972	1:2	1:2	110	1800	0.5/0.4
10	Baihe	China	25	250	1973	1:1.5	1:1.5	135	540	0.15
11	Danghe (1)	China	58	230	1974	1:3	1:3.5	1450	11010	1.5-0.5
12	Eixendorf	Germany	28	150	1975	1:1.75/1:2	1:4/1:2	150	1850	0.6/0.4
13	Eicherscheid	Germany	18	175	1975	1:3.5	1:2.5/1:3.5	110	1450	0.4
14	Jiulikeng	China	44	107	1977	1:1.2	1:1.2	145	1200	0.5-0.3
15	Guotaizi	China	21	290	1977	1:3.5	1:3.5	290	1370	0.3
16	High Island West	Hong Kong	95	720	1977	1:2.3	1:2.3	6120	63350	1.2/0.8
17	Los Cristales	Chile	31	190/140	1977	1:2	1:2	400	3500	0.6
18	Dachang	China	22	180	1978	1:1.2	1:1.2	78	460	0.3
19	High Island East	Hong Kong	105	420	1978	1:2.3	1:2.3	3440	34200	1.2/0.8
20	Breitenbach	Germany	13	370	1978	1:2.2	1:1.5	320	3200	0.6
21	Kamigazawa	Japan	14	170	1978	1:3	1:3.5	60	1150	0.6
22	Buri	Japan	16	173	1979	1:3.2	1:3.2	80	1000	0.6
23	Finstertal	Austria	100	652	1980	1:1.5	1:1.3	4400	25000	0.7/0.6/0.5
24	Yangjiatai	China	15	135	1980	1:1.4	1:1.4	33	340	0.3
25	Megget	Scotland, UK	56	568	1980	1:2.2	1:1.5/1:2.1	2100	13350	0.7/0.6
26	Grosse Dhuenn	Germany	63	400	1980	1:2.2	1:2.2	1400	8350	0.6
27	Vestredal	Norway	32	500	1980	1:1.5	1:1.5	360	3250	0.5
28	Katlavatn	Norway	35	265	1980	1:1.5	1:1.5	180	1800	0.5
29	Antrift	Germany	20	550	1981	-	-	400	2000	0.5
30	Langevatn	Norway	26	290	1981	1:1.5	1:1.5	300	2000	0.5
31	Erdouwan	China	30	320	1981	1:1.5	1:1.5	300	1500	0.2
32	Kurbing	China	23	153	1981	1:1.5	1:1.4	67	390	0.2
33	Dhuenn (outer dam)	Germany	12	115	1981	1:3	1:2	200	600	0.5
34	Sulby	Isle of Man, UK	36	143	1982	1:2.2	1:2.2	800	2700	0.75
35	Kleine Kinzig	Germany	70	345	1982	1:1.7/1:1.6	1:1.8/1:2	1400	10000	0.7/0.5
36	Biliuhe (left dam)	China	49	288	1983	1:3.5	1:3.2	1560	7730	0.8-0.5
37	Biliuhe (right dam)	China	33	113	1983	1:2	1:2.2	410	2050	0.5-0.4
38	Feldbach	Germany	14	110	1984	1:2	1:3	74	450	0.4
39	Wiebach	Germany	12	98	1985	-	-	126	200	0.5
40	Shichigashuko	Japan	37	300	1985	1:3.4	1:1.5	450	4900	0.5
41	Döerpe	Germany	16	118	1986	1:2	1:3	222	710	0.6
42	Lenneper Bach	Germany	11	93	1986	-	-	132	350	0.5
43	Wupper	Germany	40	280	1986	1:2	1:2.2	500	6200	0.6
44	Riskallvatn	Norway	45	600	1986	1:1.5	1:1.4	1100	8000	0.5
45	Storvatn	Norway	100	1472	1987	1:1.5	1:1.4	9500	49000	0.8-0.5
46	Berdalsvatn	Norway	65	465	1988	1:1.5	1:1.4	1000	6800	0.5
47	Borovitza	Bulgaria	76	218	1988	1:2.2	1:2.1	1000	7660	0.8-0.7
48	Rottach	Germany	38	190	1989	1:2.2	1:2	250	2500	0.6
49	Styggevatn	Norway	52	880	1990	1:1.5	1:1.5	2500	15275	0.5
50	Feistritzbach	Austria	88	380	1990	1:1.5	1:1.4	1600	8750	0.7/0.6/0.5
51	Hintermuhr	Austria	40	270	1990	1:1.1	1:1.1	320	3750	0.7/0.5
52	Queens Valley	Jersey, UK	29	170	1991	1:2	1:2	250	2100	0.6
53	Schmalwasser	Germany	76	325	1992	1:2.3	1:2.4	1400	13350	0.8
54	Muscat	Oman	26	110	1993	1:2	1:1.5	100	800	0.4
55	Danghe (2)	China	74	304	1994	1:3.5	1:2	360	2140	0.5
56	Urar	Norway	40	151	1997	1:1.5	1:1.5	140	1500	0.5
57	Storglomvatn	Norway	128	830	1997	1:1.5	1:1.4	5200	22500	0.95-0.5
58	Holmvatn	Norway	60	396	1997	1:1.5	1:1.5	1200	7000	0.5
59	Hatta	Dubai, UAE	45	422	1998	1:2	1:1.64/1:1.8	1000	7600	0.6
60	Greater Ceres	South Africa	60	280	1998	1:2.4	1:1.5	5500	4500	0.5

61	Algar	Spain	30	485	1999	1:2	1:2	-	2300	0.6
62	Goldistal (outer dam)	Germany	26	142	1999	1:2	1:3.5	200	1150	0.4
63	Dongtang	China	48	142	2000	1:3.5	1:2	514	4430	0.5
64	Duolate	China	35	112	2000	1:2.0	1:1.75			0.5
65	Kanerqi	China	51	319	2000	12.5	1:2	1650	6360	0.6/0.4
66	Tuo Li	China	22	340	2000	1:2.5	1:2.5	-	-	0.4
67	Majiagou	China	38	264	2001	1:2.5-1:3	1:2-1:2.5	700	4500	0.5
68	Yatang	China	57	407	2003	1:3.5	1:3.5	1900	10400	1-0.5
69	Jiayintala	China	26	160	2003	1:1-1:1.3	1:2.2	-	-	0.4
70	Maopingxi	China	104	1840	2003	1:3.5	1:2.2	12130	48500	1.2-0.6
71	New Hatta (main dam)	Dubai, UAE	37	228	2003	1:2	1:2.2	389	4000	0.6
72	New Hatta (saddle dam)	Dubai, UAE	12.5	208	2003	1:2	1:2.2	50	1000	0.6
73	Qiapuqihai (coffer dam)	China	50	110	2003	-	-	-	1000	0.4
74	Meyeran	Iran	52	186	2004	1:2.2	1:2.4	385	6000	1
75	Mora de Rubielos	Spain	34	215	2005	1:1.5	1:1.5	160	1600	0.5
76	Yele	China	125	411	2005	1:2	1:2.2	6600	38700	1.2-0.6
77	Ni'erji	China	40	1829	2005	1:2.25-1:2.5	1:2-1:2.25	7200	36500	0.7-0.6
78	Zhaobishan	China	71	121	2005	1:3.5	1:2	79	3000	0.7/0.5
79	Miduk	Iran	43	250	2006	1:2	1:1.8	400	4000	0.6
80	Müglitz	Germany	43	260	2006	1:2.2	1:2.4	500	5000	0.6
81	Kalasuke cofferdams	China	32/12	265/300	2006	1:1.25	1:1.25	800	3000	0.3
82	Yangjiang	China	43	210	2006	-	-	-	9000	0.8/0.5
83	Cgengbei	China	47	197	2008	1:2.5	1:2.25	-	3800	0.5
84	Murwani (saddle dam 1)	Saudi Arabia	30	437	2008	1:2.1	1:2	650	3700	0.5
85	Lontoushi	China	72.5	371	2008	1:2.2	1:2.2	2440	15700	1-0.5
86	Kjøsnesfjorden (main dam)	Norway	25	360	2008	1:1.5	1:1.5	100	1400	0.4
87	Kjøsnesfjorden (dam)	Norway	20	110	2008	1:1.5	1:1.5	40	600	0.4
88	Nemiscau (dam 1)	Canada	16,2	336	2008	1:1.8	1:1.45	52	750	0.4
89	Guanyindong	China	60	350	2009	1:2.25	1:2.25	1800	10200	1.1/0.5
90	Qiechanggou	China	30	261	2009	1:1.5	1:1.7	-	-	0.3/0.2
91	Xiabandi	China	78	406	2009	1:2.6-1:2.8	1:2.3-1:2.5	4919	22000	1.2-0.6
92	Bulongkou-Gonggeer	China	35	331	2010	1:3.0	1:2.75	-	-	0.6
93	Kaiputaixi	China	48	195	2010	1:3.0	1:2.75		4000	1.2/0.7
94	Kezijiaer	China	63	356	2010	1:2.2	1:2.0	1700	11000	0.8/0.5
95	Yutan	China	50	320	2010	1:2.25	1:2.4	2000	10000	1.0/0.5
96	Murwani (main dam)	Saudi Arabia	101	575	2010	1:2.1	1:2	5350	23800	1-0.5
97	Zletovica	Macedonia	85	270	2010	1:2.2	1:2.2	1700	8400	0.6
98	Rennersdorf	Germany	18,50	300	2010	1:1,24	1:1,22		2500	2,4/1,8/1,2/0,8/0,6
99	Foz do Chapeco	Brazil	48	600	2010	1:1.4	1:1.4	1500	14000	0.5
100	Shur River(main dam)	Iran	80	480	2010	1:1.75	1:1.5	2985	10200	0,6
101	Shur River(saddle)	Iran	34	164	2010	1:1.75	1:1.5	52	750	0,5
102	Dazhuhe	China	96	560	2011	1:2-1:2.1	1:1.9-1:2	-	22000	1.2-0.6
103	Gongmuzhi	China	45	250	2011	1:2.5	1:2.7	350	1900	0.5
104	Kushitay cofferdam	China	50	300	2011	1:2.5	1:2.5		4700	0.4
105	Kushitay main dam	China	91	360	2011	1:2.2	1:2.0		15000	0.8-0.4
106	Sheyuegou	China	35	386	2011	1:2.25	1:2.0			0.4
107	Xiagou	China	36	216	2011	1:2.2	1:2.2	1900	12000	1.2/0.5
108	Jinwangsi	China	59	400	2012	1:2	1:1.8	-	12000	0.5
109	Jirau Dam	Brazil	93	900	2012	1:1.4	1:1.4	2000	17200	0.6
110	Shaertuohai	China	58	-	2012	-	-	-	4800	0.6/0.5
111	Shimen	China	106	310	2012	1:2.2	1:2.5	-	20000	1.2/0.5
112	Tewule	China	65	180	2012	-	-	-	-	0.6
113	Aikou	China	80	217	2013	1:1.4	1:2.4	1390	11643	1.2/0.6
114	Jinping	China	60	300	2013	1:2	1:1.8	-	10000	0.7/0.5
115	Nuerjia	China	81	469	2013	1:2.5	1:2.0	3300	20000	0.6/0.4
116	Shuangqiao	China	73	260	2013	1:2.5	1:2.5	-	7000	0.5
117	La Romaine 2 (main dam)	Canada	109	496	2013	1:1.6/1:1.8	1:1.45	4546	18850	0.8/0.5
118	La Romaine 2, Dike A2	Canada	31	144	2013	1:1.8	1:1.45	88	1040	0.5
119	La Romaine 2, Dike B2	Canada	28	115	2013	1:1.6/1:1.8	1:1.45	73	790	0.5
120	La Romaine 2, Dike D2	Canada	48	728	2013	1:1.6/1:1.8	1:1.45	666	6330	0.5
121	La Romaine 2, Dike E2	Canada	39	407	2013	1:1.6/1:1,8	1:1.45	218	2470	0.5
122	La Romaine 2, Dike F2	Canada	84	423	2013	1:1.6/1:1,8	1:1.45	1947	10700	0.7/0.5
123	La Romaine 1 (main dam)	Canada	41	850	2014	1:1.6/1:1,8	1:1.45	608	5600	0.5
124	Sanzuodian	China	52	614	2014	1:1.5~1:2.5	1:1.5~1:2.5	2355	18352	1.5/0.8/0.5
125	Pangduo	China	80	1052	2014	1:2.7	1:2.1	-	60000	0.5/1.2
126	Xiangbicui	China	55	123	2014	-	-	-	1800	0.7/0.5
127	Alagou	China	105	366	2015	1:2.2	1:2.0	-	17533	1.0/0.5
128	Erlangmiao	China	69	254	2015	1:2.25	1:2.4	-	7000	1.1/0.5
129	Ertanggou	China	65	337	2015	1:2.25	1:2.0	-	-	1.2/0.5
130	Guanmaozhou	China	106	243	2015	1:2.25	1:2.25	-	-	1.2/0.6

