Earthquake Resistance of Asphalt Core Embankment Dams

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Summary

The report reviews the documented field performance and theoretical analyses of embankment dams with asphalt concrete facing or core subjected to earthquake excitations. The thin asphalt concrete water barriers have to adjust to and follow the cyclic and permanent strains imposed by the embankment without cracking or other material degradation. Therefore, a review is made of the documented laboratory testing of asphalt concrete subjected to simulated earthquake loading. The report presents results of specimens in cyclic triaxial compression, direct shear, flexure and direct tension. Special attention is paid to the effects of loading rate (strain rate) and temperature on the amount of tensile strain that asphalt concrete can undergo (tolerate) without cracking. Ways to improve material ductility are discussed.

The asphalt concrete in a dam core is subjected to much less severe environmental conditions and earthquake loading conditions than asphalt concrete in an upstream face slab. A properly designed rockfill embankment dam is very resistant to earthquake excitations, and the earthquake has to be very strong to cause any detrimental cracking or material degradation of the properties of a ductile asphalt concrete core.

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1 INTRODUCTION AND SCOPE

Rockfill embankment dams are able to withstand strong earthquake shaking (e.g. ICOLD, 2001; Weiland, 2003; ICOLD, 2004). Some permanent crest settlements and slope deformations occur due to severe earthquake excitations, but there have not been reported any serious damage or signs of instability, although many rockfill dams have been built in seismic regions.

The amount of damage incurred, or the magnitude of leakage as a result of the earthquake, depend, among other factors, on the type and location of the impervious element in the embankment. The stresses and strains imposed on a central core of earth or asphalt concrete are quite different from those imposed upon an upstream facing, both during (cyclic deformations) and subsequent to (residual deformations) the earthquake shaking. This is documented by field observations as well as by theoretical seismic analyses, e.g. Belloni et al. (1988); Le Coreller et al.(1988); Gazetas and Dakoulas (1992); Uddin and Gazetas (1995); Ghanooni and Salehi (2000); Ghanooni and Roosta (2002); Baziar et al. (2003); Jafarzadeh and Javaheri (2003); Nenghui et al. (2003), and Yasuda et al. (2003)

It is the embankment as a whole, and primarily the rockfill shoulders, that govern the dam behaviour. The thin upstream facing and the core have to be able to adjust to the imposed strains during the shaking and the post-cyclic permanent deformations without undergoing significant cracking or material degradation.

The main purpose of this report is to summarize the information available on the behaviour of asphalt concrete subjected to cyclic loads caused by earthquakes and to compare the conditions for an upstream asphalt facing with those for a central core in a rockfill dam.

2 REPORTED FIELD PERFORMANCE

There are several asphalt concrete core rockfill dams (ACRD) built in earthquake regions (e.g. China, Japan, Bulgaria). However, there are no reports of any damage due to earthquake shaking. This may be due to the fact that no severe shaking has taken place although the first asphalt core dams were built in the 1950s.

There are some reported cases of damage to upstream dam facings of concrete (CFRD) or asphalt (AFRD). Cracking has occurred due to cyclic tensile stresses (tensile strains) during the shaking and due to permanent deformations of the upstream embankment shoulder under the facing. One reported case is that of the 25m high Higashifuji Dam, Japan, with an upstream asphalt concrete facing (Ohne et al., 2002). The dam was completed in 1971 and was damaged by an earthquake in 1996. According to the authors several severe cracks developed in the asphalt concrete facing. However, it should be noted that the dam was not built of rockfill but of volcanic sand, which undoubtedly underwent significant permanent deformations (compaction) due to the earthquake shaking and therefore also caused differential displacements under the face slab and bending and shear stresses.

There are several other papers published by Japanese authors discussing the design and observed behaviour or AFRDs subjected to earthquake loading. The papers include analytical (numerical) design predictions as well as recorded field behaviour, e.g. Daicho (1988); Ishii and Kamijo (1988); Hasegawa and Kikusawa (1988); Terada et al. (1997), and Kawashima et al. (1997).

3 ASPHALT CONCRETE BEHAVIOUR IN LABORATORY TESTS

Much research has 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. There are only a few papers that provide information on the behaviour of asphalt concrete used as impervious water barriers in dams (upstream facing or interior core) when subjected to simulated earthquake loading. The barrier must be designed to sustain cyclic compression as well as shear and tension stresses, and laboratory tests have been performed to study the material behaviour under such conditions.

3.1 Cyclic Tests in Triaxial Cell

The first experimental research done on the earthquake resistance of asphalt concrete used in dam cores was done by Breth and Schwab (1973) in Germany. Using the dynamic shear beam analysis method described by Seed and Martin (1966) for embankment dams, Breth and Schwab (1973) computed the dynamic shear stresses imposed on a central vertical core in a 180 m high ACRD subjected to the horizontal N-S component of the El Centro earthquake. They then devised a very interesting experimental set-up to impose the computed cyclic horizontal shear stresses on representative elements of the asphalt concrete core (see Fig. 1). The triaxial specimen was first subjected to static initial stresses (σ_1 and σ_3), and then horizontal cyclic (dynamic) shear stresses were imposed as indicated in Fig. 1. The cyclic frequency was set at 3.5 Hz which was judged to be the mean frequency of the significant horizontal shaking from the El Centro earthquake.

Two test series were undertaken both with initial stress ratio σ_1/σ_3 as high as 4. This means that there were significant static shear stresses in the specimens prior to the imposed cyclic stresses. In one test series σ_3 = 0.5 MPa and in the other σ_3 = 0.85 MPa. The imposed horizontal cyclic (dynamic) shear stress was 0.2 MPa (i.e. cycled between +0.2 MPa and -0.2 MPa), giving a maximum cyclic shear strain amplitude of ca. 0.2 % (Fig.1).

Breth and Schwab (1973) concluded that in both test series "the 200 load repetitions failed to change the structure and the strength characteristics of the asphalt concrete. The deformations remained linear with regard to the applied shear forces and decreased to zero with each release of the shear force. The asphalt concrete behaved like an elastic body under the dynamic stresses even with the static conditions applied being very unfavourable".

