

Unbound and hydraulically bound mixtures —

Part 7: Cyclic load triaxial test for unbound mixtures

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National foreword

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The UK participation in its preparation was entrusted by Technical Committee B/510, Road materials, to Subcommittee B/510/4, Cementitious bound materials, unbound granular materials, waste materials and marginal materials, which has the responsibility to:

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Foreword

This document (EN 13286-7:2004) has been prepared by Technical Committee CEN/TC 227 "Road materials", the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by July 2004, and conflicting national standards shall be withdrawn at the latest by July 2004.

Annexes A, B, C and D are informative.

This European Standard is one of a series of standards as listed below.

EN 13286-1, Unbound and hydraulically bound mixtures — Part 1: Test methods for laboratory reference density and water content — Introduction, general requirements and sampling.

prEN 13286-2, Unbound and hydraulically bound mixtures — Part 2: Test method for the determination of the laboratory reference density and water content — Proctor compaction.

EN 13286-3, Unbound and hydraulically bound mixtures — Part 3: Test methods for laboratory reference density and water content — Vibrocompression with controlled parameters.

EN 13286-4, Unbound and hydraulically bound mixtures — Part 4: Test methods for laboratory reference density and water content — Vibrating hammer.

EN 13286-5, Unbound and hydraulically bound mixtures — Part 5: Test methods for laboratory reference density and water content — Vibrating table.

EN 13286-7, Unbound and hydraulically bound mixtures — Test methods - Part 7: Cyclic load triaxial test for unbound mixtures.

EN 13286-40, Unbound and hydraulically bound mixtures — Part 40: Test method for the determination of the direct tensile strength of hydraulically bound mixtures.

EN 13286-41, Unbound and hydraulically bound mixtures — Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures.

EN 13286-42, Unbound and hydraulically bound mixtures — Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures.

EN 13286-43, Unbound and hydraulically bound mixtures — Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures.

EN 13286-44, Unbound and hydraulically bound mixtures — Part 44: Test method for the determination of the alpha coefficient of vitrified blast furnace slag.

prEN 13286-45, Unbound and hydraulically bound mixtures — Part 45: Test method for the determination of the workability period of hydraulically bound mixtures.

EN 13286-46, Unbound and hydraulically bound mixtures — Part 46: Test method for the determination of the moisture condition value.

EN 13286-47, Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of the California bearing ratio, immediate bearing index and linear swelling.

prEN 13286-48, Unbound and hydraulically bound mixtures — Part 48: Test method for the determination of the degree of pulverisation.

prEN 13286-49, Unbound and hydraulically bound mixtures — Part 49: Accelerated swelling test of soil treated by lime and/or hydraulic binder.

prEN 13286-50, Unbound and hydraulically bound mixtures — Part 50: Methods for making test specimens using proctor equipment or vibrating table compaction.

prEN 13286-51, Unbound and hydraulically bound mixtures — Part 51: Methods for making test specimens by vibrating hammer compaction.

prEN 13286-52, Unbound and hydraulically bound mixtures — Methods for making test specimens - Part 52: Making specimens by vibro-compression.

prEN 13286-53, Unbound and hydraulically bound mixtures — Methods for making test specimens - Part 53: Making cylindrical specimens by axial compression

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

1 Scope

This European Standard specifies test procedures for determining the resilient and permanent behaviour of unbound mixtures under conditions that simulate the physical conditions and stress states of these materials in pavement layers subjected to moving loads. These procedures allow to determine mechanical properties that can be used for performance ranking of materials and for calculating the structural responses of pavement structures.

The test is applicable to cylindrical specimens of unbound mixtures prepared by laboratory compaction, with an absolute maximum particle size smaller than one fifth of the specimen diameter.

For the loading of the specimen, two methods are provided :

Method A: The Variable Confining Pressure method in which the cell pressure is cycled in phase with the axial load.

Method B: The Constant Confining Pressure method in which only cyclic axial loading and constant confining pressure are performed.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

EN 13285, Unbound mixtures - Specification.

3 Symbols and abbreviations

For the purposes of this European Standard, the symbols and definitions in Table 1 apply.

Table 1 — Symbols and definitions

Symbol	Definition	Unit
w	Water content	%
ρ_d	Dry density	Mg/m ³
N	Number of load cycles	
σ	Normal stress	kPa
σ_1	Total axial stress (major principal stress)	kPa
$\sigma_{1\min}, \sigma_{1\max}$	Minimum and maximum values of σ_1 during one load cycle	kPa
σ_{1r}	Resilient axial stress, $\sigma_{1r} = \sigma_{1\max} - \sigma_{1\min}$	kPa
σ_3	Total radial stress; i.e. the applied confining pressure in the triaxial chamber or the vacuum inside the specimen when no triaxial chamber is used (minor and intermediate principal stress)	kPa
$\sigma_{3\min}, \sigma_{3\max}$	Minimum and maximum values of σ_3 during one load cycle	kPa
σ_{3r}	Resilient radial stress, $\sigma_{3r} = \sigma_{3\max} - \sigma_{3\min}$	kPa
σ_d	Deviator stress, $\sigma_d = \sigma_1 - \sigma_3$	kPa
L_0	Gauge length for axial displacement, immediately following specimen preparation	mm
R_0	Gauge length for radial displacement, immediately following specimen preparation	mm
$L_p(N)$	Permanent axial displacement at cycle N , defined as the displacement accumulated during the application of a single stress combination, from the beginning of the first cycle to the end of cycle N	mm
$R_p(N)$	Permanent radial displacement at cycle N , defined as the displacement accumulated during the application of a single stress combination, from the beginning of the first cycle to the end of cycle N	mm
$L_r(N)$	Resilient axial displacement at cycle N , defined as the displacement during the unloading part of the cycle (between the point where the applied stresses are maximum and the end of the cycle)	mm
$R_r(N)$	Resilient radial displacement at cycle N , defined as the displacement during the unloading part of the cycle	mm
ε_{1r}	Resilient or recovered axial strain. At cycle N , $\varepsilon_{1r}(N) = L_r(N) / L_0$	10 ⁻³
ε_{1p}	Permanent axial strain. At cycle N , $\varepsilon_{1p}(N) = L_p(N) / L_0$	10 ⁻³
ε_{3r}	Resilient or recovered radial strain. At cycle N , $\varepsilon_{3r}(N) = R_r(N) / R_0$	10 ⁻³
ε_{3p}	Permanent radial strain. At cycle N , $\varepsilon_{3p}(N) = R_p(N) / R_0$	10 ⁻³
E_r	Resilient modulus, $E_r = \frac{\sigma_{1r}}{\varepsilon_{1r} + \varepsilon_{3r} - 2\varepsilon_{\alpha}}$	MPa