131	Huangjinping	China	81	402	2015	1:1.8	1:1.8	-	27000	1/0.6
132	Jinwangsi	China	59	400	2015	1:2.0	1:1.8		12000	0.5
133	Wuyi	China	103	374	2015	1:2.5	1:2.0	-	16000	1.2/0.6
134	Tianxingqiao	China	40	350	2015	1:2.5	1:2.5	130	12000	0.5
135	Zhaizihe	China	93.5	256	2015	1:1.8	1:1.8	1720	12480	1.0/0.6
136	Shuangqiao	China	73	260	2015	1:2.5	1:2.5		7000	0.5
137	Nuerjia	China	60	220	2015	1:2.5	1:2.5		6000	0.6/0.4
138	Tabalah	Saudi Arabia	47	390	2015	1:2.4	1:2.4	-	7500	0.5
139	Sanxianhu	China	41	360	2016	1:2.5	1:2.3	-	6343	0.6
140	Maanshan	China	80	300	2016	1:2.0	1:2.2		7000	0.8/0.6
141	Kayingdebulake	China	70	360	2016	1:2.5	1:2.5		12000	0.7/0.6
142	Longsheng	China	50	600	2016	1.2.5	1:2.5		10000	0.7/0.5
143	Milanshankou	China	81	450	2016	1:1.8	1:1.8		17000	1.0/0.8/0.6
144	Nagore Dam	Spain	30	660	2016	1:1.5	1:1.5	-	8000	0.5
145	Laojiaoxi	China	56	280	2016	1:2.0	1:2.0		6000	0.7/0.5
146	Bajiao	China	60	460	2016	1:2.0	1.2.2		7000	0.7/0.5
147	Wantanhe	China	89	254	2016	-	-	2482	12300	0.7/0.5
148	Quxue	China	174	219	2017	1:1.9	1:1.8	490	20000	1.3-0.6
149	Zhongye	China	72	360	2017	1:1.8	1:1.8		7000	0.7/0.5
150	Bajiao	China	60	450	2017	1:2.5	1:2.5		7500	0.7/0.5
151	Qiongzhong	China	30	600	2017	1:2.2	1:2.0		400	0.6/0.5
152	Wadi Fulaij Dam (Sur)	Oman	23	900	2017	1:2.5	1:2.5	1Mio	14000	1,2/0,8
153	Nuer	China	80	600	u/c	1:2.0	1:2.0		31000	0.8-0.5
154	Honggeer	China	69	400	u/c	1:2.0	1:2.0		10000	0.7/0.5
155	Xiaqinggou	China	50	210	u/c	1:2.0	1:2.0		2500	0.5
156	Qiayang	China	40	500	u/c	1:2.5	1:2.5		7000	0.5
157	Jieba	China	70	450	u/c	1:2.5	1:2.5		7000	0.7/0.5
158	Yalong	China	80	460	u/c	1;2.5	1:2.5		20000	0.7/0.5
159	Bingguohe	China	60	260	u/c	1;2.5	1:2.5		4000	0.6
160	Yangjiahe	China	40	400	u/c	1;2.5	1:2.5		6000	0.5
161	Tongchang	China	81	350	u/c	1.2.0	1:2.0		10000	0.7/0.5
162	Hexin	China	63	200	u/c	1:2.5	1:2.2		2600	0.7/0.5
163	Jiaozishan	China	101	400	u/c	1:2.5	1:2.2		23000	1/1/0.9/0.7
164	Badashi	China	113	300	u/c	1:2.25	1:2.0	-	-	-
165	Dashimen	China	128	194	u/c	1:2.5	1:2.5	-	15000	1.4/0.6
166	Leyuan	China	67	165	u/c	1:1.8	1:2.25	-	5283	0.6/0.7
167	Dunhua(upper dam)	China	48	952	u/c	1:2.0	1:2.5		23600	0.8/0.6
168	Dunhua(lower dam)	China	70	410	u/c	1:2.0	1:2.0		12300	1.0/0.8/0.6
169	Shuangxiahuo	China	70	180	u/c	1:2.0	1:2.0		7000	0.8/0.6
170	Karakurt Dam	Turkey	141	498	u/c	1:1.45	1:1.25	4000	35500	0.5/1.2
171	Antamina talings Dam	Peru	22	1000	u/c	1:1.7	1:1.7		44000	2.0
172	Al-Lith	Saudi Arabia	79	420	u/c	-	-	-	10600	-
173	Namsvatn	Norway	30	300	a/c	-	-	-	3000	0.5
174	Cetin dam	Turkey	160	490	u/c	1:1.55	1:1.45	8500	35000	0.5/1.2
175	Ferreira Gomes	Brazil	25	730	u/c	1:1.5	1:1.5		8700	0.5
176	Zarema May Day Dam	Ethiopia	153	695	u/c	1:2	1:1.8	-	-	-
177	Fulaij Flood Protection Dam	Oman	24	1005	u/d	1:2.5	1:2.5	-	17300	0.8
178	Kitsault Dam	Canada	125	700	u/d	1:1.5	1:1.5	-	29000	0.9/0.5
179	Moglice Dam	Albania	150	295	u/d	1:1.5	1:1.5	-	19000	-
180	Namsvatn	Norway	30	300	u/d	-	-	-	3000	0.5
181	Nenskra Dam	Georgia	125	820	u/d	1:1.7	1:1.5	-	50000	1.1/0.5
182	New Kjerka (main dam)	Norway	60	460	u/d	1:1.5	1:1.5	600	7700	0.5
183	New Kjerka, Heddersvika	Norway	30	550	u/d	1:1.5	1:1.5	400	4500	0.5
184	Plovdivtsi Dam	Bulgaria	46	225	u/d	1:1.8	1:1.7	-	3500	0.6/0.5
185	Xinba	China	52	213	u/d	1:1.8	1:1.8	7180	4645	-
186	Hongshuihe	China	87	600	u/d	1:2.0	1:2.2		30000	1.0/0.8/0.6
187	Aoyiaezi	China	93	502	u/d	1:2.0	1:2.0	-	-	1.2/0.6
188	New Skjerka (main dam)	Norway	60	460	u/d	1:1.5	1:1.5	600	7700	0.5
189	New Skjerka, Heddersvika	Norway	30	550	u/d	1:1.5	1:1.5	400	4500	0.5

APPENDIX B

DAMS WITH ASPHALT CONCRETE CORES OF SELECTED PROJECTS

B.1 Eberlaste Dam, Austria

Table B.1.1 Eberlaste Dam – General Information

Dam Name	**Eberlaste**
Country	Austria
Purpose	HPP Zemm/Ziller
Year of Completion	1971
Dam Height (Axis)	28 m
Storage Capacity Total	8.2 Mio. m³
Dam Volume	0.79 Mio. m³
Upstream Slope	1 : 1.75 and 1 : 2.5
Downstream Slope	1 : 2
Asphalt Concrete Core	6,600 m³, vertical
Underground Sealing	Slurry cut-off wall
Fill Material, Dam Shoulders	Talus material, gravels
Dam Foundation, Central Valley	River deposits and alluvium material, interlocked permeable talus material, depth about 125 m
Dam Foundation, Abutments	Granitic gneiss