After the rather convincing test results by Breth and Schwab (1973) there does not seem to have been any concern about the ability of rockfill dams with asphalt concrete core barriers to withstand earthquakes. However, the construction of such dams in very seismic regions like Japan, parts of China and Iran has renewed the interest in the issue.

Wang (2004) recently reports an extensive series of cyclic loading tests on triaxial specimens of asphalt concrete. The specimens were first subjected to initial static stresses before additional cyclic axial stresses were imposed. The loading was one-way cyclic compression as the net axial stress (static + cyclic) was never negative (no tension). The initial ratio between static stresses (σ_1/σ_3) was varied between 1.2 and 1.8 for different specimens. The confining stress (σ_3) was kept constant during each test, but was varied between 0.2 MPa and 1.2 MPa for the different specimens. The frequency of cyclic loading was 1 Hz, and the cyclic stress was applied in parcels of 5 cycles before the cyclic stress was increased to the next level and a higher degree of strength mobilization. The temperature test range was 3.4°C to 20°C.

During each parcel of load cycles Wang (2004) recorded axial cyclic strains and any axial residual (permanent) strains. He also computed dynamic secant modulus as a function of cyclic strain level and the dynamic damping (Fig.2). For both diagrams shown in Fig.2 the initial ratio between the major and minor principal stress was 1.2. Based on this extensive study conducted for a range of realistic stress–strain conditions in an asphalt concrete core subjected to earthquake loading conditions, Wang (2004) concluded: There was no sign of cracking (fissuring) or degradation of the asphalt concrete. The axial dynamic strains were essentially elastic (recoverable). Some tests were run with thousands of load cycles to study whether there was a long–term degradation (fatigue) phenomenon. That was not found to be the case up to 7000 cycles. The cyclic strain amplitudes remained virtually constant even for the large number of cycles, while the residual strains increased. However, the residual strain was primarily caused by creep under the average static stress and was not a sign of material degradation due to cyclic repetitive loading. This was checked by performing creep tests (without cyclic loading) with the same average static stress condition as in the cyclic tests.

After the cyclic earthquake loading has taken place, a monotonic loading test to failure may be performed. The post–cyclic monotonic stress–strain–strength curve may then be compared to the corresponding curve for specimens not first subjected to cyclic loading, to study any sign of material degradation due to the cyclic loading. Likewise, permeability tests may be performed on specimens which have been subjected to cyclic loading and the results compared to the measured permeability on specimens not first subjected to cyclic loading. Wang also performed such tests.

Ohne et al. (2002) performed one–way cyclic triaxial compression tests on specimens drilled out of the asphalt concrete facing of Higashifuji Dam (built 1971) which was damaged by an earthquake in 1996 (see Chapter 2). The size of the test specimen is not specified in the article, but it is assumed to be ca 50 mm diameter and 100 mm in height. The specimens were unconfined during testing, simulating the behaviour of elements on the unloaded asphalt concrete facing. Each specimen was first subjected to a static axial stress. Then an axial cyclic stress was applied, but such that static + cyclic stress always was larger than zero (no tension). Twenty stress cycles were applied at each static stress level. Then the axial static stress was increased and a new series of 20 stress cycles was applied in the multi-stage test until large axial deformations occurred as the axial stress level approached the unconfined compressive strength of the asphalt concrete.

The cyclic axial strains are not reported in the article, only the residual strains accumulated during each parcel of 20 cycles. Ohne et al. (2002) chose to call this strain a dynamic strain although it is a permanent strain. This strain is plotted as a function of cyclic axial stress which is defined as twice the axial stress level during each parcel. The cyclic stress level was increased until the axial residual deformations started to increase very rapidly (yielding). By drawing a tangent to the initial portion of such a “stress-residual strain” curve and determining the tangent’s intersection with the yield plateau, the authors defined the dynamic yield strain for the asphalt concrete. This magnitude of residual strain, which is a very conservative estimate of “yield strain”, was determined for test temperatures 6°C and 16°C.

The writer finds it difficult to interpret the results as presented in this brief article. The authors conclude that the observed cracks that opened in the facing of the Higashifuji Dam were caused by cyclic (dynamic) compression stresses. It seems more likely that cracks were opened by tension and flexural stresses in the facing during the earthquake and due to differential settlements of the sand embankment caused by the cyclic earthquake loading. However, the experiments only simulated the dynamic compression behaviour.

The article does not present the asphalt concrete mix used in the facing which was built in 1971 and subjected to weathering during ca. 30 years before the test specimens were drilled out for testing. The authors report very low values for the compressive yield strains as defined above, and the results do not agree with other results reported herein and in the literature. One main reason for that may be that the asphalt concrete in the facing had aged and become brittle due to the exposure during 30 years. The authors therefore argue that asphalt concrete to be used in upstream facings should employ special additives to make the asphalt concrete more flexible and ductile (see Section 3.2).

3.2 Tension and Bending Tests

It is important to determine the level of tension stress and the amount of tensile strain that asphalt concrete in a dam core or facing can sustain before it cracks. This strain level is clearly a function of temperature and rate of loading. The higher the temperature and the lower the strain rate, the larger is the critical tensile strain (elongation).

Daicho (1988) and later Terada et al. (1997) report on the design analyses and performance of the Tataragi Dam, Japan. It is a rockfill dam with an asphalt concrete facing (AFRD), max. height 64.5m, and built during the years 1971-73. The dam was subjected to the Hyogo-ken Nanbu earthquake in 1995. In his paper Daicho (1988) presents the results from beam bending tests of asphalt concrete, plate flexibility tests (Fig.3), biaxial tension tests and uniaxial tension tests at temperatures between -10ºC and 40ºC (Fig.4). The rate of loading used was $6{\cdot}10^{-3}$ %/s (i.e. 0.36 %/min. or 21.6 %/hr).

