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Experimental study of asphaltic concrete dynamic properties as an impervious core in embankment dams

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HIGHLIGHTS

► Asphalitic concrete core retains its stability even after a moderate earthquake.
► The higher Bitumen content, the more is the amount of failure axial stress.
► The more the Bitumen content and confining stress, the less is the Secant modulus.
► Increasing the values of $K_c$, will increase modules both in tension and compression.
► The least and the most damping is observed at 6% and 7% Bitumen respectively.

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ABSTRACT

The seismic behaviour of asphaltic concrete used as an impervious core in embankment dams was investigated.

To evaluate the specimen’s dynamic behaviour, an extensive series of monotonic and cyclic triaxial tests were carried out. Bitumen content between 5.5% and 7.0% with 0.5% increments were selected for the tests. Isotropic and anisotropic initial stress conditions with different principal stress ratio were also considered in this study. Thousands of cycles were imposed on some of the specimens, to study their fatigue behaviour due to seismic loading. A small degradation could be seen but no cracking was observed on the cutting surfaces. All tests were carried out at a constant temperature of 22 °C simulating a constant temperature inside a dam in tropical climate regions. Shear modulus in the compression region ($G_c$) and tension region ($G_e$) are presented for different Bitumen content, confining stress, stress ratio ($K_c$) and loading type. The damping ratio was also presented for different loading states. A regression equation was also derived for determining cyclic and maximum shear modulus ($G_{max}$) of the asphaltic concrete for different Bitumen content as a function of confining stress which can be used in numerical studies.

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1. Introduction

Using asphaltic concrete as a water barrier in embankment dams began in Germany 50 years ago. Progresses in the design and construction of these types of dams have been achieved in recent years [1,2]. Significantly important engineering properties of asphaltic concrete including impermeability, flexibility, resistance against erosion, self healing [3] and independence of its placement from weather conditions, make it more a suitable and economically viable material in comparison with clay core in many locations [1,2]. Saxegaard provided an overview of asphaltic core dams constructed or currently under construction in the world [4]. The Yele dam is the highest asphalt concrete core dam built in China with a height of 125 m. Wang et al. provided some information on the design and performance of the Yele dam [5]. Although monitoring of these dams showed good performance during construction and operation, the behaviour of the slender asphaltic concrete core subjected to a severe earthquake needs more attention and exploration [6]. A large number of researches (examples from authors [7,8]) have been done on asphalt concrete used for road and airfield pavements. The effects of dynamic traffic loading on material behaviour and durability have been studied but there are only a few studies that provide information on the behaviour of asphaltic concrete used as a water barrier in hydraulic structures when subjected to simulated earthquake loading. The barrier must be designed to sustain cyclic compression as well as shear and tension stresses. Laboratory tests have been performed to study the material behaviour under such conditions [6].
This research was part of a comprehensive study on an asphaltic concrete core dam that is under construction in the south of Kerman province, Iran and is the highest asphaltic concrete core rock-fill dam in the country [9]. The dam is located in a region with high average temperature around the year. Reviewing the temperature recorded data in the region showed that 22 °C is a good estimation of temperature inside the dam most of the year, so all tests were carried out at this temperature [10].

1.1. Previous experimental studies

The first experimental research in the field of seismic behaviour of asphaltic concrete used in hydraulic structures was performed by Breth and Schwab [11]. They concluded that asphaltic concrete behaves as an elastic body under seismic loading [11].

Ohme et al. performed uniaxial cyclic tests on specimens drilled out from Higashifuji dam [12]. They defined and measured the dynamic yield strain for the asphaltic material and concluded that applied compressive stresses can lead to cracking in specimens.

Wang reported a series of triaxial cyclic tests on specimens and showed that there was no sign of cracking or degradation on the specimens under the testing conditions used [13].

Nakamura et al. performed some tests to study tensile strength and tensile cracking strain of the asphaltic concrete [14]. The main goal of their study was to investigate the difference between engineering properties of conventional asphaltic concrete with a special admixture (called Superflex-asphalt). They showed that the new type of mix has a higher tensile cracking strain than commonly used asphaltic concrete.

It is important to determine the level of tensile strain that can cause cracking in the asphaltic concrete. This strain level is clearly a function of temperature and rate of loading. In earthquake prone regions, the asphalt mix is usually made with soft grade Bitumen and an added Bitumen content (0.5–1)% to increase flexibility and tensile cracking strain [15].