Resilient modulus, $E_r =$

$$E_r = \frac{\sigma_{1r}}{\varepsilon_{1r} + \varepsilon_{3r} - 2\varepsilon_{\alpha}}$$

1 3 3

When $\sigma_r = 0$, (constant confining pressure) :

$$E = \frac{\sigma_r}{\epsilon_r}$$

NOTE Compressive stresses and strains are positive.

4 Principle

The cyclic triaxial test consists of imposing, on a cylindrical specimen of unbound granular material, cyclic stresses that reproduce the stress range in an unbound pavement layer, and in measuring the axial and radial strains of the specimen induced by this loading. In method A (Variable Confining Pressure), a cyclic axial deviator stress and a variable (cyclic) confining cell pressure, varying in phase, are applied. A simplified stress regime with a cyclic axial deviator stress and a constant confining pressure may also be adopted, method B.

The standard proposes three different test procedures, described below.

4.1 Procedure for the study of the resilient behaviour

The resilient behaviour of the material represents the behaviour during one load application. The results of the test can be used to determine values of the elastic modulus of the material for different stress levels, or parameters of non linear elastic models which can be used in analytical and numerical pavement design procedures.

In this procedure, a cyclic conditioning is first applied to stabilise the permanent strains of the material and attain a resilient behaviour. This conditioning is performed by applying a large number of cycles of a stress path that corresponds to the maximum stress level applied during the test. The resilient behaviour is then observed for several stress paths applied each one with a small number of cycles on the same specimen.

4.2 Procedure for the study of permanent deformations

Each permanent deformation test consists in applying a large number of load cycles of a single stress combination, without prior conditioning. This procedure can be used to determine permanent deformations of the material for a particular stress level, or parameters of models of prediction of permanent deformations, which can be used for pavement analysis and design.

4.3 Multi-stage procedure

This procedure can be used for a rapid evaluation of permanent deformations produced by different stress levels. It consists of applying several load sequences, with increasing stress levels, to the same specimen, until the cumulated permanent axial deformation exceeds a specified limit.

5 Apparatus

5.1 General

The test apparatus shall be able to apply the required cyclic loading to a cylindrical specimen with a diameter larger than 5 times the maximum particle size of the material, and a height twice the diameter ($\pm 2\%$).

In test method A, the apparatus shall be able to cycle the cell pressure in phase with the axial load. Hence, a triaxial cell shall be used.

In test method B, only the axial load is cyclic, and the confining pressure is held constant. Hence, the triaxial cell may not be necessary, and the constant confining pressure may be applied by partial vacuum inside the specimen.

NOTE Using a system without a triaxial cell will prevent applying some of the additional stress paths in this standard that are considered important for some types of structures.

5.2 Triaxial pressure chamber ('cell')

5.2.1 General

The pressure chamber, or 'cell', is similar to most conventional triaxial cells except that it is somewhat larger to facilitate the internally mounted load and deformation measuring equipment, and has additional outlets for the electrical leads from the measuring devices.

5.2.2 Chamber medium

Water, air, silicon oil or other suitable medium may be used as the chamber medium. Water is not suitable if the instrumentation does not have fully sealed electrical connections.

5.2.3 Top and bottom plate

Top and bottom plate alignment is critical to maintain uniform stresses and strains in the specimen. A ball joint may be suitable for alignment.

5.3 Loading device

5.3.1 Method A – Variable confining pressure

For test procedures with variable confining pressure (described in 7.2 and 8.2.2) the loading device shall satisfy the following requirements:

The loading device shall be capable of applying variable repeated axial loads and confining pressures, in fixed cycles of load and release.

During loading, the axial load and the confining pressure shall remain proportional and vary in phase.

The axial loading device shall be able to apply a maximum deviatoric stress of 600 kPa on the specimen, and the cyclic pressure control system shall be able to apply a maximum confining pressure of 300 kPa.

During each cycle, the minimum and maximum values of deviatoric stress and confining pressure shall be applied with an accuracy of ± 2 kPa or 1 %, whichever is the greater.

The frequency of loading shall be maintained between 0,2 Hz and 10 Hz.

The phase difference between the pulses of the axial load and of the confining pressure shall not exceed 1 % of the cycle duration.

5.3.2 Method B - Constant confining pressure

For test procedures with constant confining pressure (described in 7.3, 8.2.3 and 8.3), the loading device shall satisfy the following requirements:

The axial loading device shall be able to apply variable repeated axial loads, in fixed cycles of load and release, and to apply a maximum deviatoric stress of 600 kPa on the specimen.

The pressure control system shall be able to apply a maximum confining pressure of at least 70 kPa.

The confining pressure may also be applied by partial vacuum inside the specimen.

During each cycle, the minimum and maximum values of deviatoric stress and the constant confining pressure shall be applied with an accuracy of ± 2 kPa or 1 %, whichever is the greater.

The frequency of axial loading shall be maintained between 0,2 Hz and 10 Hz.

5.4 Pressure transducers

The confining pressures in the cell or the partial vacuum in the specimen shall be monitored by pressure transducers with suitable sensitivity ranges, and with an accuracy of ± 2 kPa.

5.5 Axial load transducer

The axial load applied to the specimen shall be monitored by a transducer with a suitable sensitivity range which will yield measurements of axial stress to an accuracy of ± 2 kPa. The load transducer shall preferably be placed inside the triaxial cell, in direct contact with the specimen cap.