The uniaxial tension tests gave the lowest tensile cracking strain, about half the magnitude of the values from beam bending tests. Daicho (1988) concluded that a lower limit for the test results was that the tensile cracking strain was about 3 % for 5ºC and somewhat higher for higher temperatures (Fig.4). Terada et al. (1997) used the results presented by Daicho and compared the asphalt concrete tensile cracking strain with the computed tensile strains in the upstream facing of Tataragi Dam during the Hygo-ken Nanbu earthquake. The maximum tensile strain computed by a dynamic finite element analysis was 0.023 %. The experimental tensile cracking strain shown in Fig.4 is given for a strain rate of $6{\cdot}10^{-3}$ %/s, while the strain rate during earthquake shaking is of the order of 10^{-1} %/s, some 15 times higher. Terada et al. (1997) concluded that even if the tensile cracking strain at that higher strain rate should be an order of magnitude smaller than that given in Fig.4, the facing would be safe against tensile strains caused by the seismic shaking (see Fig.5 for more information).

Ishii and Kamijo (1988) and Kawashima et al. (1997) discuss the design analyses and construction of a 90.5 m high rockfill dam with asphalt concrete facing (AFRD), completed in Japan in 1995. Finite element analyses were done for the design earthquake to compute the potential tensile strains in the upstream facing. The computed strains were compared with the experimental tensile cracking strain from beam bending tests at different testing temperatures (–15º to 30ºC) and different tension loading rates (strain rates from $7{\cdot}10^{-3}$ %/s to 7 %/s) (Figure 5). At 5ºC the tensile cracking strain for a strain rate of 10^{-2} %/s is 4 %, while for the much faster rate of 1 %/s, the cracking strain is 1 %. For an earthquake the strain rate may be of the order 10^{-1} %/s. At 0ºC the cracking strain for a strain rate of 10^{-2} %/s is 2 % while for 1 %/s it is approximately 0.5 %, i.e. a factor of 4 reductions for both temperatures.

Ishii and Kamijo (1988) and Kawashima et al. (1997) also report beam bending tests with long-term cyclic loading (tens of thousands of cycles). The testing temperature as well as the cyclic frequency and cyclic strain amplitude were varied. The results showed that when one exceeded a certain number of load cycles, the beam bending deflections rapidly increased, i.e. the deformation modulus rapidly declined (Fig. 6a). Figure 6b shows the strain amplitude of the cyclic beam loading on the vertical axis and the number of load cycles to yielding on the horizontal axis. The variables are loading frequency (0.1 Hz vs. 2 Hz) and testing temperature (–15ºC and 5ºC). The number of cycles to yielding increases with increasing temperature and decreases with frequency and strain amplitude. The authors conclude that for their 90.5 m high rockfill dam with asphalt concrete facing (AFRD), it would take in the order of 100.000 cycles to obtain yielding.

The most recent paper discussing the tensile strength and tensile cracking strain (elongation strain) of asphalt concrete is the one presented by Nakamura et al. (2004). They revisit the experience from the Higashifuji Dam described by Ohne et al. (2002) and discussed previously in Section 3.1. In this recent paper the authors evaluate the behaviour and cracking of the asphalt concrete facing in terms of tension rather than compression. The authors are concerned about the development of tension cracks in the upstream facing during low winter temperatures and high loading rates (strain rates) from the cyclic earthquake shaking.

The main goal of the paper by Nakamura et al. (2004) is to compare the engineering properties of conventional asphalt concrete used in upstream facings with those of asphalt concrete with a special admixture (called Superflex-phalt).

Uniaxial tension strength tests were performed with strain rates from 10^{-2} %/s to 10 %/s. This is similar to the test range used by Ishii and Kamijo (1988) and Kawashawa et al. (1997). The results are shown in Fig. 7. Figure 7a compares tension stress-strain results for a conventional asphalt concrete mix (called straight asphalt 60/80) and for Superflex-phalt. The testing temperature is 0ºC and the strain rate 1 %/s. Figure 7b shows a comparison of tensile cracking strain for different strain rates at 0ºC. From Fig. 7 it is clearly seen that the Superflex-phalt has a much lower tensile strength and a much higher tensile cracking strain than the conventional asphalt concrete used in their tests. For the conventional asphalt concrete the tensile cracking strain is reduced from approx. 1 % to 0.2 % , i.e. a factor of 5, when the strain rate is increased from 10^{-2} %/s to 1 %/s. This strain rate effect is in fair agreement with the results previously reported by Ishii and Kamijo (1988) and Kawashima et al. (1997) who found a factor of 4 for a similar increase in strain rate. This factor will undoubtedly depend somewhat on the properties of the asphalt concrete mix and the testing temperature.

Nakamura et al. (2004) also report the result of cyclic uniaxial tension tests, using three different loading frequencies, 1 Hz, 2 Hz and 4 Hz, and three different testing temperatures 4ºC, 0ºC and –5º. For the cyclic tension loading the authors provide very interesting results on the damping characteristics and the reduction in shear modulus with level of imposed shear strain both for the conventional asphalt concrete and the Superflex-phalt. A diagram of yield shear strain vs. loading frequency shows that the results are not sensitive to the cyclic frequency in the range 1 – 4 Hz.

It should be noted that the Superflex-phalt is compared with a conventional asphalt concrete mix using a fairly stiff bitumen. In situations where the upstream dam facing may be subjected to severe earthquake loading and very cold temperatures above the reservoir level, it may be advantageous to use a mix with special admixtures to increase flexibility and ductility. However, some of the same effect may also be achieved by using a softer bitumen, and the type and amount of asphalt concrete compaction has also significant effects on the ductility and stress-strain behaviour of asphalt concrete (e.g. Wang and Höeg, 2002). One of the advantages of using asphalt concrete in water barriers for embankment dams is that the asphalt concrete mix may be “tailored” to suit the relevant design conditions and requirements (Höeg, 1993; Creegan and Monismith,1996, and Schönian,1999).