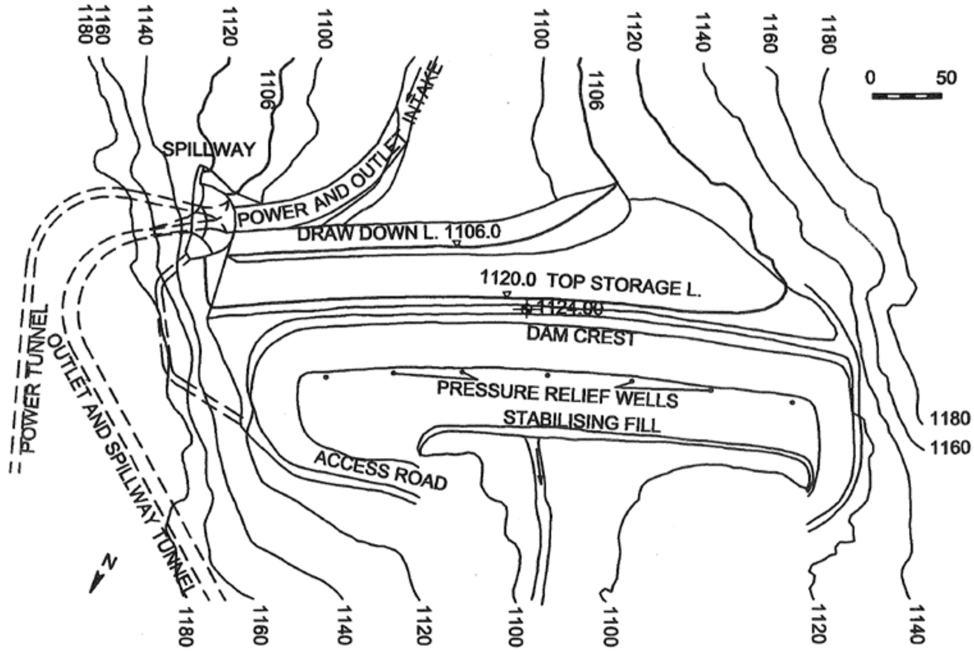


Figure B.1.1 Eberlaste Dam – Layout

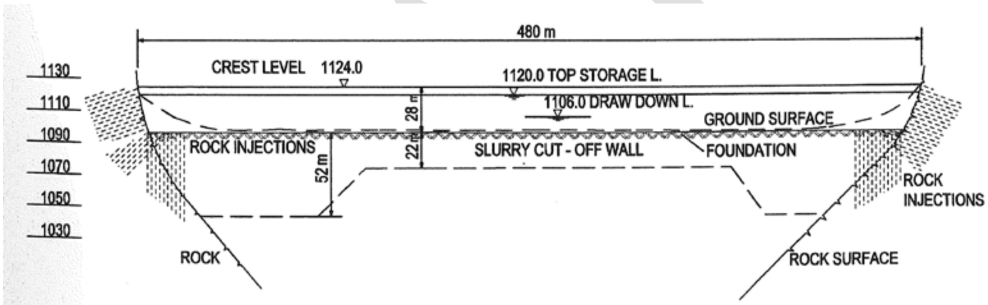


Figure B.1.2 Eberlaste Dam – Longitudinal section

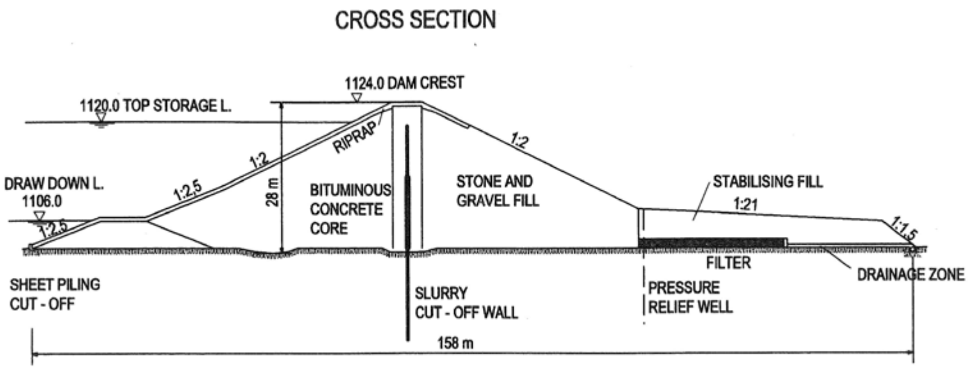


Figure B.1.3 Eberlaste Dam – Cross section

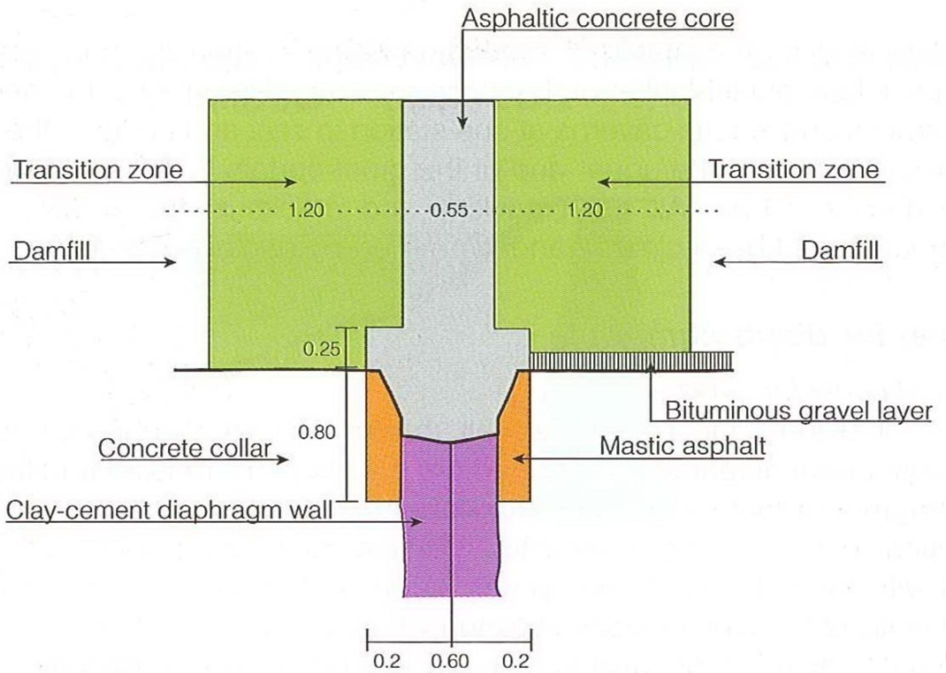


Figure B.1.4 Detail Connection AC Core/Cut-off Wall

Table B.1.2 Eberlaste Dam - Construction Details

Shell Material	Talus material and sorted gravels
Filter Zone Upstream and Downstream	1.2 m wide, 80 mm
ACED Width	50, 40 cm
ACED Placing Thickness	approx. 25 cm
Bitumen	B300 (Penetration range up to 300/10 mm)
Bitumen Content	8 %
Max. Grain Size, Aggregates	25 mm
Filler Content	8 %, Limestone
AC Paving Equipment	STRABAG, 2nd generation
Compaction Equipment	3 vibratory rollers
Instrumentation	Seepage measuring devices, 14 piezometers, 15 relief wells, geodetic monitoring
Quality Control	As defined by the Employer
Numerical Analyses	No

Special Design Features

- The slurry used for the foundation cut-off wall consisted of soil cement with 0 to 40 mm aggregates, cement, bentonite and chemical additives.
- A cut-off wall to reduce the seepage through the foundation to a reasonable amount was constructed; a complete imperviousness of the foundation cannot be achieved.
- The cut-off wall depth in central valley is 22 m. Permeable interlayers with boulders prevailing at the abutments required a cut-off extension to a depth of 52 m.
- A 50 m long stabilizing fill was placed adjacent to the downstream dam toe to ensure adequate safety against foundation failure.
- Differential settlements of the dam foundation and the asphalt concrete core as well as the slurry-trench cut-off were subjected to substantial stresses.
- Greater settlements of dam foundation and embankment dam were expected and therefore a very soft asphalt concrete mix was used.
- During the construction, the foundation settled about 2.20 m in middle of the valley. After the construction secondary settlements of more than 20 cm were observed.

B.2 Grosse Dhünn, Germany

Table B.2.1 Grosse Dhünn Dam – General Information

Dam Name	**Grosse Dhünn**
Country	Germany
Purpose	Water supply, flood protection
Year of Completion	1984
Dam Height (Axis)	63 m
Storage Capacity Total	84 Mio. m^3
Dam Volume	1.2 Mio. m^3
Upstream Slope	1 : 1.75
Downstream Slope	1 : 1.75
Asphalt Concrete Core	8,000 m^3, vertical and inclined
Underground Sealing	Grout curtain, 1 and 2 rows
Fill Material, Dam Shoulders	Rockfill
Dam Foundation, Central Valley	Partly overburden, different rock foundations, silt and sandstone
Dam Foundation, Abutments	Silt and sandstone

Table B.2.2 Grosse Dhünn Dam - Construction Details

Shell Material	Rockfill, max. grain size inner zone 30 cm and outer zone 60 cm
Filter Zone Upstream and Downstream	3 m width each, 22/56 mm
AC Width	60 cm
AC Placing Thickness	approx. 25 cm
Bitumen	B 80
Bitumen Content	6.5 %
Max. Grain Size, Aggregates	16 mm
Filler Content	14 % Limestone Filler
AC Paving Equipment	STRABAG, 3rd generation
Compaction Equipment	3 vibratory rollers
Instrumentation	Floating shaft, internal horizontal and vertical deformation gauges, extensometers, earth and asphalt concrete pressure cells, asphalt concrete core thickness measuring devices, sectioned seepage

	control, geodetic monitoring
Quality Control	As defined by the Employer
Numerical Analyses	Yes

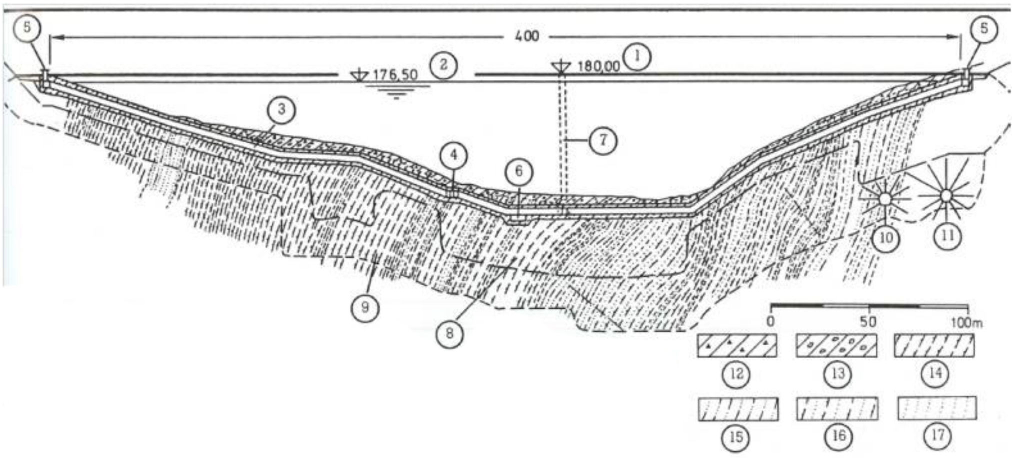
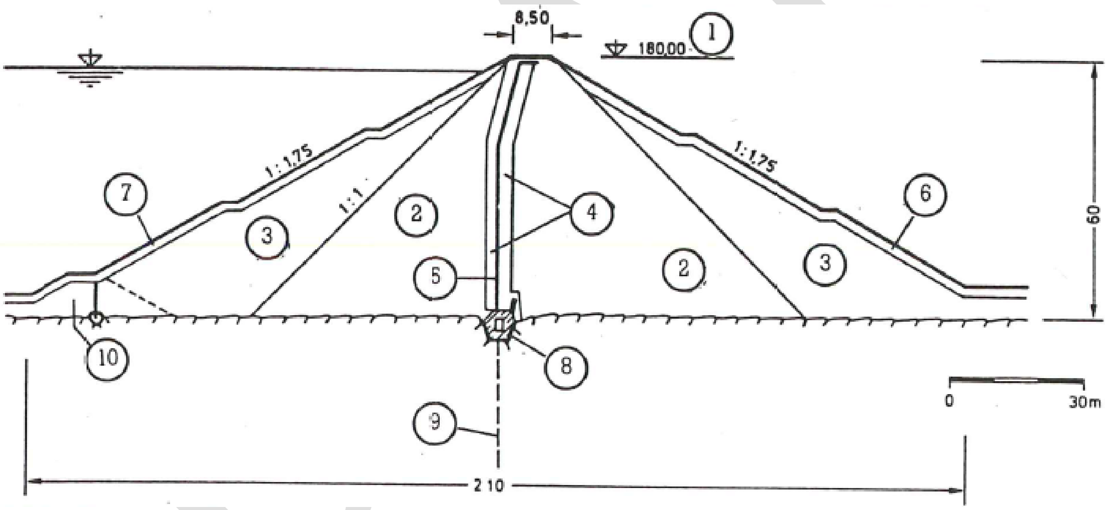