Baziar et al. performed a 3D finite difference analysis on the asphalt of Meijaran dam with a height of 60 m in Iran. Some cyclic tests were also carried out to estimate the shear modulus of the asphaltic concrete. Their numerical study showed that the upper part of the core will experience some plastic shear strains in a maximum earthquake level (MDL). They also concluded that the numerical response of the dam is not significantly dependent on the amount of shear modulus of the asphaltic core in a range of 800–1800 Mpa [16]. A small scale centrifuge modelling of the dam was also performed under impact load. They indicated that the numerical results agreed well with the data recorded during centrifuge tests and the asphaltic core showed similar behaviour in the numerical and centrifuge models. The results of the numerical study for the case study showed that in a severe earthquake, the asphaltic core behaves in a safe manner [17].

Feizi et al. performed an extensive series of monotonic and cyclic tests on triaxial specimens with constant Bitumen content at the Norwegian Geotechnical Institute [18]. Temperature and frequency effects on specimen behaviour and specimen degradation were studied under the cyclic loads in both isotropic and anisotropic conditions. Their findings showed that the dynamic shear modulus (G) derived from hysteresis loops were between 1.6 and 4.0 GPa at 5 °C and 0.75–1.75 GPa at 18 °C. They also reported extension behaviour during cyclic loading for some of the specimens at a higher temperature (18 °C).

Recently, Wang and Hoeg studied the effects of cyclic loading on the stress-strain behaviour and permeability of asphaltic concrete at different temperatures under static and cyclic stress conditions [19]. Their study indicates that at a mean sustained stress of 1.0 MPa, the cyclic modulus (E g not G) is about 900 MPa at 20 °C, 1900 MPa at 9 °C, and about 2500 MPa at 3.5 °C [19]. They also concluded that the number of load cycles has no significant effect on the post-cyclic monotonic stress–strain–behaviour and permeability (water tightness) of the asphalt concrete.

Previous studies indicate that the main parameters affecting dynamic properties of the asphaltic concrete are temperature, confining stress, initial stress ratio, loading type, loading speed, frequency and Bitumen content. Only a few publications provide information on some of these parameters [18,19], however there is a lack in these studies especially in the field of Bitumen content effect and for seismic behaviour of asphalt concrete used in warm climate regions because most asphaltic concrete core dams have been constructed in cold regions. Also, previous studies did not clearly address the dynamic shear modulus of the material which can be used in nonlinear dynamic numerical analysis.

So this study tries to cover the main topics as mentioned below:

- Determination of monotonic and cyclic response of the asphalt concrete.
- Effects of different parameters on the behaviour of specimens.
- Fatigue behaviour and cracking possibility of the samples.
- Post-cyclic behaviour and degradation of the specimens due to cyclic loading.
- Suggestion of geotechnical parameters to be used for numerical analyses.

2. Mix design and specimen preparation

The coarse aggregates used were crushed silicate sand and gravel satisfying Fuller distribution given by following equation:

$$P_i = 100 \left( \frac{d_i}{d_{	ext{max}}} \right)^{0.41} \% $$

where $P_i$ is the percent by weight of material smaller than grain size $d_i$ and $d_{	ext{max}}$ is the nominal size of the aggregates. Marshal tests according to ASTM-D1559 were carried out with a Bitumen content of 5.5, 6.0, 6.5, 6.75 and 7.0 percentages by weight. B60 type Bitumen was used for all tests.

Bitumen content between 5.5% and 7.0% are permissible in asphaltic concrete used as a water barrier, but researchers commonly advise the use of between 6.5% and 7.0% by weight of aggregates [1]. This range of the Bitumen content is selected for most of the asphaltic concrete core dams in the world to achieve flexibility during and after an earthquake loading [1]. However, there is not much information on the effect of Bitumen content on the dynamic properties of asphaltic concrete used in dams. Hence, different percentages of Bitumen content from 5.5 to 7.0 by weight of aggregates were selected for this study.

The laboratory triaxial specimens were prepared in a 100 mm diameter and 200 mm height mould. Portland cement was used as filler in the mix. The specimens were built in four equal thickness layers using the compaction method which is in good accordance with field roller compaction in the field [20]. All samples were trimmed with a diamond cutter and the surfaces of specimens were polished to decrease the bedding error effect during the tests.