4 ASPHALT FACING VS. ASPHALT CORE

As stated in Chapter 1, the thin upstream facing and the core have to adjust to and follow the cyclic and permanent strains imposed by the dam embankment during and after the earthquake shaking without undergoing any significant cracking or material degradation. The stresses and strains imposed by the earthquake, as well as the environmental conditions, are very different for an upstream asphalt concrete facing and a central core, respectively. Some of the differences are discussed below and must be considered in the dam design requirements.

Embankment dams with upstream facing have the advantage that the upstream part of the embankment rockfill is not submerged, and there is no real concern about pore pressure build-up during earthquake shaking. The upstream slope for a dam with a facing may therefore be made steeper than that for a similar embankment with a central core.

However, with respect to water barrier construction requirements and requirements to the engineering properties of the asphalt concrete used, the central core has several advantages:

1. The upstream facing is exposed to weathering, possible ice and floating debris, sun radiation, oxidation, and significant temperature variations above the reservoir water level. In cold climates, at winter

temperatures, the asphalt concrete loses much of its flexibility and the tensile cracking strain level is significantly reduced. The environmental conditions on the upstream face may lead to asphalt concrete material degradation, cracking and brittleness (aging), and regular maintenance may be required. The central core has much more favourable environmental conditions inside the embankment.

2. Earthquake shaking leads to tensile stresses and strains along the upstream facing, particularly in the top part and locally against the plinth at the upstream toe. The tension imposed on a central core is much smaller and, if present, is localized to the top 1/5 − 1/4 part of the core (e.g. Ghanooni and Roosta, 2002).

3. Embankment dams always undergo some crest compaction settlements and lateral displacements due to earthquake shaking and some shear displacements and distortions in the embankment slopes. These post-cyclic permanent slope deformations will have relatively little effect on a central core, but cause deflections and possibly tension and shear in an upstream facing.

4. The upstream asphalt concrete facing has no lateral stress confinement above the reservoir water level, and only water pressure confinement beneath the reservoir level. A central core has uniform lateral confinement from the specially compacted filter/transition zones on either side of the core. Thus, cracking is much less likely in an interior core than in an upstream unconfined facing.

In summary, it is easier to satisfy the design requirements for the asphalt concrete to be used in a dam core than in an upstream facing. The requirements to flexibility and ductility, tensile cracking strain and cyclic resistance are more severe for a facing than for a core. Therefore the need for using admixtures to improve the properties, as for instance in the Superflex-phalt described by Nakamura et al. (2004), is more relevant for an asphalt concrete facing than for an asphalt concrete core. However, increased ductility is always an advantage unless by using admixtures other hydro-mechanical properties of the asphalt concrete deteriorate.

If cracking or other damage occurs to the upstream facing, it may be exposed and repaired by lowering the reservoir level. It is more difficult to repair any cracks in the core. However, as stated above, the probability of cracking in the core is very much lower than cracking in the face. Repair of the core may be achieved by drilling and grouting in the filter/transition zone on the upstream side of the asphalt core. The gradation of the upstream filter/transition zone is usually 0 – 60 mm, and its permeability will limit any leakage even if a crack/fissure should develop through the core. In strongly seismic regions one may put extra silt or fine sand in the upstream filter/transition zone, as this silt serves as “crack healer” should core cracking/fissuring occur. This is the same method as applied for CFRDs, especially in the lower part where the concrete facing connects to the perimeter plinth. On several occasions underwater placement of silt or fine sand has been used to seal leakages through joints or cracks that have opened up in concrete facings. The success of this procedure requires that there is a proper filter placed under the face slab.

Any fissures or cracks in an asphalt core self-heal (self-seal) with time due to the overburden stresses and the beneficial visco-plastic behaviour of the asphalt concrete. This has been described and shown by many investigators, e.g. Kolo Veidekke (2000).

In earthquake regions, the asphalt core concrete mix is usually made with a soft grade bitumen and/or an added 0.5 – 1 % bitumen content to increase the core flexibility and ductility and the tensile cracking strain. If earthquake design analyses show tension in the top part of the core, admixtures may be introduced in the asphalt concrete mix used for the top part to further improve the ductility of the material in this region.

5 SUMMARY AND CONCLUSIONS

Rockfill embankment dams are very resistant to earthquake excitations (e.g. ICOLD, 2001, 2004).

This report presents a review of the available documented field performance and theoretical analyses of dams with asphalt concrete facing or core subjected to earthquake shaking. The thin asphalt concrete water barriers have to adjust to and follow the cyclic and permanent strains imposed by the dam embankment without cracking or other material degradation. The asphalt concrete in a core is subjected to much less severe environmental conditions and earthquake loading conditions than the asphalt concrete in an upstream facing.

A review is made of the documented laboratory testing of asphalt concrete subjected to simulated cyclic earthquake loading. The review includes results of tests in cyclic triaxial compression, direct shear, bending, and direct tension. Special attention has been paid to the effects of loading rate (strain rate) and temperature on the amount of tensile strain asphalt concrete can undergo (tolerate) before cracks open. Much research has been done on asphalt concrete used in pavement design and on the effects of dynamic traffic loading on material behaviour. There are only a relatively few papers that provide information on the behaviour of asphalt concrete used as impervious water barriers in dams when subjected to earthquake loading. However, as shown in Figs. 1–7, some important findings are:

- For realistic earthquake loading conditions in cyclic compression and shear the asphalt concrete does not undergo material degradation and cracking. Under cyclic stress the cyclic strain amplitudes remain essentially constant and the residual (permanent) strains are negligible for short-term earthquake loading. For a large number of load cycles, much larger than in an earthquake, residual strains accumulate, but that is mainly due to creep under the sustained average stress rather than due to degradation of material properties caused by the cyclic loading (Figs. 1 and 2).

- The tensile strength and the tensile strain (elongation) at which tension cracks open, depend on the properties of the asphalt concrete mix, the testing temperature and the loading rate (strain rate). At a given temperature, the tensile cracking strain decreases by approximately a factor of 5 when the strain rate is increased by two orders of magnitude, from 10^{-2} %/s to 1 %/s. For an earthquake the strain rate may typically be of the order 10^{-1} %/s (Figs. 4, 5 and 7).