Figure B.2.1 Longitudinal section



1) Dam crest	6) Vegetation zone
2) Inner dam shell zone	7) Riprap protection
3) Outer dam shell zone	8) Grouting and inspection gallery
4) Filter zone	9) Grout curtain
5) Asphalt concrete core	10) Coffer dam

Figure B.2.2 Cross section

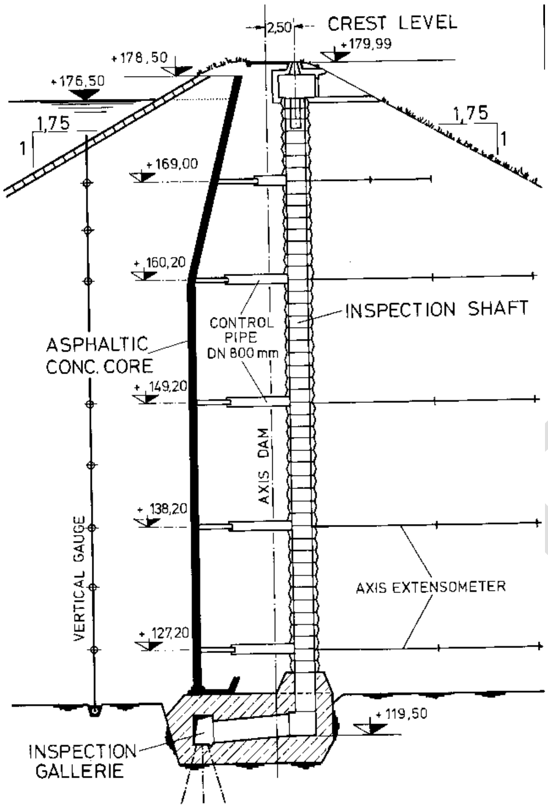


Figure B.2.3 Dam monitoring instrumentation

Special Design Features

- Inclined asphalt concrete core in the upper part to increase load on the asphalt concrete core and to reduce displacements to the upstream dam slope.
- Extensive dam instrumentation for the research of the asphalt concrete core technology and analyzing the behavior of the embankment dam as well as the AC core.

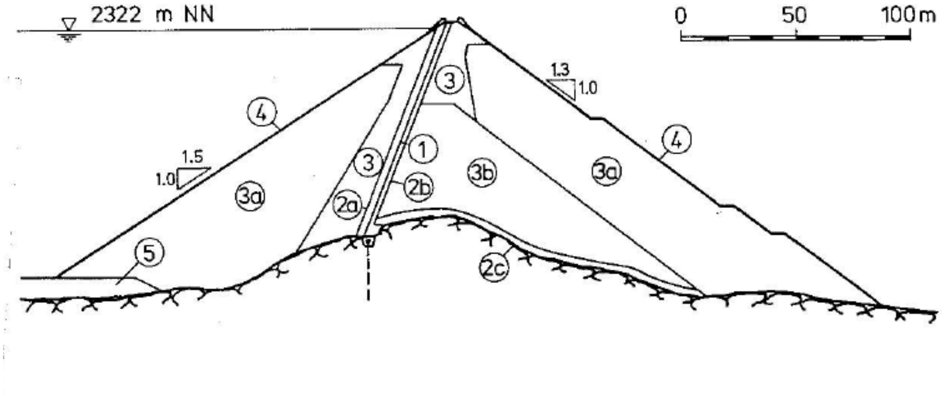
B.3 Finstertal Dam, Austria

Table B.3.1 Finstertal Dam – General Information

Dam Name	**Finstertal**
Country	Austria
Purpose	HHP Sellrain/Silz
Year of Completion	1980
Dam Height (Axis)	95 m
Dam Height (Downstream Dam Toe)	155 m
Storage Capacity, Total	60 Mio. m³
Dam Volume	4.4 Mio. m³
Upstream Slope	1 : 1.5
Downstream Slope	1 : 1.3
Asphalt Concrete Core	24,000 m³, inclined 1 : 0.4
Fill Material	Solid and sound grano-diorite, stiff moraine

Table B.3.2 Finstertal Dam – Construction Details

Upstream Dam Shoulder (Shell)	Grano-diorite, max. Ø 700 mm, void content about 21 - 24 %
Downstream Dam Shoulders (Shell)	Grano-diorite and moraine max. Ø 700 mm
Upstream Filter and Downstream Filter Zone	Upstream filter zone 2 m, downstream filter zone 3 m, max. 100 mm, upstream screened moraine, downstream screened quarry material
AC Core Width	0.7, 0.6, 0.5 m
AC Placing Thickness	20 – 25 cm
Bitumen	B 65
Bitumen Content	6.3 %
Max. Grain Size, Aggregates	16 mm
Filler Content	Total 12 % ± 2 % with approx. 8 % limestone powder plus 2 to 3 % reclaimed filler
AC Paving Equipment	STRABAG, 2^{nd} generation



FINSTERTAL DAM: cross-section of dam

	Zone	Material	d_{max} [mm]
1	Impervious core wall	asphaltic concrete	16
2a	Transition zone upstream	screened-out moraine	100
2b	Transition zone downstream	screened-out quarry material	100
2c	Drainage zone	quarry material	700
3	Shoulder	quarry material	700
3a	Shoulder	quarry material	700
3b	Shoulder	moraine	700
4	Surface course	blocks	500–1000 (length of stone)
5	Remaining overburden	moraine	

Figure B.3.1 Finstertal Dam – Cross section

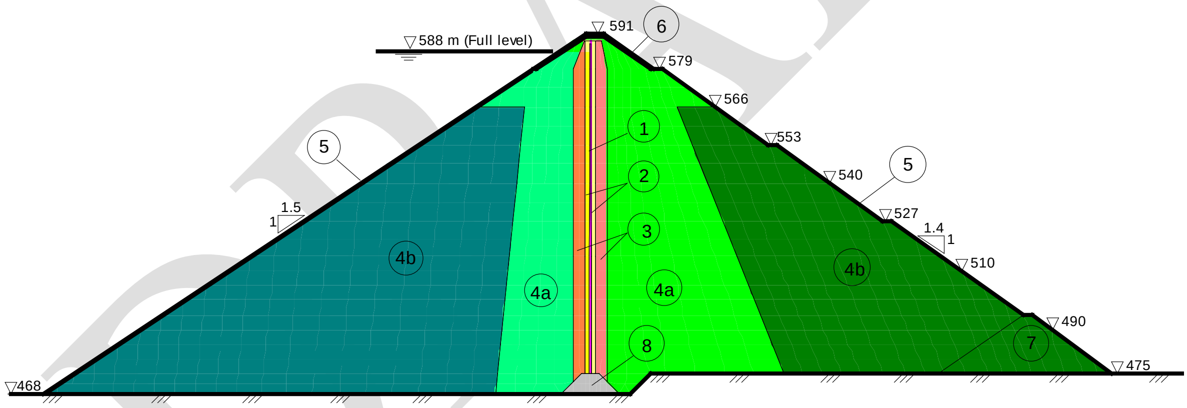
Special Design Features

- Very small seepage flows through the 40,000 m² asphalt concrete core were detected after the first impounding (about 9 l/s). Up to now the seepage decreased to less than 3 l/s.
- Inclined ACED related to the complex rock foundation geometry – double curved layout. The downstream dam shell is very stiff and the overall deformations of the dam are relatively small.

B.4 Storglomvatn Dam, Norway

Table B.4.1 Storglomvatn Dam – General Information

Dam Name	**Storglomvatn dam**
Country	Norway
Purpose	HPP
Year of completion	1997
Dam height (Axis)	128 m
Upstream slope	1:1.5
Downstream slope	1:1.4
Asphalt concrete core volume	22,500 m^3, vertical
Underground sealing	Grout curtain and in part of the foundation blasted tunnel for potential later grouting
Main fill material for dam	Rockfill, Limestone
Dam foundation	Solid rock, but karst in parts of the foundation



1. Asphalt concrete core
2. Transition zone (0 - 60 mm)
3.Transition zone (0 - 150 mm)
4a. Quarried rockfill (0 - 500 mm)
4b. Quarried rockfill (0 - 1000 mm)
5. Slope protection, riprap (blocks, min.0.5 m3)
6. Crown cap (blocks)
7. Toe drain (blocks, min. 0.5 m3)
8. Concrete plinth for AC core connection

Figure B.4.1 Storglomvatn Dam – Cross section

Figure B.4.2 Storglomvatn Dam

Table B.4.2 Storglomvatn Dam – Construction Details

Upstream Dam Shoulder (Shell)	Limestone
Downstream Dam Shoulders (Shell)	Limestone
Outer Upstream and Downstream Transition Zone	max. 150 mm, crushed rock
Inner Upstream and Downstream Transition Zone	1.3 m wide at the bottom and increasing to 1.5 m at upper part, max. 60 mm, natural gravel and crushed rock
AC Core Width	At the bottom: 95 cm decreasing to 50 cm for the upper part
AC Placing Thickness	25 cm
Bitumen	B 180
Bitumen Content	6.7 %
Max. Grain Size, Aggregates	16 mm
Filler Content and Type	13%, Retrieved aggregate filler and limestone 50/50
AC Paving Equipment	Veidekke, last generation

Special Design Features

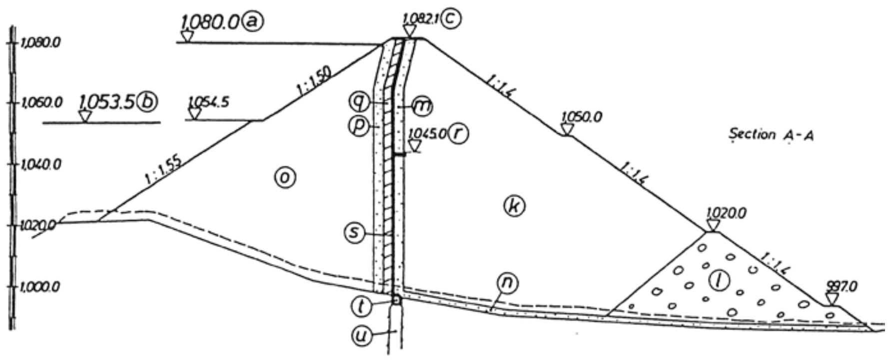
- Storglomvatn dam is one of two rockfill dams for the reservoir of one of Norway's major hydropower scheme. It is located in northern Norway under a major glacier. The climate is cold, foggy with high precipitation and the annual construction season was short with a period from May/June to middle of October.
- The natural gravel used for the asphalt concrete aggregates and for the inner transition zone was partly very weak with varying petrographic and mineralogical origin.