5.6 Response measuring equipment

The axial deformations of the specimen shall be measured using at least two displacement transducers attached directly to the central part of the specimen (such that the gauge length does not exceed half of the height of the specimen). An appropriate system for measuring axial deformations, using three linear variable displacement is presented in annex A.

The radial deformations of the specimen shall be measured at mid-height of the specimen, using transducers attached directly to the specimen. An appropriate system for measuring radial deformations, using three linear variable displacement is presented in annex A.

The axial and radial strains shall be measured with an accuracy of $5 \times 10^{-3} \text{ mm} + 10^{-3} L$ (where L is the measured displacement in millimetre).

Readings of all transducers should be recorded separately.

5.7 Other equipment

It is necessary to provide suitable signal excitation, conditioning, and recording equipment in addition to the measuring devices for simultaneous recording of axial load, confining pressure and axial and radial deformations.

The recording system shall operate at a frequency, or be of a type, which is able to capture both the minimum and the maximum values of stress applied and strain incurred at the frequency of testing which is to be employed.

5.8 Specimen cap and base

The specimen cap and base shall be designed to provide drainage from both ends of the specimen. They shall be constructed of a rigid, non-corrosive, impermeable material, and each shall, except for the drainage provision, have a circular plane surface in contact with the porous discs of circular cross section. The diameter of the cap and base shall be equal to or larger than the initial diameter of the specimen. The specimen base shall be connected to the triaxial compression chamber to prevent lateral motion or tilting, and the specimen cap shall be designed such that eccentricity of the loading piston-to-cap contact relative to the vertical axis of the specimen does not exceed 1 % of the specimen's diameter. The cylindrical surface of the specimen base and cap that contacts the membrane to form a seal shall be smooth and free of scratches.

5.9 Porous discs

The specimen shall be separated from the specimen cap and base by rigid porous discs fastened to the specimen cap and base of a diameter equal to or a little smaller than that of the specimen. The discs shall be regularly checked by passing air or water under pressure through them to determine whether they have

become clogged. If found to be clogged, new porous discs should be used to ensure effective drainage of the specimen at the cap and base.

5.10 Semi-permeable filters

When performing constant moisture tests in which the moisture/suction regime is controlled, it is necessary to use semi-permeable filters. These shall be both waterproof and air permeable. They shall be placed between the specimen and cap and between the specimen and base. The diameter of filters shall be equal to that of the specimen and the mass per unit area should be between 50 g/m² and 80 g/m².

the specimen and the mass per unit area should be between 50 g/m² and 80 g/m².

5.11 Membrane

The membrane used to encase the specimen shall provide reliable protection against leakage. To offer minimum restraint to the specimen, the unstretched membrane diameter shall be not less than 95 % of the specimen diameter. The membrane thickness shall not exceed 0,8 % of the diameter of the specimen. The membrane shall be fixed to the specimen cap and base with rubber O-rings for which the unstretched inside diameter is less than 90 % of the diameter of the cap and base, or by other means that will provide a positive seal.

NOTE For some materials two membranes may be needed to prevent any risk of piercing of the membrane by the material. In this case, the total thickness of the two membrane should not exceed 0,8 % of the diameter of the specimen.

5.12 Specimen-size measurement devices

Devices used to determine the height and diameter of the specimen shall measure the respective dimensions to an accuracy of 0,2 % of the total dimensions and shall be constructed such that their use will not disturb the specimen.

NOTE Circumferential measuring tapes are recommended over callipers for measuring the diameter. Measure the height with a dial gauge mounted on a stand.

5.13 Balance

The weighing device shall determine the mass of the specimen to an accuracy within $\pm 0,2$ %.

5.14 Testing environment

The test shall be performed in an environment in which temperature fluctuations are less than ± 4 °C and where there is no direct sunlight.

6 Preparation

6.1 General

The tested specimen shall have a diameter larger than 5 times the maximum particle size of the material, and a height twice the diameter (± 2 %).

Different preparation methods to achieve the required state conditions (moisture content and density) are applicable. The method should produce uniform state conditions within the specimen. Examples of suitable preparation methods are given in annex B. The preparation method shall be reported.

NOTE 1 For some materials, it may be necessary to store the specimen for at least 24 h in water-tight conditions (in the compaction mould or in the triaxial cell) before testing, to achieve a uniform water content.

NOTE 2 It has been shown that different methods of reconstituting specimens to the same density may result in significantly different deformation behaviour, and especially different resistance to permanent deformation.

6.2 Set up of specimen and deformation measuring equipment

When mounting the specimen in the triaxial cell, place a porous stone and a semi-permeable porous disc (optional) between each end plate and the specimen. Place the membrane over the specimen and seal the membrane to the end plates with O-rings or other pressure seals. Leave the drainage outlets open to the atmosphere during the test.

Axial and radial deformation-measuring equipment shall be attached directly to the specimen. For method A the measurement system shall be in intimate contact with the specimen. For method B and the multistage method (see 8.3) the measurement system may alternatively be connected to the membrane.

NOTE For method A the requirements for the measurement system are designed to avoid the effects of membrane deformation and penetration.

7 Test procedures for the study of the resilient behaviour

7.1 Principle

This procedure consists of applying, to the same specimen, a cyclic conditioning (large number of load cycles), followed by a series of cyclic loadings along different stress paths, in order to study the resilient behaviour. The test can be performed using variable confining pressure loading (method A) or constant confining pressure loading (method B).

The objective of the conditioning is to eliminate the permanent deformations occurring during the first load cycles of the test, and to obtain stable resilient behaviour (independent of the number of cycles). The achievement of this objective should be verified by plotting the variation of the permanent axial strain and of the resilient modulus with the number of load cycles.

7.2 Method A: Variable confining pressure

7.2.1 General

In this method, the cell pressure is cycled in phase with the axial load. The maximum stress level can be selected for the conditioning and the subsequent stress paths from two options: A high stress level with a maximum deviatoric stress $\sigma_d = 600$ kPa and a low stress level with a maximum deviatoric stress $\sigma_d = 300$ kPa. The applied stress levels should cover the stress range to which the material will be submitted in the field.