3. Static triaxial tests

Twelve triaxial compression tests were carried out to investigate the static behaviour of the asphaltic concrete. Membrane was used for all the test specimens. All specimens were placed into a constant temperature bath to reach 22 °C prior to monotonic testing. The triaxial cell was also filled with de-aerated 22 °C water. All monotonic tests were carried out using a strain-controlled compression loading system. After applying the predefined confining
stress and reaching a constant temperature, an axial load with a 2% strain rate per hour was applied until failure.

The results of the monotonic triaxial tests are illustrated in Table 1. Fig. 1a–d also shows the axial stress vs. axial strains for each Bitumen content considered. Imposed confining pressures were 250, 500 and 1000 kPa. As it was expected, the higher the confining stress, the more the amount of axial failure stress and axial failure strain.

Secant modulus in 1% strain was derived from the initial stage of the curves as presented in Table 1. For this range of confining stress, Secant modulus varied from 28 MPa to 151 MPa. For asphaltic concrete material, it is common to use an equation such as Eq. (2) to derive the Secant modulus [18,19]:

$$E_{1\%} = \frac{A}{\sigma_0^2}$$

where $A$ and $y$ are constant parameters.

Based on the monotonic results (Table 1), the value of $y$ is calculated for each Bitumen content as shown below:

$$E_{1\%} = \frac{A}{\sigma_0^2^{53}} \text{ (Bitumen content = 5.5%) }$$
$$E_{1\%} = \frac{A}{\sigma_0^2^{43}} \text{ (Bitumen content = 6.0%) }$$
$$E_{1\%} = \frac{A}{\sigma_0^2^{23}} \text{ (Bitumen content = 6.5%) }$$
$$E_{1\%} = \frac{A}{\sigma_0^{0.18}} \text{ (Bitumen content = 7.0%) }$$

Results generally show that the Secant modulus increases with increasing confining stress especially for lower Bitumen content. However, in the higher Bitumen percentage, this dependency decreases. This is because in higher Bitumen content the aggregates are more saturated with Bitumen and Bitumen controls the general behaviour of the material. Therefore, some differences from the common behaviour expected for soils, can be observed. However, for strain values of more than 1%, an increase in shear strength is reported while increasing confining pressures [18,21].

### 4. Cyclic loading triaxial tests

#### 4.1. Tests condition and planning

Fifty three cyclic triaxial tests were carried out in this research. The specimens were tested with different percentages of Bitumen content from 5.5 to 7.0 by 0.5% increments. They were also loaded under initial isotropic conditions ($K_c = \sigma_1/\sigma_3 = 1.0$) and anisotropic initial stress conditions ($K_c = 2.0$ and 3.0). Previous numerical studies [22–24] showed that in a real dam, the top of the dam is affected by a confining pressure of 100–500 kPa when subjected to an earthquake loading, so this range of confining pressures was selected in this research.

Two types of cyclic loading were subjected to the specimens in triaxial tests, type A and type B. Type A was a two-way loading and extension together with compression were applied until failure.
only compressive loading. In this type of loading, the deviatoric loading reaches a negative value corresponding to axial stress of nearly 0.0 kPa. Fig. 2 shows two types of loading as an example for 500 kPa confining stress (Kc = 3.0).

The majority of tests were carried out with 50 cycles of Sine wave loading as summarized in Table 2. All of these tests were performed with a frequency of 2 Hz, because most of the energy in a real earthquake is transmitted with 1–4 frequency components [25].

However, six additional tests were carried out with 1000 cycles of loading and frequency of 1–5 Hz. The results of this series of tests are described later.

4.2. Hysteresis loops

Figs. 3–10 show the hysteresis loop of the cyclic loading as examples. The hysteresis loops were plotted for the first, tenth and fiftieth cycle of loading for the main tests.

Hysteresis loops for anisotropic conditions with Kc = 3 (K25E-Series) for different Bitumen content with confining pressure of 250 kPa are plotted in Figs. 3–6 and for confining pressure of 500 kPa in Figs. 7–10 (K25E-Series).