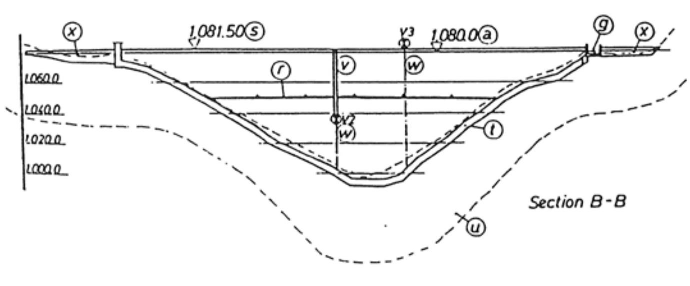
- The main embankment fill material of limestone was generally weak and therefore some materials had to be rejected. After the vibratory roller compaction, the rockfill surface was in some cases so shattered that the top layer was removed before the next layer could be placed. Even so, the vertical settlement has been very small. The maximum horizontal displacement on the downstream slope at the elevation 510 m measured was 0.48 m after impounding.
- The seepage measured at the dam toe after 9 years of the dam completion is very low with 7 l/sec. and gradually decreasing as silt and sand close the cracks in the foundation.

B.5 Feistritzbach Dam, Austria

Table B.5.1 Feistritzbach Dam – General Information

Dam Name	**Feistritzbach**
Country	Austria
Purpose	HPP Koralpe
Year of Completion	1990
Dam Height (Axis)	85.5 m
Storage Capacity Total	22.2 Mio. m³
Dam Volume	1.6 Mio. m³
Upstream Slope	1 : 1.5 and 1 : 1.55
Downstream Slope	1 : 1.4
Asphalt Concrete Core	Lower part vertical, upper part inclined, 8,500 m^3
Concrete Core	400 m²
Underground Sealing	Two-row grout curtain (max. depth 70 m), Contact grouting (3 planes)
Seepage Control	Drainage and grouting gallery
Fill Material, Dam Shoulders	Solid and soft, weathered rock





(a) Normal water level

(b) Minimum operating level

(l) Drainage zone

(m) Downstream filter

(c) Dam crest with road

(d) Intake bottom outlet

(e) Intake headrace tunnel

(f) Valve chamber headrace tunnel

(g) Intake spillway

(h) Stilling basin

(i) Access drainage and grouting gallery

(j) Embankment dam for diversion during construction

(k) Downstream shell

(n) Filter on downstream dam foundation

(o) Upstream shell

(p) Upstream filter

(q) Fine-grained zone

(r) Horizontal bituminous concrete sectioning

(s) Bituminous concrete membrane

(t) Grouting and drainage gallery

(u) Grout curtain

(v) Floating shaft

Figure B.5.1 Feistritzbach Dam - Cross and longitudinal section

Figure B.5.2 Rock material used for dam shoulders (grey solid rock – upstream dam shoulder, brown weathered rock – downstream dam shoulder)

Table B.5.2 Feistritzbach Dam – Construction Details

Shell Material	max. layer thickness 60 cm, max. grain size 40 cm
Compaction	320 kN dynamic load rollers, 2 to 4 roller passes
Filter Zone Downstream and Transition Zone Upstream	each 1.5 m wide, layer thickness 20 cm, placed together with AC paver, max. diameter 60 mm
AC Core Width	70, 60 and 50 cm
AC Placing Thickness	20 cm, after compaction
Bitumen	Bitumen B70
Bitumen Content	6.5 %
Max. Grain Size Aggregates	16 mm
Number of Layers per Day	Max. 3

AC Paving Equipment	STRABAG, 3rd generation

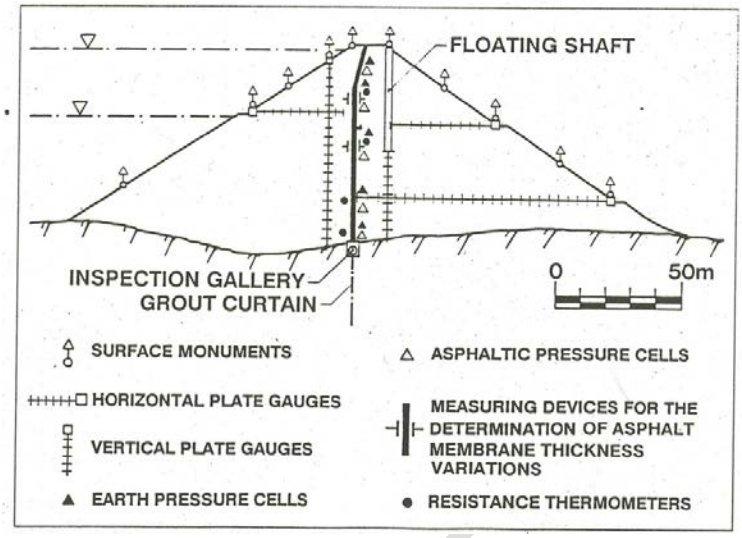


Figure B.5.3 Feistritzbach Dam – Monitoring instrumentation

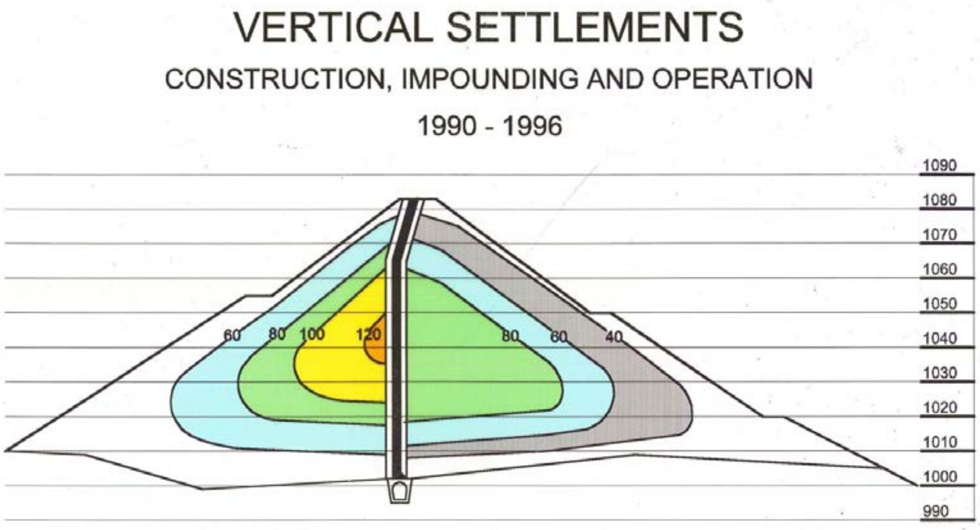


Figure B.5.4 Feistritzbach Dam – Vertical Settlements

Special Design and Construction Features

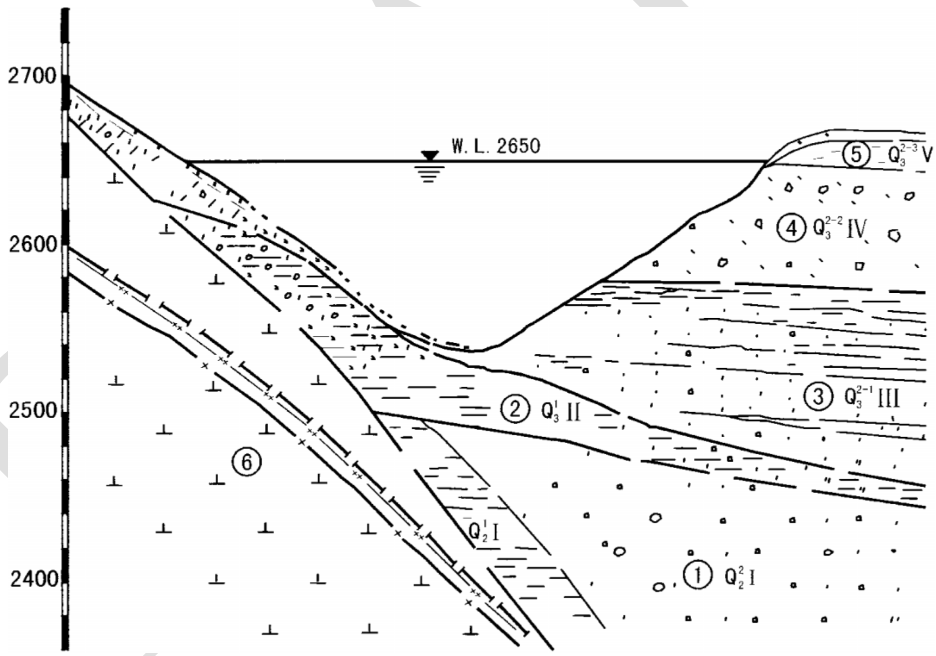
- The maximum dam settlement occurring during construction (in two seasons) was about 80 cm in the upstream shoulder. The deformations in the direction of the dam axis as well as the horizontal displacements did not exceed a few cm.
- At the level of the horizontal gauge H 1, the modulus of deformation back-calculated from the measured settlements by vertical gauges was around 62 to 67 MN/m².
- After three years of operation the upstream settlements increased at vertical gauge V1 to about 106 cm. Higher saturation settlements were measured at the horizontal gauge H3 (about 102 cm).
- Since 1994 and up to 2009 no significant increasing of the settlements occurred (max. 120 cm at gauge V1).