- For a conventional asphalt concrete used as water barrier in dams, the bending cracking strain at 5°C may typically be 4 % at a strain rate of 10^{-2} %/s and 1 % at a strain rate of 1 %/s. At -5°C the corresponding bending cracking strains are 1 % and 0.2 %. At cold temperatures the tensile cracking strains are significantly reduced (Fig.5).

- The magnitude of tensile cracking strain can be significantly increased by using a richer asphalt concrete mix, softer grade of bitumen or by adding admixtures to improve asphalt concrete ductility.

- For a large number of load cycles (e.g. 50.000 - 100.000, i.e. orders of magnitude larger than in an earthquake), asphalt concrete experiences yielding and fatigue in cyclic beam bending tests. The number of cycles to reach this level of yielding depends on asphalt concrete mix, temperature, imposed cyclic strain amplitude and cyclic frequency (Fig.6).

The environmental conditions for the asphalt concrete in a central core of a rockfill dam (ACRD) are favourable, and the stress-strain conditions during and after the earthquake shaking are such that it is unlikely that cracking or material degradation will occur due to imposed cyclic compression, shear and tensile strains.

In a seismic region the design of the embankment cross section and the asphalt concrete barrier should be checked by case-specific analyses and computations. Embankment dimensions (e.g. crest width and slopes) and material properties (rockfill properties and compaction) may have to be changed if the design earthquake is very severe. The asphalt concrete mix for a core may be designed to achieve increased ductility and tensile cracking strain, especially in the top part of the core, where tensile stresses may occur due to amplification of the ground earthquake motion.

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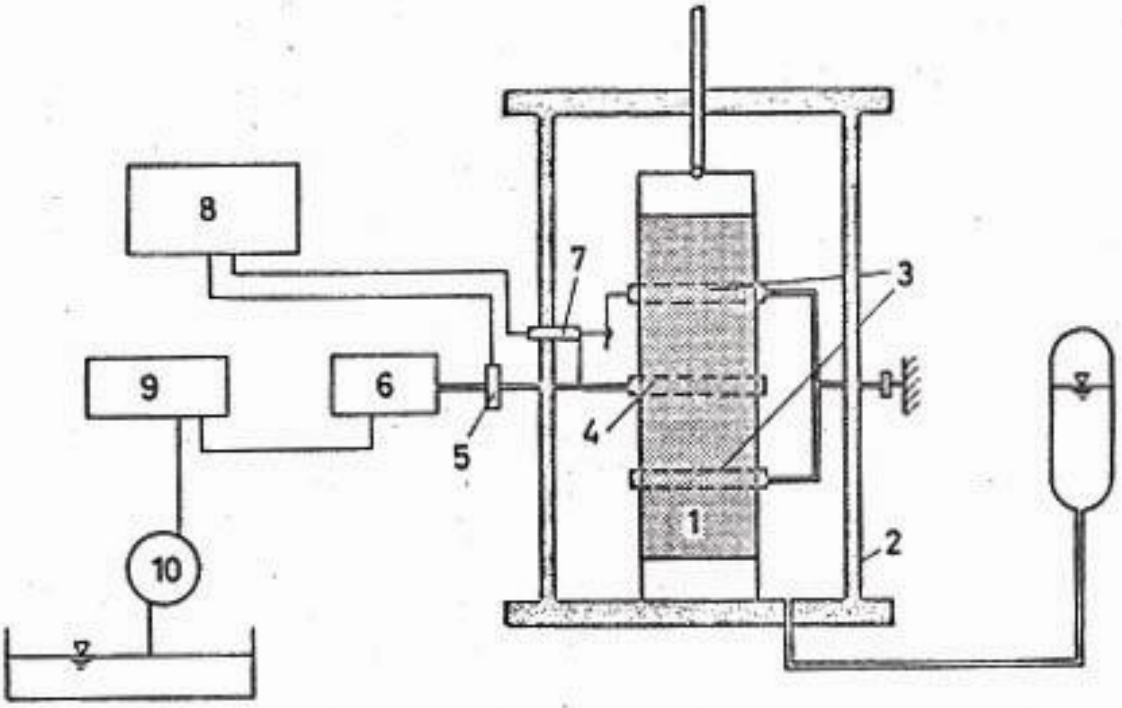


Schematic illustration of the test apparatus for static and dynamic loading.
1 = Specimen, 2 = triaxial cell, 3 = retainer rings, 4 = ring for introducing dynamic load, 5 = pressure recorder, 6 = hydraulic pulsator, 7 = deformation recorder, 8 = recording apparatus, 9 = Frequency controller, 10 = oil pump

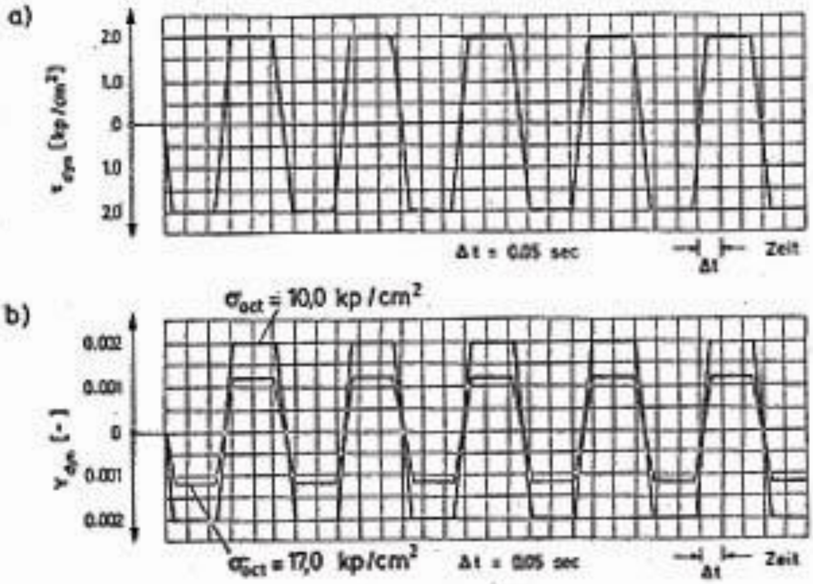


Figure 1 Test apparatus and results by Breth and Schwab (1973)
a) Imposed cyclic shear stress at 3.5 Hz
b) Resulting cyclic shear strains