The hysteresis loops show the shear stress vs. axial strain in the cyclic loading stage of the triaxial tests which can be used to calculate shear modulus and damping ratio as described later. It can be observed from hysteresis loop shapes plotted in Figs. 3–10 that the curve inclination in the upper part of a hysteresis loop is more than the curve inclination in the lower part of the shape so the asphaltic material has a higher shear modulus in compression (Gc) than in extension (Gt). Moreover, the comparison between average curve inclinations in the hysteresis loops for different cycles in a test is a good criterion to investigate the material degradation. This comparison shows that by increasing the number of cycles, the amount of average curve inclination (that can be indicated by dynamic shear modulus) does not significantly decrease for this range of stress applied to the specimens (Table 2). Some more tests were continued to a thousand cycles of loading to study whether there is a long-term degradation (Fatigue Phenomenon). Results indicated no noticeable change in shear modulus even after 1000 cycles of loading (Fig. 19).

For all tests, the specimens show a compression behaviour during cyclic loading which means with increase in number of cycles, residual axial strains develops. This phenomenon can be explained in a way that in the first stage of tests (static loading), period is not long enough to reach a fully “creep stable state” so the residual axial strains recorded during cyclic loading, are predominantly creep strains caused by the sustained static deviator stresses [19].

4.3. Dynamic properties of asphalt concrete

Axial stiffness and damping parameters can be derived from shear stress vs. axial strain charts for triaxial dynamic tests using the following relations:

\[
E = \frac{\tau}{\varepsilon_a}, \quad \gamma = (1 + v) \cdot \varepsilon_a \tag{7}
\]

\[
G = \frac{E}{2(1 + v)} \tag{8}
\]

where \(\tau\) = shear stress, \(\varepsilon_a\) = axial strain, \(\gamma\) = shear strain and \(v\) = Poisson ratio and \(G\) is shear modulus.

Shear modulus varies during cyclic loading so the 1st, 10th and 50th cycle were chosen to calculate the shear modulus. Table 2 present the shear modulus and damping ratio for the 1st, 10th and 50th cycle for the main and additional tests.

All shear modulus parameters for different cycles were obtained from the upper part (Gc) and lower part (Gt) of the hysteresis loops because of the difference between the curve inclinations in compression and tension regions.

The damping ratio (D) was calculated using Eq. (9) [25]:

\[
D = \frac{1}{4\pi} \times \frac{W_0}{W_t} \times 100(\%) \tag{9}
\]

where \(W_0\) is the area of a hysteresis loop and \(W_t\) is the area of the triangle indicated in Fig. 11. Values of the damping ratio varied from 0.08 to 0.3.

Shear modulus of the asphaltic concrete in this temperature (22 °C) varied between 150 and 450 MPa in the compression region (Gc) and 80–290 MPa in the tension region (Gt), depending on the Bitumen content, confining stress, stress ratio (Kc) and loading type.

It should be noted that the damping ratio percentages obtained in the present study for the asphalt concrete is high and it is comparable with coarse aggregate material [26].

Different parameters such as Bitumen content, confining stress, anisotropy, loading type and frequency affect the shear modulus and damping ratio. The effects of the above parameters are described in details in the following sections.

4.3.1. Effect of Bitumen content

General advice in the asphaltic concrete core dam design, is to use higher Bitumen content to ensure flexibility against seismic loading [6], however its effect on dynamic properties are not well-known.