- The settlements of the AC core were measured by special devices. A 13 m wide zone between the core and the floating shaft settled fairly even. The settlements of the AC core were initiated by the dam shell and the transition and filter zones.
- The instrumentation at elevation 1,045 m to determine thickness changes in the downstream half of AC core uses a ball and steel plate embedded in the core. Displacements are transmitted via glass fiber extensometer rods and ending in the inspection shaft. The increasing of the AC core thickness of membrane at Feistritzbach dam was less than 1 cm.
- The seepage through the AC core and all the connections between the AC core and the concrete gallery was in the range of max. 2 l/s for the whole dam. The maximum seepage loss measured in the grouted foundation and the abutments was approx. 20 l/s.

B.6 Yele Dam, China

Table B.6.1 Yele Dam – General Information

Dam Name	**Yele**
Country	China, Sichuan province
Purpose	HPP
Year of completion	2005
Dam height	124.5 m
Upstream slope	1:2
Downstream slope	1:2.2
Asphalt Concrete Core	38,700 m^3, vertical
Underground sealing	Plastic concrete cut off wall
Main embankment fill material	Quarried rock
Dam foundation	Partly on deep overburden



1) gravel with silty sand layers

2) stiff overconsolidated cohesive soils with stones

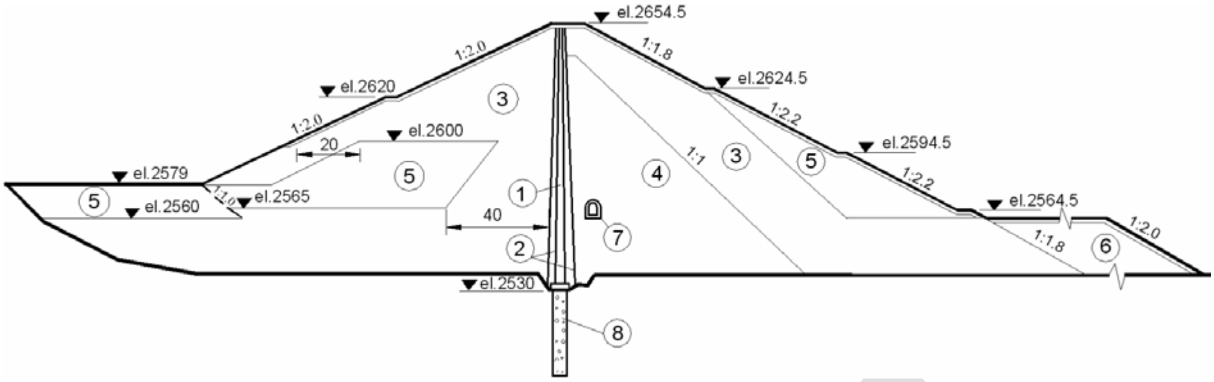
3) gravel with layers of loam

4) gravel

5) sandy soil with loam and carbonized plant fragments

6) quartz diorite bedrock

Figure B.6.1 Longitudinal section and dam foundation condition



1) asphalt concrete core

2) filter zone

3) and 6) rock shell and downstream dam tow

4) downstream rock fill shell

5) natural gravel or rock fill

6) toe berm

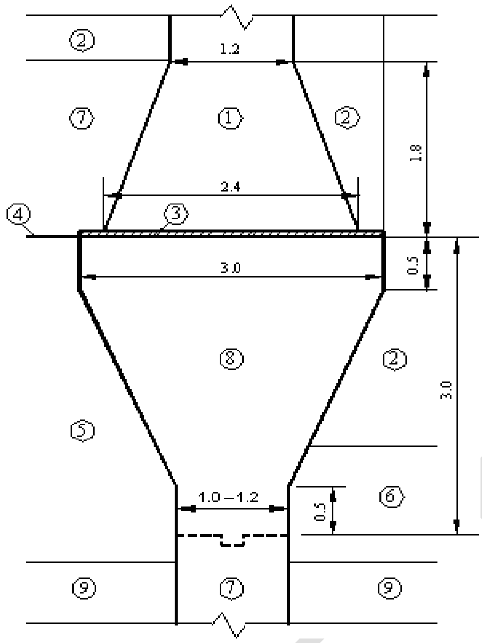
7) inspection gallery

8) concrete cut-off wall

Figure B.6.2 Cross section Yele Dam

Table B.6.2 Yele Dam – Construction details

Asphalt Concrete Core Width	120 cm at the bottom decreasing gradually to 60 cm at the upper part
Filter Zone Width and Type	1.3 m at the bottom increasing to 1.6 m at the top section. Gravel 0 - 80mm.
Type of Asphalt Concrete Aggregates	Quartz diorite with 30 % natural sand
Bitumen	B70
Bitumen Content	6.3%
Filler Content	12 %
AC Placing Thickness	26 cm (after compaction)



1) Asphalt concrete core

2) Filter zone

3) Sandy asphalt mastic

4) Geo-membrane covering upstream foundation to upstream dam toe

5) Silt

6) Filter/ drainage layer

7) Concrete cut-off wall

8) Reinforced concrete plinth plinth

9) Foundation over- burden

Figure B.6.3 Structural connection between the asphalt concrete core and concrete plinth

Special Design and Construction Features

- The dam is located in an earthquake area with design intensity of peak ground acceleration of 0.45 g and with very gentle slopes. Furthermore, the foundation is very complex and challenging. A 20 to 60 m deep concrete cut-off wall was in part constructed through the over burden and down to the sloping diorite bedrock at the left bank. A grout curtain was injected into the quartz diorite through the concrete cut-off wall. A 150 m long and 80 m deep grout curtain was injected into the quartz diorite from the construction gallery. For the river bed overburden, a 30 to 60 m concrete cut- off wall was integrated 5 m into the relatively impervious soil layer. For the right bank, the overburden was so deep that the water barriers had to be built in four stages. The upper first barrier is the 15 m high concrete wall extension built in the open excavation; the second barrier is the concrete cut-off wall with a depth of 70 m down to the top of the second level construction gallery; the third is 60 - 84 m deep concrete cut-off wall installed from the second level construction gallery, and the fourth is the grouting curtain with a maximum depth of 120 m installed through the concrete cut-off wall.

- Top elevation of the dam is 2,654.5 m and as such the weather is generally cold, wet and humid, therefore challenging for the daily asphalt concrete work.
- The Wenchuan earthquake in May 2008 resulted in additional crest settlement of 15 mm at the central section. The dam site is 258 km from the epicenter of the earthquake. The several other earthquakes that have occurred since the end of construction have had insignificant effects on the dam.
- After impounding, significant seepage resulting from under flowing the cut-off wall was detected. A deep drainage well was installed in the foundation through the observation gallery in 2006. Total seepage was then reduced to 358 l/s in December 2007 which is less than the maximum seepage value of 500 l/s anticipated during the design.
- From September 2008, addition grouting has been carried and a new drainage well was included. This has resulted in reducing the seepage further.

B.7 Foz de Chapeco, Brazil

Table B.7.1 Foz de Chapeco – General Information

Dam Name	**Foz do Chapeco**
Purpose	Hydropower
Year of completion	2010
Dam height	48
Upstream slope	1.4 :1
Downstream slope	1.4 : 1
Asphalt concrete volume	1400 m^3
Underground sealing	Ordinary grouting
Main fill material for dam	Good and hard basalt rock
Dam foundation	Solid rock

This hydropower project is a BOT project with the main contractor, Camargo Corrêa, also part of the owner group. The consultant was CNEC Engenharia, Brazil. This was the first asphalt concrete core dam to be built in Brazil.

The dam was originally designed with a clay core. But the main contractor believed that an asphalt core design could shorten the construction time considerable and thereby reducing total cost with the hydropower production commencing earlier.

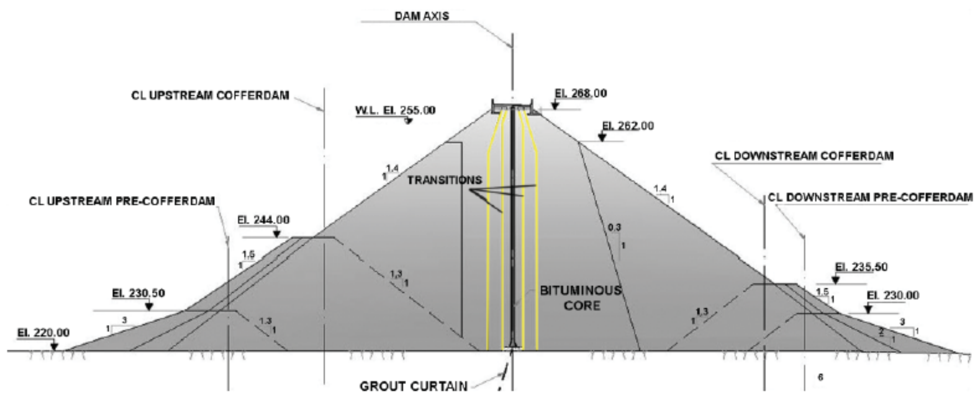


Figure B.7.1 Cross section Foz do Chapeco Dam

B.7.2 Work in progress

Figure B.7.3 Overview of dam and spillway

Special features

On the right side, the asphalt concrete core and the dam is connected to the concrete spillway, with a slope of 1 H : 10 V. In order to ensure good contact between the asphalt concrete core and the spillway structure, the contact area between the concrete structure and the asphalt concrete core was sloped about 1:4 towards downstream. The upstream water load will impose an additional pressure on the asphalt concrete core towards the concrete spillway.

The fairly steep embankment slopes are in accordance with Brazilian experience and practice. The concrete plinth was cast continuously without joints and water-stops.

Construction history

The asphalt concrete mix design was established in Oslo in the fall 2009 with materials shipped from Brazil. All the aggregates were based on crushed solid basalt rock with high specific weight. The aggregates had a fair amount of porosity.

On arrival in Brazil for preliminary work it became evident that the aggregates tested in Norway where not representative to that now stockpiled at the construction site. Further, the materials had been produced at the crusher plant in both dry as well as rainy conditions. This resulted in considerable variation of fines in the 0-4 mm fraction. Work in order to homogenize the 0-4 mm stock pile was initiated. A revised asphalt concrete mix design was established in Brazil with 6.3 % bitumen.

After a successful trial section, the works commenced on the dam in December 2009. However, after approximately 2 weeks, severe flooding occurred overtopping both upstream and downstream cofferdams. After the water between the cofferdams had been pumped off, work could continue, no damage was detected on the asphalt concrete core or the filter zone (0-50 mm crushed rock).

After a short time, bubbles started to occur on the asphalt concrete core surface. This proved to be vapor that had been interlocked in the coarse aggregates also after passing through the heating drum of the asphalt concrete. The small openings where vapor had passed were only of temporary character and had no influence on the void content and permeability of the core. The occurrence of the bubbles stopped after decreasing the production speed of the asphalt plant thus slowing down the speed of the aggregates through the heating drum.