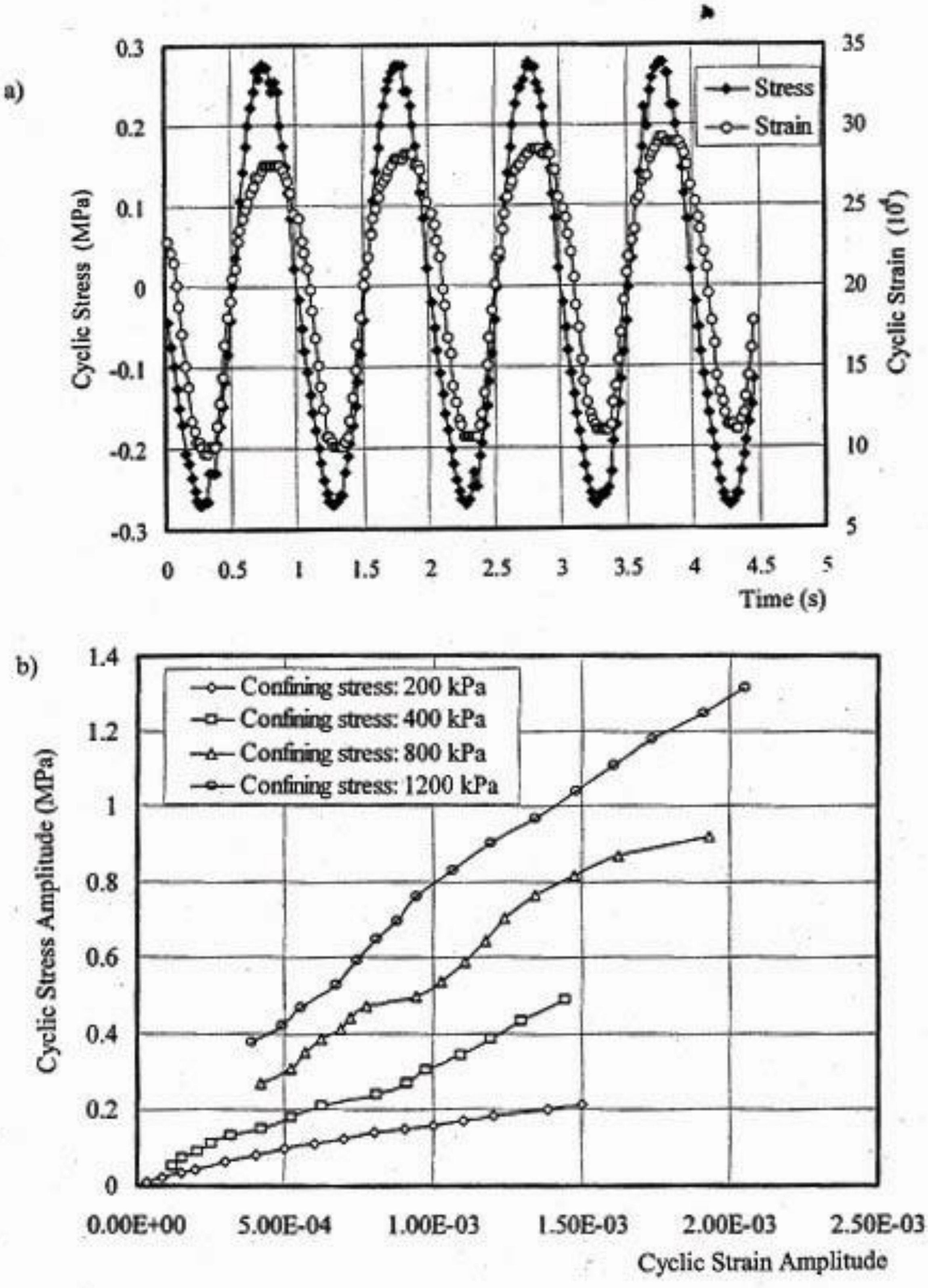
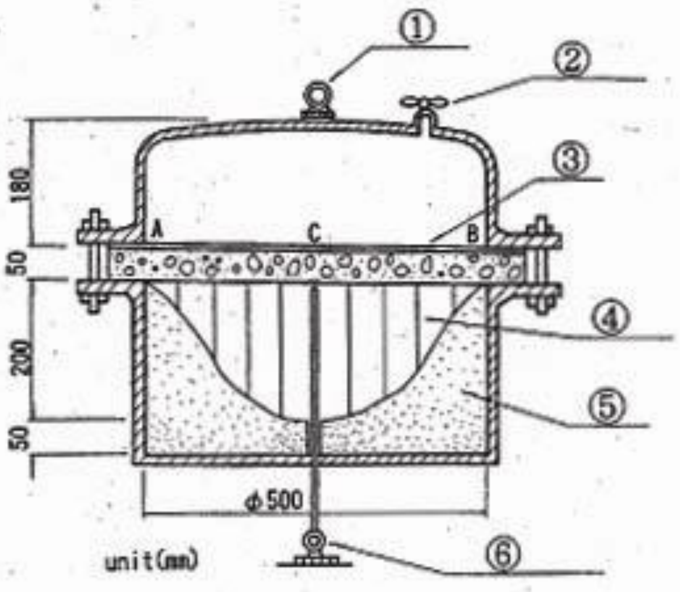


Figure 2 Typical results from tests by Wang (2004)
a) Cyclic test with confining stress 400 kPa
b) Cyclic axial stress amplitude vs. cyclic strain amplitude for different levels of confining stress