7.2.2 Conditioning of the specimen

Select the maximum stress level for the conditioning from Table 2.

Start by applying the initial stresses σ_{\min} ($= 10$ kPa) and σ_{\min} . In Table 2, it is assumed that $\sigma_{\min} = 0$, but with some equipment a positive value may be necessary (which shall not exceed 5 kPa). Then remove any internal partial vacuum if used during specimen preparation.

For the selected stress level, apply the stresses according to Table 2 for 20 000 cycles. The conditioning may be stopped at a lesser number of cycles if the permanent axial strain and the resilient modulus become stable. (This condition is satisfied if the axial permanent strain rate becomes less than 10^{-7} per cycle, and if the rate of variation of the resilient modulus becomes less than 5 kPa per cycle).

NOTE 1 For large specimens, the minimum and maximum confining pressures in Table 2 can be increased by 10 kPa, to reduce the influence of the hydrostatic pressure gradient of the chamber fluid.

Table 2 — Conditioning stress levels (method A)

	Confining stress σ_3 kPa		Deviator stress σ_d kPa	
	min	max	min	max
High stress level	10	110	0	600
Low stress level	10	110	0	300

Read and record at least the following values:

load cycle number,

minimum and maximum axial stresses: $\sigma_{1\min}$ and $\sigma_{1\max}$,

minimum and maximum confining stresses: $\sigma_{3\min}$ and $\sigma_{3\max}$,

resilient and permanent axial strains: ε_{1r} and ε_{1p} ,

resilient and permanent radial strains: ε_{3r} and ε_{3p} .

Readings should be taken continuously during the first 20 cycles, and then at the following cycle numbers (at least). At each selected cycle number, the readings should be recorded for 10 consecutive cycles.

$N \in \{1 \text{ to } 20; 50; 100; 200; 400; 1\,000; 2\,500; 5\,000; 7\,500; 10\,000; 12\,500; 15\,000; 20\,000\}$.

Interrupt the test if this specimen fails (or an excessively large deformation occurs – more than 2 %) before 20 000 cycles are completed.

NOTE 2 If the specimen cannot sustain the high stress level, another test may be performed using the low stress level. If the specimen cannot sustain the low stress level, note that the test method is not suitable for this material.

7.2.3 Repeated loading for resilient testing

Apply the appropriate $\sigma_{3\min}$ and $\sigma_{d\min}$ (same values as during conditioning) and allow sufficient time for strain stabilisation (e.g. a rate of change of less than 10^{-4} per minute).

Then, according to the selected maximum stress level, apply successively the cyclic stress paths defined in Table 3. Apply each cyclic loading during 100 cycles, recording the stress and strain values (as in 7.2.2) at least at cycle numbers 90 to 100.

Table 3 — Stress levels for the resilient behaviour (method A)

High stress level				Low stress level			
Confining stress σ_3 kPa		Deviator stress σ_1 kPa		Confining stress σ_3 kPa		Deviator stress σ_1 kPa	
min	max	min	max	min	max	min	max
10	60	0	0	10	60	0	0
10	110	0	0	10	110	0	0
10	185	0	0	10	185	0	0
10	260	0	0	10	260	0	0
10	77	0	100	10	60	0	30
10	143	0	200	10	110	0	60
10	210	0	300	10	185	0	105
10	277	0	400	10	260	0	150
10	60	0	150	10	60	0	75
10	110	0	300	10	110	0	150
10	160	0	450	10	160	0	225
10	210	0	600	10	210	0	300
10	35	0	150	10	35	0	75
10	60	0	300	10	60	0	150
10	85	0	450	10	85	0	225
10	110	0	600	10	110	0	300
10	15	0	75	10	20	0	60
10	20	0	150	10	30	0	120
10	25	0	225	10	35	0	150

NOTE For large specimens, if the increased minimum confining pressure was used during conditioning, the minimum and maximum confining pressure values in Table 3 should also be increased by 10 kPa, to reduce the influence of the hydrostatic pressure gradient of the chamber fluid.

When the stress paths are completed, remove the specimen from the cell, take off the measuring system and membrane and determine the water content using all of the specimen.

7.3 Method B: Constant confining pressure

7.3.1 General

In this test method the confining pressure is not cycled. The maximum stress level can be selected for the conditioning and the subsequent stress paths from two options: A high stress level with a maximum deviatoric stress $\sigma_1 = 340$ kPa and a low stress level with a maximum deviatoric stress $\sigma_1 = 200$ kPa. The applied stress levels should cover the stress range to which the material will be submitted in the field.

7.3.2 Conditioning of the specimen

Select the maximum stress level for the conditioning from Table 4.

Start by applying the initial stresses, σ , either by cell pressure or by an internal partial vacuum and σ_{\min} , as shown in Table 4. In Table 4, it is assumed that $\sigma_{\min} = 0$, but with some equipment a positive value may be necessary (which shall not exceed 5 kPa). If a cell pressure is used, remove any internal partial vacuum used during specimen preparation once the initial external stress state has been applied.

For the selected stress level, apply the cyclic deviator stresses according to Table 4 for 20 000 cycles. The conditioning may be stopped at a lesser number of cycles if the permanent axial strain and the resilient modulus become stable. (This condition is satisfied if the axial permanent strain rate becomes less than 10^{-7} per cycle, and if the rate of variation of the resilient modulus becomes less than 5 kPa per cycle)

Table 4 — Conditioning stress levels (method B)

	Confining stress, σ	Deviator stress, σ	
	kPa	kPa	
	constant	min	max
High stress level	70	0	340
Low stress level	70	0	200

Read and record at least the following values:

load cycle number,

minimum and maximum axial stresses: σ_{\min} and σ_{\max} ,

minimum and maximum confining stresses: σ_{\min} and σ_{\max} ,

resilient and permanent axial strains: ϵ_{1r} and ϵ_{1p} ,

resilient and permanent radial strains: ϵ_{3r} and ϵ_{3p} .

