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Simplified material model for analysis of asphalt core in embankment dams

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HIGHLIGHTS

- Long-term triaxial creep tests carried out for asphalt specimens.
- Various types of loading conditions simulated in the tests for an asphalt core in an embankment dam.
- Simplified material model proposed for the various types of loading conditions.
- The proposed model and equivalent secant moduli may be used in finite element analyses of the asphalt core in the dam.

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ABSTRACT

Asphalt concrete exhibits time- and temperature-dependent viscoelastoplastic behavior which is difficult to model and implement in practical dam design analyses. The main goal of the paper is to develop a simplified material model for the various types of loading conditions experienced by an asphalt core in an embankment dam. The types of loading conditions are simulated by conducting long-term triaxial creep tests with stepwise loading corresponding to the slow construction of the asphalt core and dam embankment; unloading-reloading cycles corresponding to seasonal reservoir fluctuations, and dynamic cyclic tests corresponding to earthquake loading. The results of the long-term triaxial creep tests show that creep strains accumulate until a "creep-stable state" is reached when virtually no further creep is occurring at that level of sustained deviator stress and temperature, and a corresponding "creep-stable stress-strain modulus" is defined. Based on the test results, a simplified material model expressed in terms of deviator stress is proposed and formulated analytically with a plastic yield boundary (PYB). The unloading-reloading and dynamic behavior was found to be almost linearly elastic, and the unloading-reloading modulus and dynamic secant modulus to be in the order of 20 and 40 times the creep-stable modulus, respectively. The proposed simplified material model and equivalent secant moduli may be used in finite element analyses of the asphalt core and its interaction with adjacent gravel and rockfill zones in the dam.

1. Introduction

The International Journal on Hydropower and Dams [1] provides a listing of 200 embankment dams with asphalt concrete core (ACED) that have been built or are under construction in different countries [2–9]. Recent comparisons with other types of embankment dams have shown the ACED to be a very competitive alternative. Among the dams listed, the 153-m high Zarema Dam in Ethiopia and the 167-m high Quxue Dam in China will be completed by the end of 2016. The Moglice Dam in Albania is in the early stage of construction and will be about 160 m high.

Finite element and finite difference analyses have been used to analyze the behavior of asphalt core dams [10–13]. The simplified non-linear model proposed by Duncan and Chang [14] is often used to analyze the behavior of embankment dams. The model is based on the concepts of elasticity theory that are familiar to most dam engineers, and, in spite of some shortcomings in modelling the general stress-strain behavior of earth- and rockfill, it is implemented in several commercial computer programs.

However, asphalt concrete presents a time-dependent, viscoelastoplastic type behavior which the Duncan-Chang model does not attempt to model. A significant amount of research has

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been done on the behavior of asphalt concrete used in road and airfield pavements, including the formulation of viscoelastoplastic models [15]. For instance, the Huet-Sayegh and 2S2P1D models are being used for asphalt pavements [16,17]. These models consider only linear viscoelastic behavior of asphalt concrete within a very small strain range. However, the model proposed and studied in this paper is to be used for an asphalt core during construction and dam operation, where the asphalt core may be subjected to strains of 1%–5% [7,8]. The requirements to a material model for an asphalt core in a dam are quite different from those for an asphalt pavement. In a very interesting contribution by Le Coroller et al. [18] the bitumen phase and the aggregate phase were modelled separately. The behavior of the bitumen phase was described by a non-linear Maxwell-Norton model, and the aggregate was modelled by an elastoplastic constitutive law based on the Mohr-Coulomb and critical state theory allowing for dilatency of the aggregate skeleton. However, models based on non-linear viscoelasticity have proved to be difficult and cumbersome to apply in practical design analyses.

A question frequently asked by the designer of an ACED is: "What modulus should be assigned to the asphalt concrete when finite element analyses are to be used to study the stresses and strains in the asphalt core and the interaction with the adjacent earth- and rockfill zones in the dam?" There is no simple answer to that question as asphalt concrete is a time- and temperature-dependent viscoelastoplastic material. The main objective of this paper is to present and analyze the results of a series of long-term triaxial creep tests. Furthermore, based on the test results, propose a simplified material model and computational procedure for analysing the stress-strain behavior of the asphalt core at different stages and for different dam loading conditions.