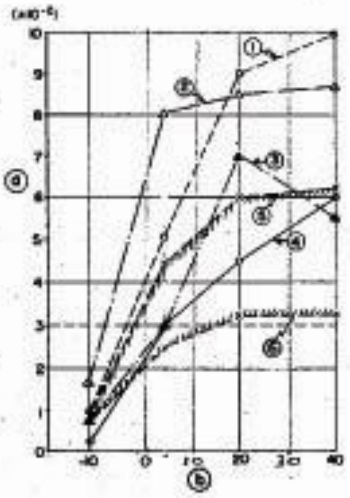


Experimental apparatus of permeability under large deformation

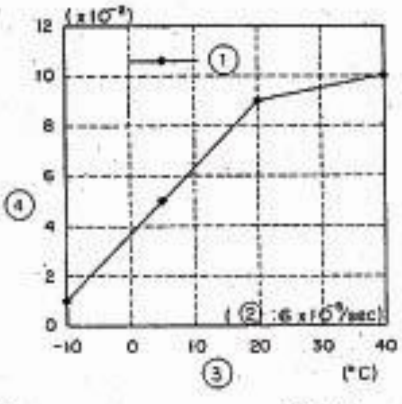
Appareil expérimental de mesure de la perméabilité sous forte déformation

① Pressure meter	① *Appareil de mesure de la pression*
② Three-way valve	② *Vanne à trois orifices*
③ Ring	③ *Anneau*
④ Perforated rubber	④ *Membrane perforée*
⑤ Gypsum	⑤ *Gypse*
⑥ Dial gauge	⑥ *Comparateur à cadran*

Figure 3 Apparatus for measuring tensile cracking strain and increase in permeability of circular asphalt concrete plate in flexure (Kawashimi et al., 1997)

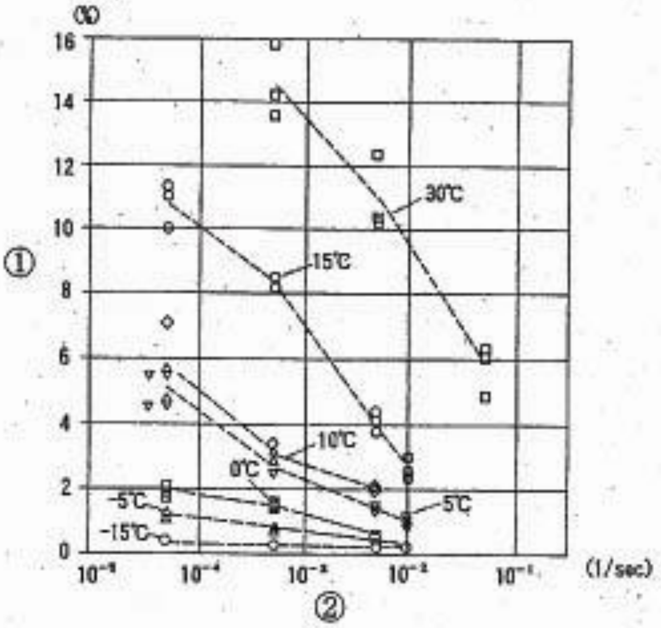


(1) Beam bending test	*(1) Essai de flexion de poutre*
(2) Flexibility test	*(2) Essai de flexibilité*
(3) Biaxial tension test	*(3) Essai de traction biaxiale*
(4) Uniaxial tension test	*(4) Essai de traction uniaxiale*
(5) Upper limit of strain on crack occurrence	*(5) Limite supérieure de la déformation à l'apparition de la fissure*
(6) Lower limit of strain on crack occurrence	*(6) Limite inférieure de la déformation à l'apparition de la fissure*
(a) Failure strain	*(a) Déformation de rupture*
(b) Temperature (°C)	*(b) Température (°C)*



① Bending strain	*① Déformation à la flexion*
② Velocity of strain	*② Vitesse de déformation*
③ Temperature	*③ Température*
④ Yield strain	*④ Déformation*

Figure 4 Results of tension and bending tests to determine tensile cracking strain for different testing conditions and temperatures. Strain rate $6 \cdot 10^{-3}$ %/s (Daicha, 1988; Terada et al., 1997)



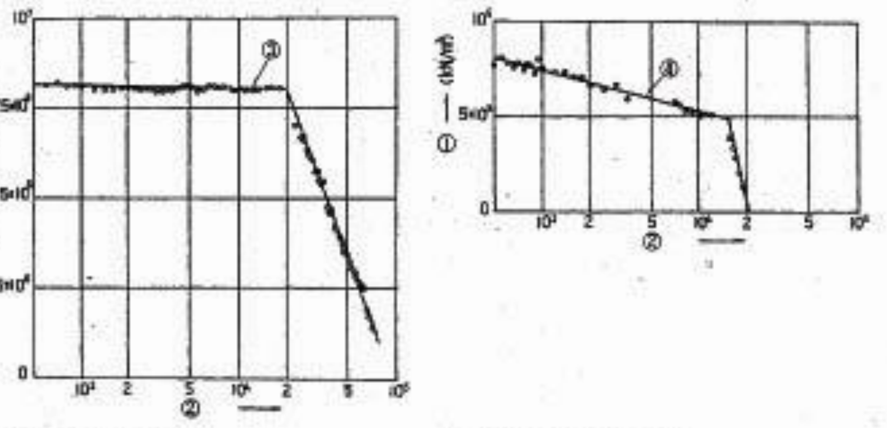
① Bending and stretching strain (%)

② Strain velocity (l/s)