Readings should be taken continuously during the first 20 cycles, and then at the following cycle numbers (at least). At each selected cycle number, the readings should be recorded for 10 consecutive cycles.

$N \in \{1 \text{ to } 20; 50; 100; 200; 400; 1\,000; 2\,500; 5\,000; 7\,500; 10\,000; 12\,500; 15\,000; 20\,000\}$.

Interrupt the test if this specimen fails (or an excessively large deformation occurs – more than 2 %) before 20 000 cycles are completed.

NOTE If the specimen cannot sustain the high stress level, another test may be performed using the low stress level. If the specimen cannot sustain the low stress level, note that the test method is not suitable for this material.

7.3.3 Repeated loading for resilient testing

Reduce the confining stress to $\sigma = 20$ kPa and allow sufficient time for strain stabilisation (e.g. a rate of change of less than 10^{-4} per minute).

Then, according to the selected maximum stress level, apply the stress levels with confining pressures of 20 kPa to 70 kPa in Table 5. If higher values of stress σ are likely to occur in the application envisaged for the material, also apply the remaining stress levels in Table 5. Apply each cyclic loading during 100 cycles, recording the stress and strain values (as in 7.3.2) at least from cycle number 90 to cycle number 100.

When the stress paths are completed, remove the specimen from the cell, take off the measuring system and membrane and determine the water content using all of the specimen.

Table 5 — Stress levels for the resilient behaviour (method B)

High stress level			Low stress level		
Confining stress σ_3 kPa	Deviator stress $\sigma_1 - \sigma_3$ kPa		Confining stress σ_3 kPa	Deviator stress $\sigma_1 - \sigma_3$ kPa	
constant	min	max	constant	min	max
20	0	30	20	0	20
20	0	50	20	0	35
20	0	80	20	0	50
20	0	115	20	0	70
35	0	50	35	0	35
35	0	80	35	0	50
35	0	115	35	0	70
35	0	150	35	0	90
35	0	200	35	0	120
50	0	80	50	0	50
50	0	115	50	0	70
50	0	150	50	0	90
50	0	200	50	0	120
50	0	280	50	0	160
70	0	115	70	0	70
70	0	150	70	0	90
70	0	200	70	0	120
70	0	280	70	0	160
70	0	340	70	0	200
100	0	150	100	0	90
100	0	200	100	0	120
100	0	280	100	0	160
100	0	340	100	0	200
100	0	400	100	0	240
150	0	200	150	0	120
150	0	280	150	0	160
150	0	340	150	0	200
150	0	400	150	0	240
150	0	475	150	0	300

8 Test procedures for the study of permanent deformation

8.1 Principle

The objective of these test procedures is to analyse the development of permanent strains with the number of cycles of loading for different stress levels. In the single stage procedure, only one stress path is repeatedly applied on each specimen. In the multi-stage procedure, several different stress paths are applied successively on the same specimen.

The permanent deformation that develops by applying the loads in a multi-stage manner may be different from that which develops when applying a single load level.

8.2 Single Stage loading

8.2.1 General

The tests can be performed using variable confining pressure loading (method A) or constant confining pressure loading (method B).

8.2.2 Method A: Variable confining pressure

In this method, the cell pressure is cycled in phase with the axial load.

The number of tests to perform and the stress level to apply in each test depend on the application. Recommendations on the selection of appropriate stress levels are given in annex C.

In each test, start by applying the initial stresses $\sigma_{b \min}$ (= 10 kPa) and $\sigma_{d \min}$. If possible, use $\sigma_{d \min} = 0$, but with some equipment a positive value may be necessary (which shall not exceed 5 kPa).

NOTE For large specimens, the minimum confining pressure can be increased to 20 kPa, to reduce the influence of the hydrostatic pressure gradient of the chamber fluid.

Then, perform the cyclic loading and apply at least 80 000 cycles.

Read and record the same stress and strain values as in 7.3.2.

Readings should be taken continuously during the first 20 cycles, and then at the following cycle numbers (at least). At each selected cycle number, the readings should be recorded for 10 consecutive cycles.

$N \in \{1 \text{ to } 20; 50; 100; 200; 400; 1\,000; 2\,500; 5\,000; 7\,500; 10\,000; 12\,500; 15\,000; 20\,000; 30\,000; 40\,000; 50\,000; 60\,000; 70\,000; 80\,000\}$.

When the loading is completed (or excessive deformations occur – more than 2 %), remove the specimen from the cell, take off the measuring system and membrane and determine the water content using all of the specimen.

8.2.3 Method B : Constant confining pressure

In this method, the confining pressure is held constant.

The number of tests to perform and the stress level to apply in each test depend on the application. Recommendations on the selection of appropriate stress levels are given in annex C.

In each test, start by applying the initial stresses σ_b (= 20 kPa) and $\sigma_{d \min}$. If possible, use $\sigma_{d \min} = 0$, but with some equipment a positive value may be necessary (which shall not exceed 5 kPa).

Then, perform the cyclic loading and apply at least 80 000 cycles.

Read and record the same stress and strain values as in 7.3.2.

Readings should be taken continuously during the first 20 cycles, and then at the following cycle numbers (at least). At each selected cycle number, the readings should be recorded for 10 consecutive cycles.

$$N \in \{1 \text{ to } 20; 50; 100; 200; 400; 1\,000; 2\,500; 5\,000; 7\,500; 10\,000; 12\,500; 15\,000; 20\,000; 30\,000; 40\,000; 50\,000; 60\,000; 70\,000; 80\,000\}.$$

When the loading is completed (or excessive deformations occur – more than 2 %), remove the specimen from the cell, take off the measuring system and membrane and determine the water content using all of the specimen.

8.3 Multi-stage loading

The objective with this procedure is to determine maximum stress levels which should not be exceeded to avoid the development of excessive permanent deformations. The procedure consists in applying different stress paths, with constant confining pressure, on the same specimen.