Fig. 12 presents the effect of Bitumen content on dynamic shear modulus of the asphaltic concrete in different confining pressure, stress ratio Kc and loading type. In the higher confining stress (250 and 500 kPa), generally higher shear modulus are related to 6.0% and then 5.5% Bitumen content. With an increase in Bitumen content from 6.5% to 7.0%, the shear modulus decreases. This behaviour is observed in the tests with a stress ratio of 2 and 3 (Kc = 2, 3) and shown in Fig. 12a–c). However, in low confining pressure (100 kPa), the behaviour of the material is different and reduction in shear modulus with increasing Bitumen content are observed (Fig. 12f and g). This behaviour can be interpreted in a
| Test id. | Bitumen content (%) | $r$ (kPa) | $K_c$ | Loading type | 1st Cycle | 10th Cycle | 50th Cycle | Damping (%)<br>Gc (MPa) | Ge (MPa)<br>Damping (%)<br>Gc (MPa) | Ge (MPa)<br>Damping (%)<br>Gc (MPa) | Ge (MPa)<br>Damping (%)<br>Gc (MPa) |
|----------|---------------------|---------|------|--------------|-----------|------------|------------|----------------|----------------|----------------|----------------|----------------|
| 55K10e   | 5.5                 | 100     | B    | 3            | 161.5     | 103.3      | 14.7       | 157.3         | 103.6         | 12.9          | 156.6         | 96.7           | 14.0          |
| 60K10e   | 6.0                 | 146.4   | 125.3| 12.0         | 174.2     | 114.6      | 11.8       | 172.6         | 114.3         | 12.5          | 155.4         | 118.1         | 11.1          |
| 70K10e   | 7.0                 | 179.2   | 140.7| 11.6         | 220.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 55K15e   | 5.5                 | 250     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 60K15e   | 6.0                 | 250     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 70K15e   | 7.0                 | 250     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 55K20e   | 5.5                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 60K20e   | 6.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 70K20e   | 7.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 55K25e   | 5.5                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 60K25e   | 6.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 70K25e   | 7.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 55K30e   | 5.5                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 60K30e   | 6.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
| 70K30e   | 7.0                 | 500     | B    | 3            | 228.7     | 128.6      | 17.4       | 228.5         | 128.9         | 16.4          | 228.0         | 121.7         | 10.5          |
way that in the high confining pressures, increasing the Bitumen content decreases the interlocking between the aggregates and also the degree of saturation of aggregates would increase with Bitumen content causing a decrease in the dynamic shear modulus. However, in the low confining pressures, the interlocking of aggregates is not supported by the confining pressure and especially in the low levels of strains the bonding between the aggregates by Bitumen determines the behaviour of the material. The increase in dynamic shear modulus is observed due to an increase in the Bitumen contents probably due to an increase in the multiplicity of particle bonds. Based on this hypothesis, it is evident that by increasing the level of strains, the effect of the bonds decreases due to their breakage. (See Fig. 12f and g).
4.3.2. Effect of confining stress

The effect of confining stress on compression and tension shear modulus based on all tests is illustrated in Fig. 13. As expected, a higher dynamic shear modulus was observed at higher values of anisotropy state, the amount of mean effective stress \( \sigma_{\text{mean}} \) increases. The effect of stress ratio \( K_c \) on damping with different Bitumen content is shown in Fig. 17. Generally, at a constant confining stress, an increase in the value of \( K_c \) results in a decrease in the damping value.

4.3.3. Effect of anisotropy

For further studying the effect of anisotropy on dynamic shear modulus, tension and compression are presented in Fig. 16 for different values of Bitumen contents and confining pressures. Generally increasing the values of \( K_c \) caused an increase of tension and compression in the modulus. This variation in modulus is affected by Bitumen content such that, in the Bitumen content of 7% and especially in the high confining pressures, the effect of increasing \( K_c \) on the shear modulus becomes negligible. This is due to the fact that at higher values of anisotropy state, the amount of the mean effective stress \( \sigma_{\text{mean}} \) increases. The effect of stress ratio \( K_c \) on damping with different Bitumen content is shown in Fig. 17. Generally, at a constant confining stress, an increase in the value of \( K_c \) results in a decrease in the damping value.

4.3.4. Effect of hysteresis loop shapes

As mentioned previously, curve inclination in the upper part of a hysteresis loop is more than the curve inclination in the lower part of the shape so shear modulus derived from the upper part (compression) will be higher than the shear modulus in the lower part (extension). During the cyclic triaxial tests, strength reaches the failure line in the extension mode. Consequently, the values of axial strain increases. With the application of compression loads, the specimen’s behaviour is changed. However, some residual strain remains. This is one of the explanations to describe lower curve inclination in the extension region. Anisotropy in asphalt concrete, due to the direction of compaction, is another reason for this change in the curve inclination [28]. Figs. 13 and 16 show the effect of Bitumen content, confining pressure and stress ratio on the shear modulus in compression \( (G_c) \) and tension \( (G_t) \). They show that the shear modulus in the tension region is about 60–70% of the shear modulus in the compression region. The former is in the specimens with 6% Bitumen content and the latter is in 5.5% Bitumen content. It is clearly observed from Figs. 13 and 16 that by increasing confining stress and/or anisotropy coefficient at a constant Bitumen content, the value of \( G_t \) decreases and \( G_c \) increases.