2. Characteristics of asphalt concrete used as impervious core in dams

The primary function of asphalt concrete used in a dam core is to create an impervious water-barrier, flexible and sufficiently ductile to accommodate the deformations imposed by the embankment, reservoir and foundation, without cracking during construction, impounding, operation, and earthquake loading. Therefore, hydraulic asphalt concrete is designed with a higher filler and bitumen content than that in the mix used for road and airfield pavements that are subjected to very different loads and environmental conditions. Typically, the contents of filler and bitumen in hydraulic asphalt are in a range of 10%–15% and 6.0%–8.0% by total weight, respectively. The air-void content (porosity) of the asphalt concrete in the dam core after compaction is required to be less than 3% to ensure a permeability coefficient less than about 10^{-10} m/s, i.e. almost impervious [2,3].

Compared with asphalt concrete pavement construction, the construction of an asphalt core is slow. The embankment shoulders and transition zones and the asphalt concrete core are placed and compacted layer by layer. Typically, the width of the dam core has been 0.5–1.0 m and up to 1.5 m for very high dams, and in conventional practice an asphalt core is constructed at a rate of 2–3 layers per day (typically 0.5 to 0.75 m per day).

It is typical to spend several construction seasons/years to construct and complete a high embankment dam, and the rate of impounding depends on the hydrological conditions and varies from dam to dam. During subsequent operation the dam is subjected to seasonal, cyclic loading by the lowering and raising of the reservoir, and dynamic earthquake shaking must be considered for dams located in seismic regions.

The asphalt core is located in the interior of the dam, protected by the embankment on both sides. The environmental conditions are very favourable with virtually no weathering effects and close to constant temperature. Typically, the temperature may be constant around 5 °C when a dam is located in sub-arctic climate and around 20 °C in sub-tropic and tropic climate. However, during construction, the asphalt concrete is usually compacted at 130–140 °C, and it takes a long time for the core to cool down and assume the temperature of the environment.

3. Typical effect of loading strain rate on hydraulic asphalt concrete response

The effect of strain rate was studied by the use of triaxial, axial compression tests with five different imposed axial strain rates. A typical asphalt mix for a core of an embankment dam in China was selected for this study and is shown in Table 1. The type of bitumen used had a penetration value of 60–80 (B70). Each asphalt concrete triaxial specimen was prepared in a split mould with a diameter of 101.6 mm and a height of 250 mm and was compacted in four consecutive layers, each initially about 60 mm thick. Each layer was compacted by 30 blows of the Marshall hammer. After compaction and cooling, the specimen was taken out of the mould and trimmed with a saw to a length of 200 mm. The results shown in Fig. 1 are for asphalt concrete specimens close to 100 mm in diameter and 200 mm in height tested with a constant radial confining stress of 1.0 MPa at a temperature of 10 °C. Fig. 2 shows the magnitude of equivalent secant Young's modulus for the asphalt concrete up to 1% of axial strain versus logarithm of axial strain rates.

Figs. 1 and 2 demonstrate that the magnitude of the equivalent Young's modulus is significantly affected by the imposed strain rate, as low strain rates result in low modulus and low deviator stress at large strains (strength level). Fig. 2 shows that the ratio between the secant modulus at an axial strain rate of 1%/min and 0.01%/min is about 2 for the asphalt concrete mix tested. However, the figure also shows that when the strain rate is below about 0.01%/min, there is no further significant reduction in modulus.

Table 1
Asphalt mix for the asphalt concrete core (% of total weight) in Kanerqi Dam, China.

Aggregates						
Sieve size (mm)	Crushed limestone aggregate size			River sands	Filler	Bitumen B70
	10–20	5–10	0.075–5	0.075–5	<0.075	
Asphalt mix (%)	23.5	18.8	31.0	10.3	10.3	6.1

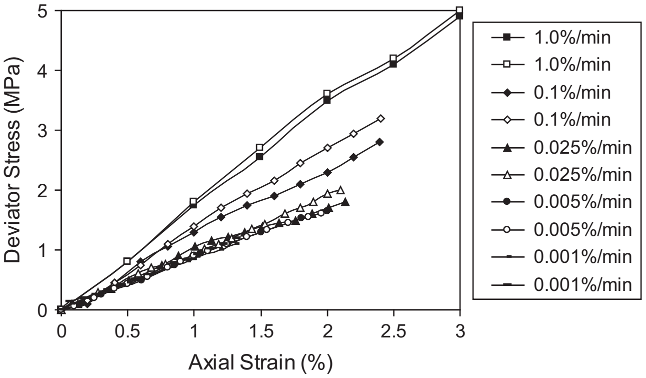

Fig. 1. Deviator stress versus axial strain for various strain rates for asphalt specimens under a radial confining stress of 1.0 MPa at 10 °C. The figure shows the results of two tests at each strain rate.