Two different loading procedures, one with high stress level and the other with low stress level are provided, in Tables 6 and 7. The applied stress levels should cover the stress range to which the material will be submitted in the field.

Start by applying the initial stresses σ_{\min} (= 20 kPa) and σ_{\min} , as defined in Tables 6 or 7. In these tables, it is assumed that $\sigma_{\min} = 0$, but with some equipment a positive value may be necessary (which shall not exceed 5 kPa).

Then, apply the cyclic loads specified in Table 6 or Table 7 (depending on the loading procedure selected), with 10 000 cycles for each stress path, starting with sequence 1.

The test is interrupted when the permanent axial strain reaches 0,5 % for each sequence and then continued with the next sequence. If it is known that more than four stress paths are necessary to reach the 0,5 % axial strain limit, the lowest stress levels can be omitted, provided that at least three stress paths are applied in that sequence.

Once testing according to sequence 1 has been completed (or terminated according to the 0,5 % strain limit), testing shall be undertaken according to sequence 2 then sequence 3. If higher values of stress σ are likely to occur in the application envisaged for the material, also apply the two additional sequences.

For each stress path in each sequence, read and record the stress and strain values as in 7.3.2.

Readings should be taken continuously during the first 20 cycles, and then at the following cycle numbers (at least). At each selected cycle number, the readings should be recorded for 10 consecutive cycles.

$$N \in \{1 \text{ to } 20; 50; 100; 200; 400; 1\,000; 2\,500; 5\,000; 7\,500; 10\,000\}.$$

When the stress paths are completed (or excessive deformations occur), remove the measuring system and membrane and determine the water content using all of the specimen.

Table 6 — Stress levels for the multi-stage test (high stress level)

Sequence 1			Sequence 2			Sequence 3			Sequence 4			Sequence 5		
Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa			
constant	min	max	constant	min	max	constant	min	max	constant	min	max	constant	min	max
20	0	50	45	0	100	70	0	120	100	0	200	150	0	200
20	0	80	45	0	180	70	0	240	100	0	300	150	0	300
20	0	110	45	0	240	70	0	320	100	0	400	150	0	400
20	0	140	45	0	300	70	0	400	100	0	500	150	0	500
20	0	170	45	0	360	70	0	480	100	0	600	150	0	600
20	0	200	45	0	420	70	0	560						

Table 7 — Stress levels for the multi-stage test (low stress level)

Sequence 1			Sequence 2			Sequence 3			Sequence 4			Sequence 5		
Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa	Confining stress, σ kPa	Deviator stress, σ_d kPa			
constant	min	max	constant	min	max	constant	min	max	constant	min	max	constant	min	max
20	0	20	45	0	60	70		80	100	0	100	150	0	100
20	0	40	45	0	90	70	0	120	100	0	150	150	0	200
20	0	60	45	0	120	70	0	160	100	0	200	150	0	300
20	0	80	45	0	150	70	0	200	100	0	250	150	0	400
20	0	100	45	0	180	70	0	240	100	0	300	150	0	500
20	0	120	45	0	210	70	0	280	100	0	350	150	0	600

9 Test report

9.1 General

The test report shall include, for all tests, the information referred to in 9.2. For resilient behaviour tests, it shall include the information referred to in 9.3 and 9.4. For permanent deformation tests, it shall include the information referred to in 9.5.

Tables suitable for presenting the data of sections 9.3 to 9.5 are shown in annex D.

9.2 General data

- Reference to this European Standard, including the test procedure used and the loading method;
- identification of the laboratory;
- date of test;

- d) identification and nature of the material;
- e) material grading – material designation and category according to EN 13285;
- f) method of preparation of the specimen and specimen size;
- g) moisture content of the specimen w , in percent (%);
- h) dry density of the specimen ρ_d ;
- i) any deviations from this European Standard as well as any incidents that could have had an effect on the results of the test.

9.3 Conditioning of the specimen

The report shall include the stress, strain and resilient modulus values measured during the conditioning.

If required, plots of the resilient axial strain, ε_{1r} , permanent axial strain, ε_{1p} , and resilient modulus, E_r , as a function of the number of load cycles, N , shall be included.

9.4 Resilient behaviour

The report shall include the stress, strain and resilient modulus values measured during each applied stress path.

If required, a plot of the resilient modulus as a function of the applied stresses shall be included.

9.5 Permanent behaviour (single stage or multi-stage loading)

The report shall include the stress, strain and resilient modulus values measured during the test.

If required, plots of the resilient axial strain, ε_{1r} , permanent axial strain ε_{1p} , and resilient modulus, E_r , as a function of the number of load cycles, N , shall be included.