4.3.5. Effect of number of cycles

Fig. 18 presents the effect of the number of cycles on strain-dependent shear modulus reduction behaviour for different Bitumen content and for a confining stress of 500 kPa in anisotropic conditions for two stress ratios of \( K_c = 2 \) and \( K_c = 3 \).

The values of shear modulus are plotted for the 1st, 10th and 50th cycles. It can be observed that, at constant Bitumen content, confining pressure and stress ratio, by increasing the number of cycles, the amount of shear modulus decreases, but this reduction is...
not noticeable especially in higher strains. This reduction in shear modulus is more distinct in low levels of shear strain. In addition, this effect is more pronounced in 5.5% and 6.0% of Bitumen content. Furthermore, at a constant confining stress, with a decrease of Bitumen content/anisotropy, the effect of number of cycles gradually decreases. In other words, in the same cyclic number, the specimen’s degradation with a lower value of Bitumen content/anisotropy coefficient ($K_c$) is less than that of higher Bitumen content/anisotropy.

Finally, as discussed in Section 4.2, no significant degradation and reduction in shear modulus can be observed.

4.3.6. Effect of frequency

Effects of frequency and number of cycles on the shear modulus and damping ratio of the asphaltic concrete for the additional 1000 cycle tests are presented in Fig. 19. As mentioned previously, the frequencies of 2–5 Hz were selected for these tests. All additional tests were performed in 7.0% Bitumen content. The confining pressure selected for these tests was 250 kPa.

As presented in Fig. 19a and b, dynamic shear modulus from compression ($G_c$) and tension ($G_e$) regions, at a constant stress ratio ($K_c = 3.0$), increases with an increase in frequency. The effect of the number of cycles on the shear modulus can also be seen in Fig. 19. As indicated earlier, the increase in the number of cycles cause a decrease in the shear modulus but it is not considerable. A small decrease in damping ratio is visible with an increase of loading frequency. This is due to the fact that, the energy absorbance capability reduces as the loading speed increases.

It should be noted that this conclusion (increase in the dynamic modulus with increase in frequency) cannot be true because the shear strains in a loop in different frequencies are not the same. To resolve the problem, a strain-dependent shear modulus for the tests should be presented. Fig. 20 illustrates the shear stress–shear strain curves for the tests with frequencies of 2–5 Hz.
There is not a significant difference between the curves for different frequencies so it can be concluded that the loading frequency in the assumed ranges has no significant influence on the strain-dependent shear modulus. On the other hand, in a same shear strain, shear modulus of the asphalt concrete is constant.
4.4. Specimens cracking

After the cyclic tests, some specimens were cut horizontally and vertically to study the possibility of cracking. Fig. 21 shows an example of the cutting surface. No cracking was observed on the cutting surfaces even after 1000 cycles.

4.5. Dynamic shear modulus of the asphaltic concrete

As presented in Section 3, dynamic modulus ($E$) can be expressed as a power function of confining stress, as in following equation:

$$E = A \times \sigma_0^m$$ \hspace{1cm} (10)

Based on the elastic theory, shear modulus ($G$) relates to axial modulus ($E$) according to Eq. (8). Assuming a constant poison’s ratio during the loading cycle, the equation can be written as following equation:

$$G = K \times \sigma_0^m$$ \hspace{1cm} (11)

where $K$ is a multiplier depends on the strain level. A statistical analysis was performed on the data from all tests with different Bitumen content at the same strains and with similar loading conditions and the average power “$m$” for different Bitumen content was calculated as follows:

- $m = 0.27$ (Bitumen content 5.5%)
- $m = 0.38$ (Bitumen content 6%)
- $m = 0.43$ (Bitumen content 6.5%)
- $m = 0.37$ (Bitumen content 7.0%)

For 7% Bitumen content, the value derived for $m$ (0.37) is in good agreement with Wang and Hoeg’s findings for the asphaltic concrete (0.33) tested at 20°C [19]. Temperature has a significant influence on the results as dynamic shear modulus decreases with an increase in temperature. Their findings also showed that a decrease in temperature from 20°C to 3.5°C can cause a 3 fold increase in the dynamic modulus.