① *Déformation en flexion et allongement de traction (%)*

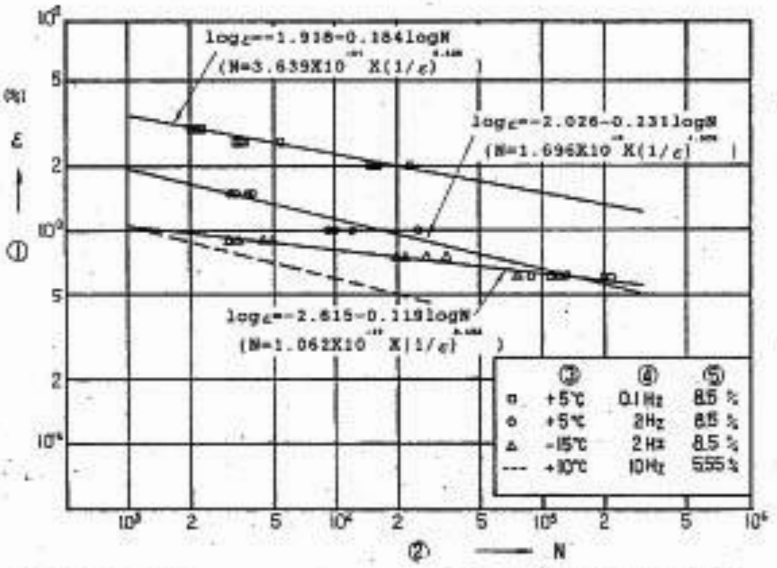
② *Vitesse de déformation (l/s)*

Figure 5 Tensile cracking strain as function of strain rate and temperature (Kawashimi et al., 1997) a)



(1) Deformation modulus	*(1) Module de déformation*
(2) Loading times (time)	*(2) Nombre de chargements (fois)*
(3) – 15° C, 2Hz strain amplitude 7.5 × 10⁻⁴	*(3) – 15° C, 2Hz amplitude de déformation 7.5 × 10⁻⁴*
(4) 5° C, 0. 1Hz strain amplitude 2.0 × 10⁻³	*(4) 5° C, 0. 1Hz amplitude de déformation 2.0 × 10⁻³*

b)



(1) Strain amplitude	*(1) Amplitude de déformation*
(2) Yield times (time)	*(2) Nombre de flexions (fois)*
(3) Temperature	*(3) Température*
(4) Frequency	*(4) Fréquence*
(5) Asphalt content	*(5) Teneur en bitume*

Figure 6 a) Relationship between number of load cycles and deformation modulus showing number of cycles to yielding in beam bending.

b) Relationship among number of cycles to yielding, imposed strain amplitude, load frequency and temperature (Ishii and Kamajo, 1988).

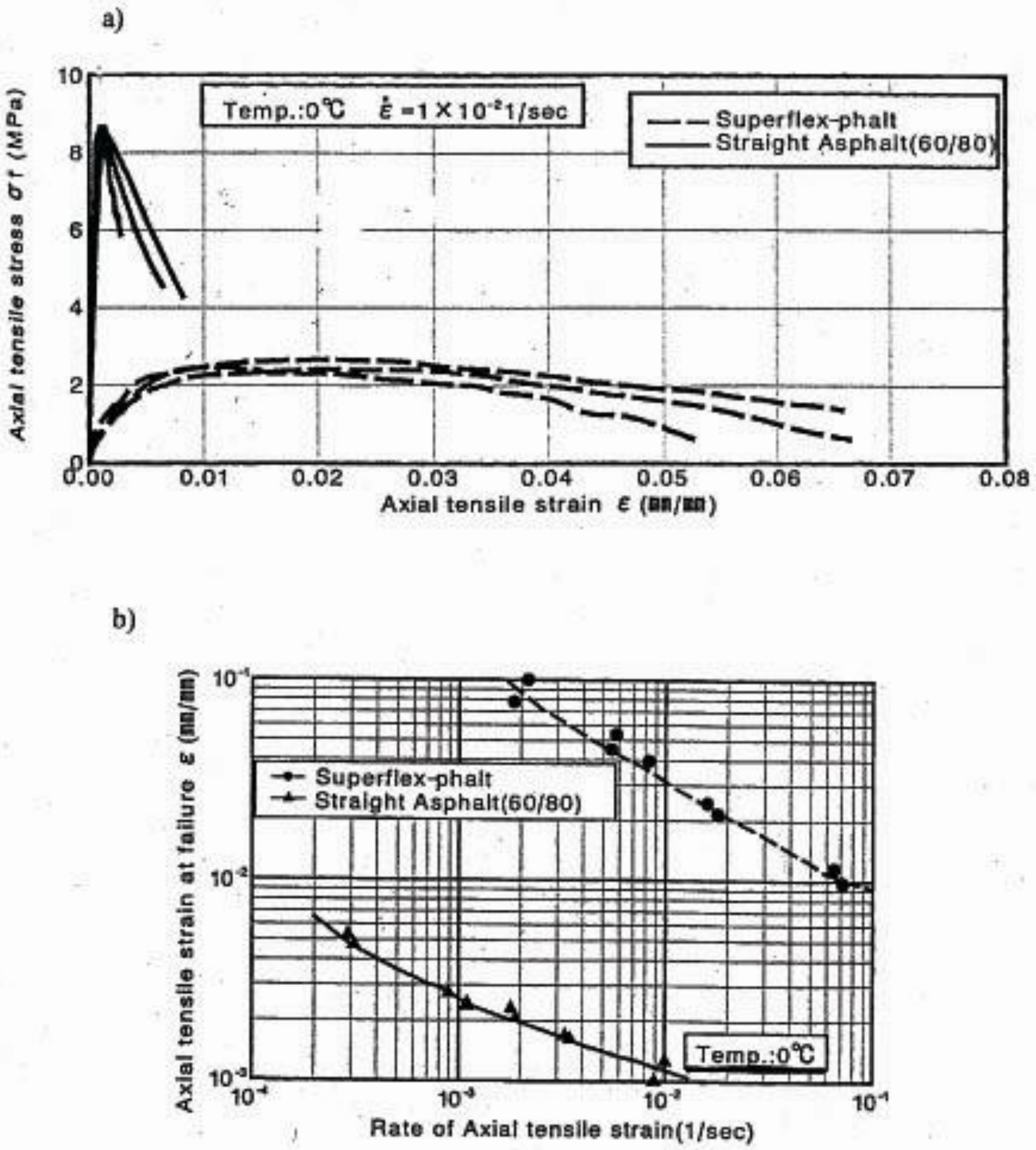


Figure 7 a) Tensile stress vs. tensile strain for a strain rate of 1 %/s and temperature 0°C
b) Tensile cracking strain for different strain rates at temperature 0°C (Nakumara et al., 2004)

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