The last asphalt concrete layer was placed on April 28th, 2010. The dam was raised in average 10.7 m per month with a maximum daily raise of 1 m (4 layers of 25 cm each). It was clearly demonstrated that progress on such dams depends on the infilling capacity of the rockfill, not on the asphalt concrete core placement.

B.8 Complexe La Romaine – Québec – Canada

Table B.8.1 Romaine-2 Dam – General Information

Dam Name	Romaine-2
Country	Canada
Purpose	Hydro Power plant
Year of Completion	2013
Dam Height (*)	109.1 m (above the concrete plinth at the axis)
Storage Capacity	3,720 Mm^3
Dam Volume	4,077,657 m^3
Upstream Slope	1.6H :1V and 1.8H :1V
Downstream Slope	1.45H :1V
Asphalt Concrete Core	Vertical, inclined near crest
Underground Sealing	Grout Curtain, 3 rows
Fill Material, Dam Shoulders	Rockfill
Dam Foundation, Central Valley	Rock (Monzonite)
Dam Foundation, Abutments	Rock (Monzonite)

(*) 130 m at the deepest point on the upstream foundation

Table B.8.2 Romaine-2 Dam – Construction Details

Shell Material	Rockfill, max. 600 mm inner shell and max. 1,200 mm outer shell
Filter Zone Upstream and Downstream	1.5 m wide, max. 200 mm
ACED Width	0.5, 0.65, 0.75 and 0.85 m
ACED Placing Thickness	225 mm
Bitumen	PG 52-34 HDR
Bitumen Content	6.6 to 7.2%
Max. Grain Size Aggregates	20 mm
Filler Content	13 to 16%
AC Paving Equipment	Svedala-Demag DF 115C
Compaction Equipment	4 Vibratory Rollers (1.6, 3.9, 10 and 15 Tons)
Instrumentation	Measuring Weir, Vertical and

	horizontal inclinometers, Pressure cells, Surveying Monuments and Geodetic Monitoring, Settlement Plates, Thermistors
Quality Control	As defined by Owner
Numerical Analyses	Yes (FLAC)

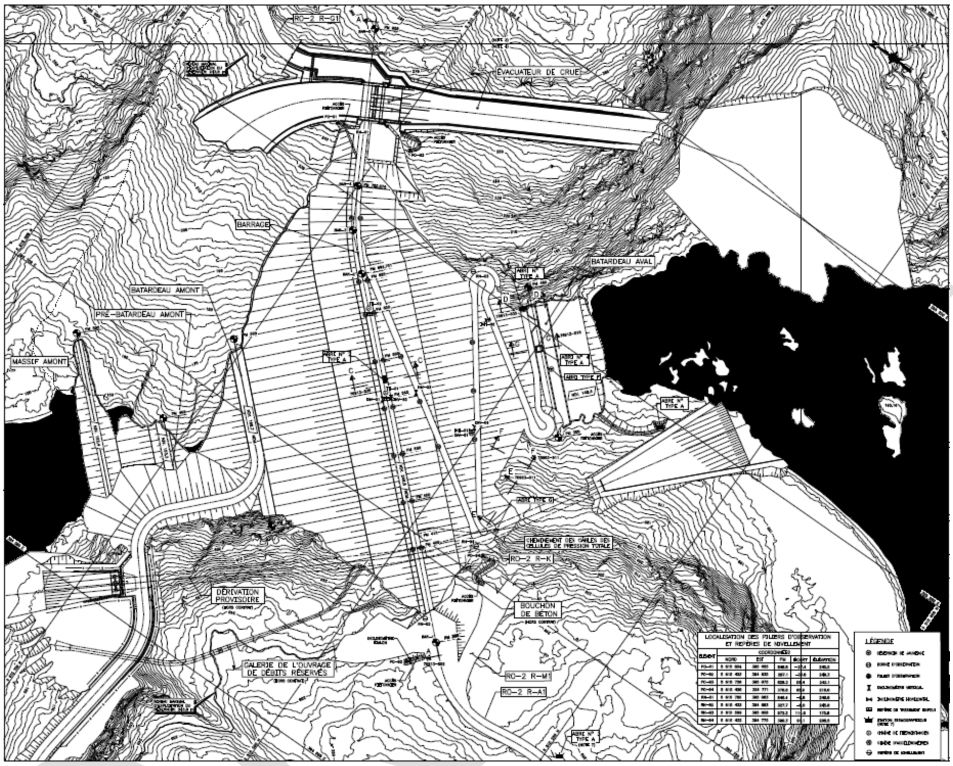


Figure B.8.1 Romaine-2 Dam – Layout

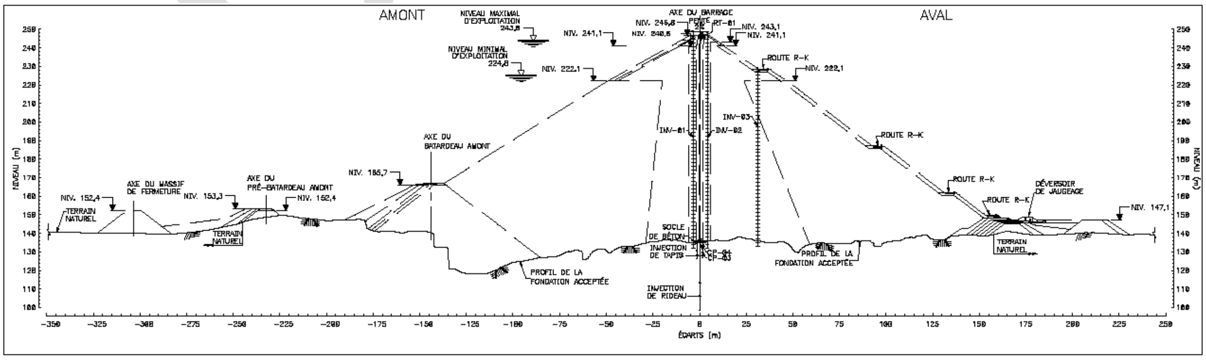


Figure B.8.2 Romaine-2 Dam – Cross Section of Instrumentation – Station 0 + 4

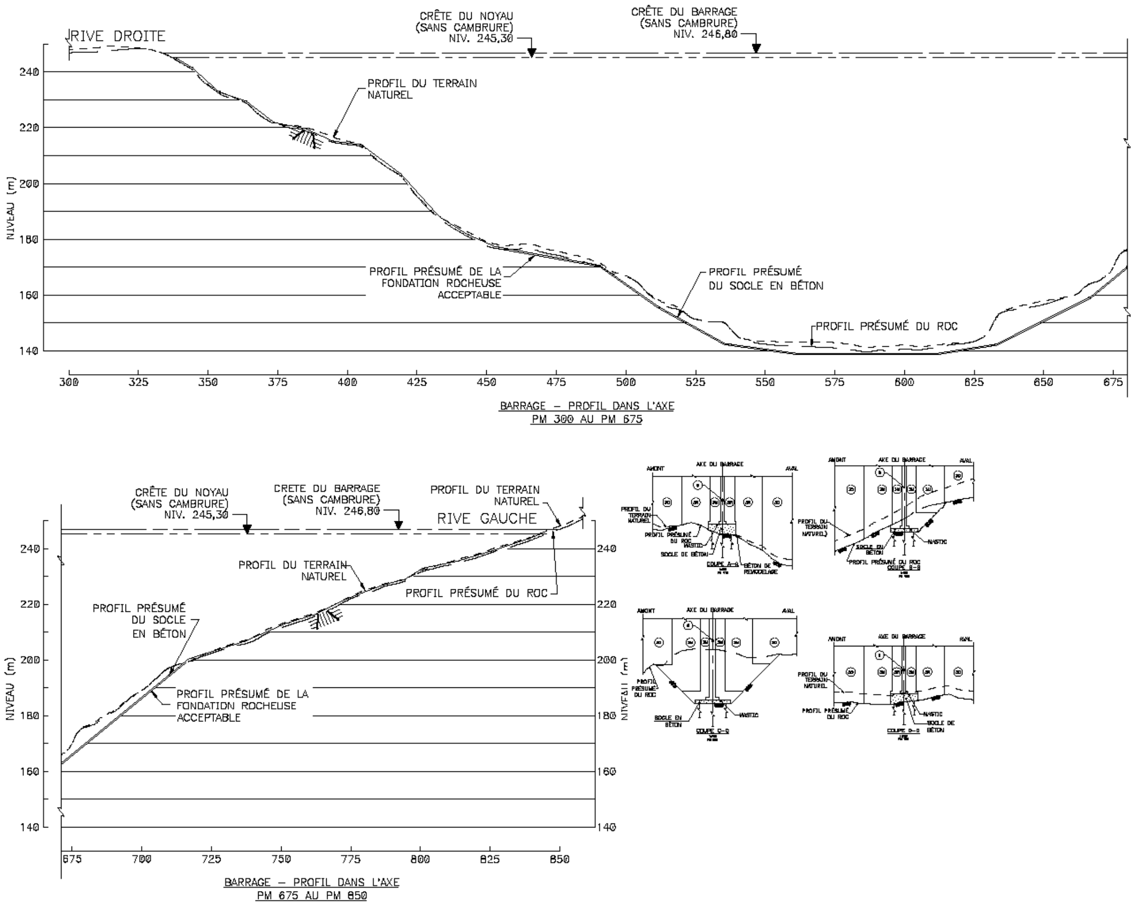


Figure B.8.3 Romaine-2 Dam – Longitudinal Profile and Concrete Sill Foundation Preparation

Figure B.8.4 Romaine-2 Dam Downstream Shoulder, Diversion Portal and Spillway

Special Design Features

- Romaine-2 dam is one of six ACRD rockfill dam/dikes comprising the Romaine-2 Project
- River diversion revealed the presence of over 300 potholes, some reaching a depth of over 3 m (> 20 m^3). Materials filling the potholes were first excavated before backfilling the potholes with either gravel or concrete
- Seepage flows measured at the downstream measuring weir are less than 2.5 l/s
- Measured settlements of the AC were 230 mm after one year of operation, less than anticipated.
- Pressure cells located directly underneath the AC and its downstream 0-80 mm caliber crushed stone support zone respond instantly to reservoir level fluctuations
- Extensive instrumentation and visual observations indicate the dam's performance is satisfactory

APPENDIX C

BOUGUCHANSKAYA DAM, RUSSIA

For the construction of rock-fill dams with an asphalt concrete core in severe Siberian climate, extreme temperatures below zero as well as the requirements for an impervious barrier have to be considered.