To determine the maximum dynamic shear modulus of the asphaltic concrete, Eq. (11) can be written as:

$$G_{\text{max}} = K_{\text{max}} \times \left( \frac{\sigma_0}{100} \right)^{0.37} \text{ (Bitumen content 7%)}$$ \hspace{1cm} (12)

where $\sigma_0$ is the confining stress in kPa and $G_{\text{max}}$ is the maximum shear modulus in MPa. Generally, the triaxial test does not have sufficient accuracy in a small strain range so $G_{\text{max}}$ cannot be calculated directly from test data. One way is to use the extrapolation method from the shear modulus–shear strain curve to obtain the small strain shear modulus ($G_{\text{max}}$). Nakamura et al. suggested a $G/G_{\text{max}}$ vs. $\gamma$ curve for the asphalt concrete used as an impervious core in embankment dams; this curve is presented in Fig. 22 [14].

Results in the middle range of strains which are obtained in triaxial tests showed good harmony in comparison with the adopted $G/G_{\text{max}}$ curve from Nakamura et al. presented in Fig. 22 [14]. A statistical analysis was performed on all the triaxial test results for 7% Bitumen content in different levels of strains and $K_{\text{max}}$ was determined as follows:

$$G_{\text{max}} = K_{\text{max}} \times \left( \frac{\sigma_0}{100} \right)^{0.37} \text{, } K_{\text{max}} = 321, \text{ where } 100 < \sigma_0 < 500 \text{ (kPa)}$$ \hspace{1cm} (13)

Eq. (13), together with assuming Nakamura’s suggested curve for $G/G_{\text{max}}$ can be used for nonlinear numerical dynamic analyses.

4.6. Post-cyclic behaviour of the asphalt concrete

To investigate the post-cyclic behaviour of the asphaltic concrete, some specimens were subjected to monotonic loading prior to cyclic loading. The loading speed for these specimens was 2% strain per hour similar to the initial monotonic tests. The post-cyclic monotonic stress–strain curves are compared with the corresponding curves for the specimens not initially subjected to cyclic loading. This comparison can show a sign of material degradation due to cyclic loading. Fig. 23 presents this phenomenon for...
Fig. 15. Effect of confining pressure (kPa) on the strain-dependent shear modulus. (a) $K_c = 2$, $T = 22^\circ$, Bitumen content 5.5%, loading type B. (b) $K_c = 2$, $T = 22^\circ$, Bitumen content 6.0%, loading type B. (c) $K_c = 3$, $T = 22^\circ$, Bitumen content 6.5%, loading type B. (d) $K_c = 3$, $T = 22^\circ$, Bitumen content 7.0%, loading type B. (e) $K_c = 3$, $T = 22^\circ$, Bitumen content 6.0%, loading type B. (f) $K_c = 3$, $T = 22^\circ$, Bitumen content 6.5%, loading type B. (g) $K_c = 3$, $T = 22^\circ$, Bitumen content 7.0%, loading type B. (h) $K_c = 3$, $T = 22^\circ$. Bitumen content 7.0%, loading type B.
6.5% and 7.0% Bitumen contents, respectively. The confining pressure was 250 kPa and the stress ratio \((K_c)\) was 3.0. After 50 cycles of stress application, no significant degradation was observed. The amount of degradation is nearly 10% at the peak point of the curves. Furthermore, similar behaviour is evident for both specimens. There is no significant difference for specimens with 6.5% or 7.0% Bitumen content.

5. Summary and conclusions

General advice for designing asphaltic concrete core rockfill dams is to use high Bitumen content to ensure flexibility against earthquake loading, however there was not enough high quality experimental data to approve this advice quantitatively. Also, many asphaltic core dams have been designed and constructed...
Fig. 18. Effect of number of cycles on the strain-dependent shear modulus. (a) $K_c = 3$, $\sigma_3 = 500$ kPa, Bitumen content 5.5%, loading B. (b) $K_c = 3$, $\sigma_3 = 500$ kPa, Bitumen content 6.0%, loading B. (c) $K_c = 3$, $\sigma_3 = 500$ kPa, Bitumen content 6.5%, loading B. (d) $K_c = 3$, $\sigma_3 = 500$ kPa, Bitumen content 7.0%, loading B. (e) $K_c = 2$, $\sigma_3 = 500$ kPa, Bitumen content 5.5%, loading B. (f) $K_c = 2$, $\sigma_3 = 500$ kPa, Bitumen content 6.0%, loading B. (g) $K_c = 2$, $\sigma_3 = 500$ kPa, Bitumen content 6.5%, loading B. (h) $K_c = 2$, $\sigma_3 = 500$ kPa, Bitumen content 7.0%, loading B.
in cold regions but there has not been sufficient information on the dynamic properties of the material in the higher temperature regions. Furthermore, some previous studies had shown that there are some concerns using asphaltic concrete as a water barrier in dams with higher temperatures [18]. These reasons were the main incentive to perform this research.