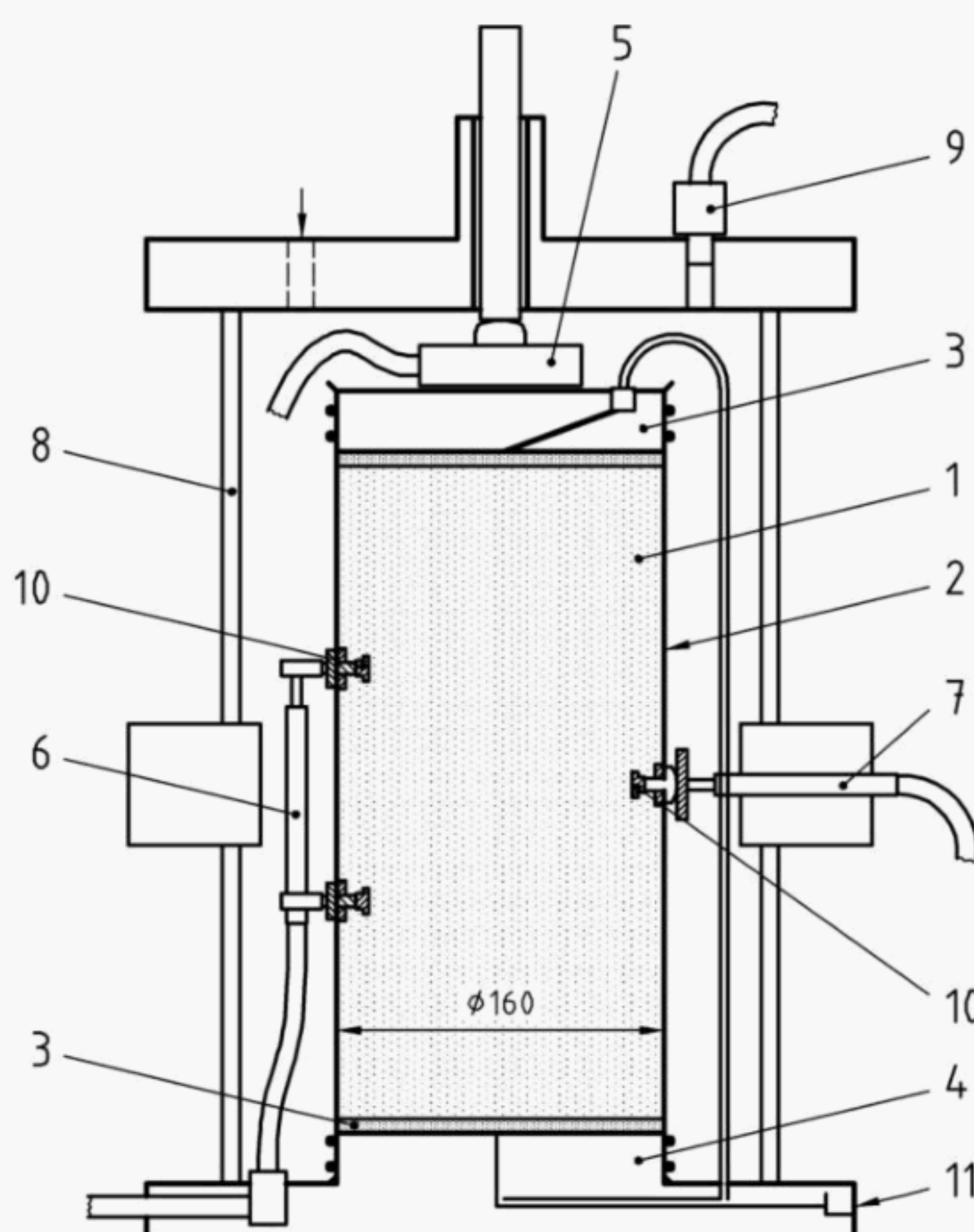
Annex A (informative)

Measurement of specimen deformations

NOTE In this annex, two examples of systems for the measurement of axial and radial strains are described

A.1 Measurement system using LVDTs

This system, presented in Figure A.1, uses three linear variable displacement transducers for the measurement of axial strains, and three linear variable displacement transducers for the measurement of radial strains.



Key

- | | | | |
|---|---------------|----|---|
| 1 | specimen | 6 | axial linear variable displacement transducers |
| 2 | membrane | 7 | radial linear variable displacement transducers |
| 3 | specimen cap | 8 | triaxial cell wall |
| 4 | specimen base | 9 | pressure transducer |
| 5 | load cell | 10 | studs supporting the displacement transducers |
| | | 11 | drainage circuit |

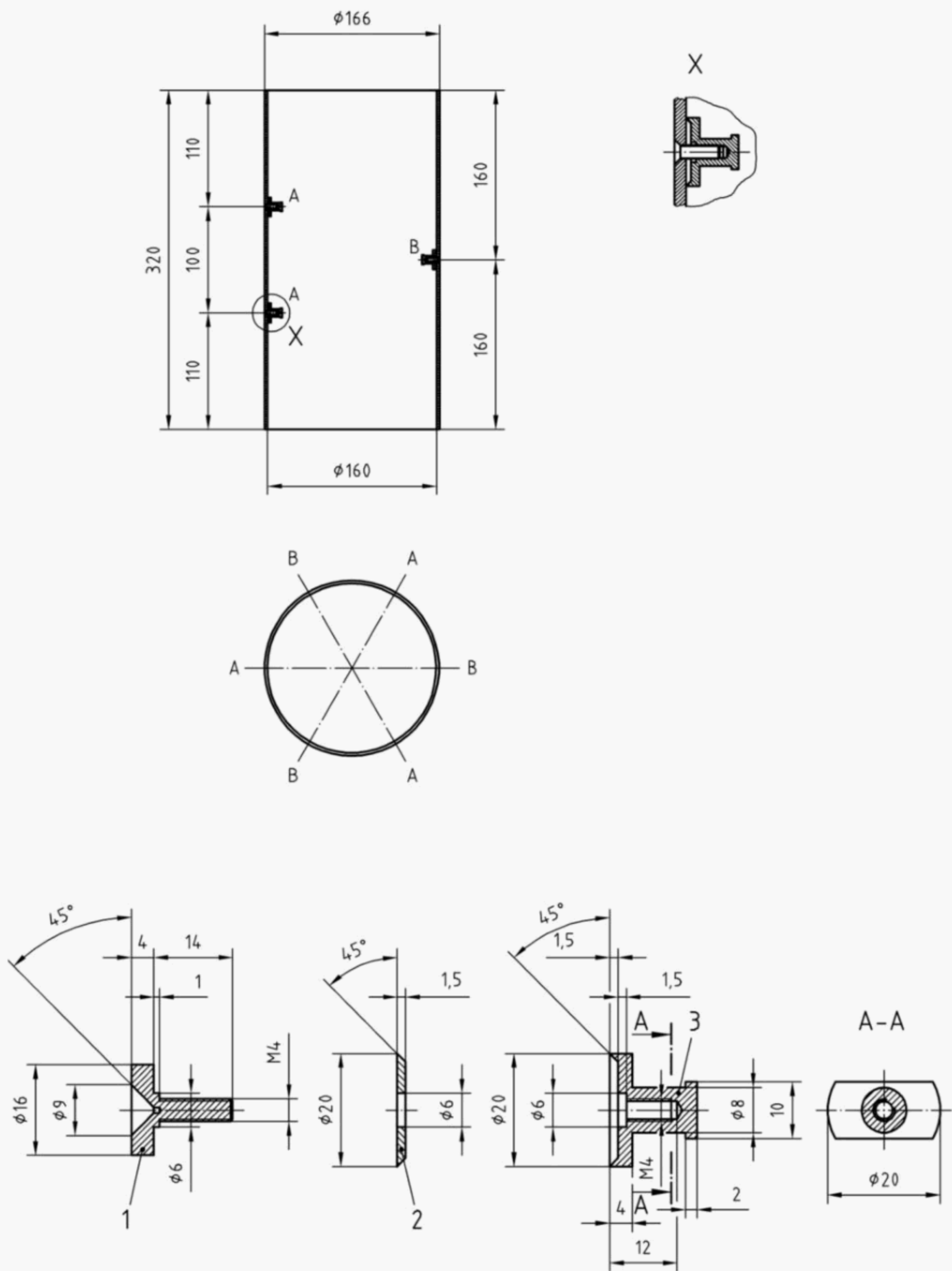
Figure A.1 — Example of triaxial cell and systems for measuring axial and radial displacements using linear variable displacement transducers