The special technology of the "stone-bitumen-method" in Russia was first used during the construction of the 32 m high earth dam for the sludge storage pit of Dneprovsk aluminum plant in the city of Zaporozhye (1979-81). Further examples for this special method are the "Khadita" hydrocomplex in Iraque (height about 60 m, length about 10 km, construction period 1981 - 1986), the Irganaiskaya HPP (a rock-fill dam of 101 m height, finished in 2007) as well as the the Boguchanskaya HPP (a rock-fill dam, finished in 2013). The special technology of the "stone-bitumen-method" was developed for dense mixes of aggregates according to the heterogeneity of the granulometric composition. The bitumen content is based on the upper target value of a stable asphalt concrete mix.

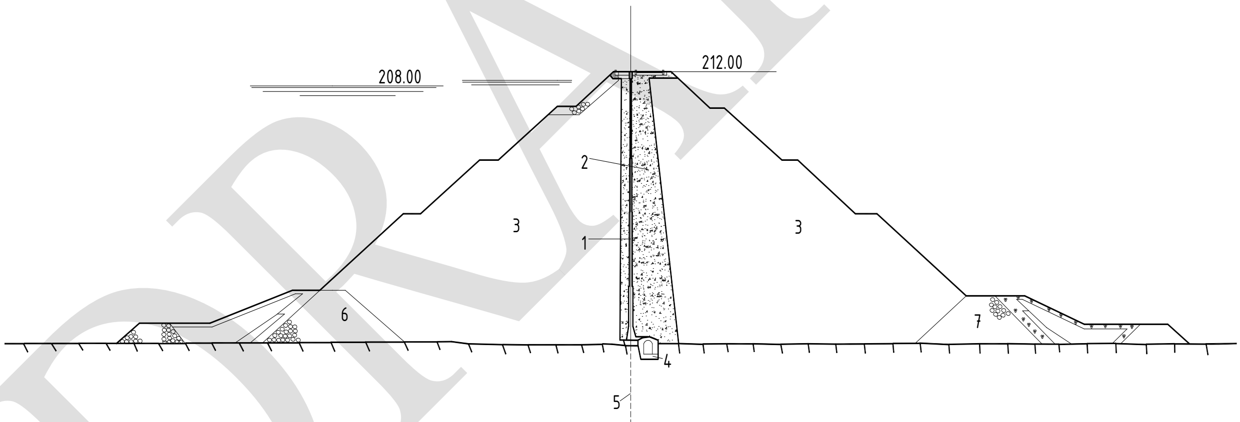


Figure C.1 Cross section of rock-fill dam Boguchanskaya HPP

1 stone-bitumen asphalt concrete core

2 transition zone

3 embankment

4 gallery

5 cement-grout curtain

6 upstream coffer dam

7 downstream coffer dam

Special Design and Construction Features

Before the construction of the rock-fill dam of Boguchanskaya HPP in Bratsk city started, a large-scale test field of the rock-fill dam with a stone-bitumen asphalt concrete core in a closed rectangle formwork with the sides of 40 x 42 m and a height of 8.5 m was completed.

The average daily air temperature in Boguchany is lower than 0° C for 190 days per year and during approx. 30 days it is raining. This means that 5 months are remaining for the construction of a conventional asphalt concrete core because this technology has limits for temperatures below 0° C and during strong rainfall. However, the stone-bitumen method can be used to construct a core barrier under such conditions.

With the stone-bitumen method the layer height for the placing may be 120 cm or more compared to the layer height of a conventional placed asphalt concrete with about 20 to 25 cm. With the stone-bitumen method self-compacting material is used and after placing no additional compaction is required to achieve an air void content of less than 2.8 %.

Since the stone-bitumen material can be placed at temperatures below 0° C, the construction work was performed at temperatures below 0° C during 64 days of the total 126 working days in 1991: 31 days at temperatures between 0 and - 10° C, 19 days at temperatures ranging from - 11 to - 20° C, 11 days at temperatures between -20 and -30°C and 3 days at temperatures between - 30° C to - 32.9° C.

The volume of the poured section of the core barrier was adjusted depending on the ambient temperature. This technical method of constant casting in sections includes the staggered removal of the partitions after casting the next section.

Figure C.2 Unloading of asphalt concrete mix from asphalt-truck into formwork

REFERENCES

Akhtarpour, A. and Khodaii, A. (2013). Experimental study of asphaltic concrete dynamic properties as an impervious core in embankment dams. Construction and Building Materials, 41 (2013) 319–334.

Alicescu, V., Tournier, J.P., and Vannobel, P. 2008. “Design and construction of Nemiscau-1 Dam, the first Asphalt Core Rockfill Dam in North-America”. Canadian Dam Association Annual Conference. Winnipeg, Manitoba. October 2008. Canadian Dam Association Bulletin, 21(1): 6–12

Alicescu, V., Tournier, J.P., Vannobel, P. and Moore V. 2011. “Design and Construction of Nemiscau-1 Dam, the first ACRD in North-America”. Proceedings of the United States Society of Dams, 2011 Annual Conference, San Diego, CA.

Alicescu, V. Tournier, J.P., Kara, R. and Rosculet, D. 2015. “Construction of La Romaine Complex in Northern Quebec: Six years of Great Accomplishments; Behaviour of Asphalt Core Dams”. Canadian Dam Association Annual Conference. Mississauga, Ontario. October 2015.

Asphaltic Concrete for Hydraulic Structures (1990). Various authors. STRABAG Schriftenreihe Nr. 45, STRABAG International GmbH, Cologne, Germany.

Bridle R (1988). Selection and Design of the Waterproofing Element for Queen's Valley Dam, Jersey, Channel Islands. Proceedings of the 16th ICOLD Congress, San Francisco, Q 61, R 35, p 643-653.

Chen,Y., Li, S. and Wang, W. (2008). Three-dimensional seismic analysis on Quxue asphalt concrete core rockfill dam. Xi’an University of Technology, Xi’an, China.

CHIDI. (2006). Three-dimensional finite element back-analysis on Yele asphalt concrete core rockfill dam and foundation.” Chengdu Hydroelectric Investigation and Design Institute, Chengdou, China.

Dymant, A. , Kuznetsov, E. (?). Cast asphalt-concrete core walls of rockfill dams. ?????

Feizi-Khankandi, S., Mirgahasemi, A.A., Ghalandarzadeh, A. and Hoeg, K. (2008): Cyclic Triaxial Tests on Asphaltic Concrete as a Water Barrier for Embankment Dams, Journal of Soils and Foundations, Vol. 48, No.3, pp 319-332.

Ghanooni, S. and Mahin-roosta, R. (2002). Seismic analysis and design of asphaltic concrete core embankment dams. Int. J. Hydropower Dams, 9(6), 75–78.

Höeg, K. (1993). Asphaltic Concrete Cores for Embankment Dams, Experience and Practice. Statkraft, Veidekke, Norwegian Geotechnical Institute.

Höeg, K. (1993). Asphaltic Concrete Core for Embankment Dams, Stikka Press, Oslo, Norway, ISBN 82-546-0163-1.

Höeg, K., Valstad, T., Kjaernsli, B. and Ruud, A.M. (2007): Asphalt Core Embankment Dams: Recent Case Studies and Research, International Journal on Hydropower & Dams, 13:5, pp.112-119.

Höeg, K. and Wang,W. (2017): Design and Construction of High Asphalt Core Embankment Dams, Symposium at ICOLD Annual Meeting, July 3-7, 2017, Prague, Czech Republic

ICOLD Bulletin 155 (2013). Guidelines for Use of Numerical Models in Dam Engineering.

Lehnert J., Geiseler W. D. (1976). High Island Water Scheme / Hongkong. Bituminöse Kerndichtung für zwei 100 m hohe Damme. STRABAG Wasserwirtschaft, Volume 66, Issue 9, p. 249-246.

Saxegaard, H. (2003). Crack self-healing properties of asphalt concrete: laboratory simulation. Hydropower & Dams, Issue Three.

Talsperre Schmalwasser. (1993). Various authors. STRABAG Schriftenreihe Asphalt-Wasserbau Nr. 49, STRABAG Tiefbau GmbH, Cologne, Germany.

Tournier, A., Mathieu, B., Vannobel, P. et Tremblay, Y. 2013. « Conception du profil et construction du socle de béton sous le noyau des ouvrages de retenue de l'aménagement hydro-électrique de la Romaine-2 ». Congrès annuel de l'Association Canadienne des Barrages. Montréal, Québec. Octobre 2013.

Tournier, J.P., Vannobel, P. et Alicescu, V. 2013. « Acquis pour Romaine-2 du projet pilote Nemiscau-1 ». Congrès annuel de l'Association Canadienne des Barrages. Montréal, Québec. Octobre 2013.

Vannobel, P., Moore, V., Kara, R., Larrivée, S. et Tremblay, Y. 2013. « Mise en place, compactage et contrôle qualitatif concernant les noyaux en béton asphaltique du projet Romaine-2 ». Congrès annuel de l'Association Canadienne des Barrages. Montréal, Québec. Octobre 2013.

Vannobel, P., Smith, M., Lefebvre, G. Karray, M. and Ethier, Y. 2013. “Control of Rockfill Placement for the Romaine-2 Asphaltic Core Dam in Northern Quebec”. Congrès annuel de l’Association Canadienne des Barrages. Montréal, Québec. Octobre 2013.

Wang, W. and Höeg, K. (2002): Effects of Compaction Method on the Properties of Asphalt Concrete for Hydraulic Structures, International Journal on Hydropower and Dams, Vol. 9, Issue 6, pp 63-71.

Wang, W. and Höeg, K. (2011). Cyclic behavior of asphalt concrete used as impervious core in embankment dams. Journal of Geotechnical and Geoenvironmental Engineering, 137(5): 536–544. doi:10.1061/(ASCE) GT.1943-5606.0000449.

Wang, W., Höeg, K. and Zhang, Y. 2010. Design and performance of the Yele asphalt-core rockfill dam. Canadian Geotechnical Journal, 47(12): 1365–1381. doi:10.1139/T10-028.

Wang, W., Zhang, Y., Höeg, K. and Zhu, Y. (2010): Investigation of the Use of Strip-Prone Aggregates in Hydraulic Asphalt Concrete, Construction and Building Materials, 24:11, pp.2157-2163.

Wang W., Zhang Y., Zhu Y. and Höeg K. (2012): The Asphalt Core Embankment Dam: An Atractive Alternative, Symposium at ICOLD Annual Meeting, June 5, 2012, Kyoto, Japan.

Wang, W. and Höeg, K. (2016): Simplified Material Model for Analysis of Asphalt Core in Embankment Dams, Construction and Building Materials, Vol.124, pp. 199 -207.

Zhang, Y., Hoeg, K., Wang, W. and Zhu, Y. (2013): Water tightness, Cracking Resistance and Self-healing of Asphalt Concrete used as a Water Barrier in Dams, Canadian Geotechnical Journal, Vol. 50, No. 3, pp 275-287.