The results obtained from this research can be summarized as follows:

- Monotonic triaxial tests have shown that the higher the Bitumen content, the greater the amount of failure axial stress. Specimens with higher Bitumen content generally showed more axial strain at failure. Also, the Secant modulus derived from all tests in 1% axial strain is a function of confining stress and Bitumen content. The more the Bitumen content and confining stress, the less the Secant modulus especially in lower Bitumen content.
- Fifty cycles were applied in the cyclic triaxial tests on different Bitumen content specimens to simulate earthquake loading. Additional tests were performed with 1000 cycles. The dynamic
shear strains were less than 0.4% for all tests and no significant degradation was detected in the specimens. No cracks on the specimen surfaces were seen even in the specimens with lower Bitumen content after 1000 cycles.

- Factors influencing dynamic properties of asphaltic concrete were studied in detail. They were Bitumen content, confining pressure, stress anisotropy and loading frequency. Dynamic shear modulus and damping ratio of the specimens were derived from test results. Dynamic shear modulus is found to be significantly dependant on the strain level.

- Generally in higher confining stresses, the higher shear modulus relates to 6.0% and then 5.5% Bitumen content. With an increase in Bitumen content, the shear modulus decreases. However, in low confining pressure (100 kPa), the behaviour of the material is different and a reduction in shear modulus with increasing Bitumen content is observed. So in the upper part of a real dam where the confining pressure is low, using an asphalt mixture with higher Bitumen content causes an increase in dynamic shear modulus at strain levels of less than 0.4%.

- A higher dynamic shear modulus was observed at higher values of confining stress. This increase has the most value for 6% Bitumen content and after that it decreases with an increase in Bitumen content. The least and the most damping was observed at 6% and 7% Bitumen content, respectively. By increasing the confining stress, the higher damping value can be obtained.

- Generally, by increasing the values of $K_c$, the increase in tension and compression modules can be seen. Also, by increasing the value of $K_c$ in a given confining stress, the values of damping would decrease.

- It is concluded that, at constant Bitumen content, confining pressure and stress ratio, the amount of shear modulus decreases as the number of cycles increase. This reduction in shear modulus is more obvious in low level shear strains.

- An increase in loading frequency causes an increase in dynamic shear modulus and decrease in damping ratio, but a shear modulus in the same shear strains seem not to be affected by the load frequency.

- After completion of cyclic loading, some specimens were subjected to monotonic loading to investigate post cyclic behaviour. Results show no significant degradation and reduction in shear strength.

- Numerical analysis has shown [22] that in a real dam subjected to a very severe earthquake, the remaining plastic shear strains might be significantly more than 0.4% (which is reached in this study) in the upper part of the asphaltic core (about upper one third), but the lower part experiences less shear strains, so it is advisable to use higher Bitumen content in the upper part to ensure flexibility and prevent tensile cracking strain and lower Bitumen content in the lower part considering financial benefits.

- The dynamic shear modulus of the asphaltic concrete has a linear relationship with the confining stress in a logarithmic scale, so based on the test results, an equation to determine the dynamic shear modulus of the asphaltic concrete was developed which can be used for numerical analysis purposes.

Fig. 22. $G/G_{\text{max}}$ vs. $\gamma$ suggested curve for the asphaltic concrete [14].

Fig. 23. Post cyclic behaviour (stress–strain curves), $\sigma_3 = 250$ kPa.
used as a water barrier in an embankment dam. In the case of dams constructed in a high seismic hazard region, which can be subjected to a very severe earthquake, a numerical analysis should be carried out to determine the level of dynamic shear strains in the core. Suitable Bitumen content in the mix depends on the dynamic shear strains, ambient temperature and Bitumen type. Results of this study indicate that in the low level of shear strains, lower Bitumen content can be used without significant reduction in flexibility of the asphaltic concrete.

References