The axial linear variable displacement transducers are placed vertically, at 120° from each other, and measure the deformations over the central 100 mm of the specimen, to avoid end effects. The radial linear variable displacement transducers are placed horizontally, at 120° from each other, at mid-height of the specimen. Both transducers are connected to the specimen using studs, embedded in the specimen during compaction. These studs consist of 3 parts, as described on Figure A.2:

A stud, placed inside the material. Each of these studs is fixed on the inner wall of the compaction mould (see Figure A.2) before the compaction of the material, and embedded in the specimen during compaction.

A ring and a screw, placed outside the membrane, and screwed into the studs after making a small hole in the membrane. The head of the screw is in contact with the core of the linear variable displacement transducers.

Dimensions in millimetres



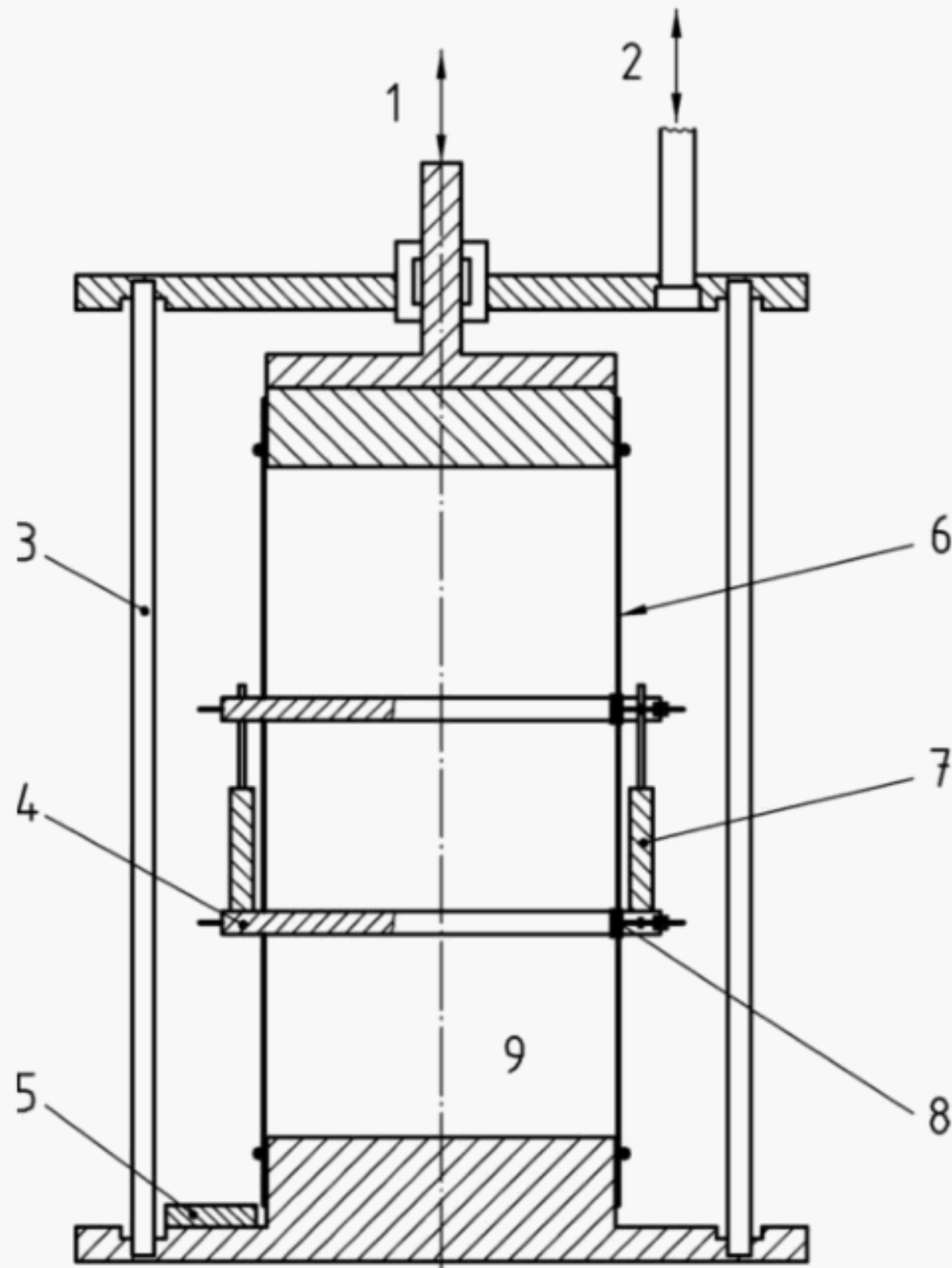
- Key**
- 1 stud placed inside the material
 - 2 ring
 - 3 screw supporting axial linear variable displacement transducers

Figure A.2 — Studs supporting the displacement transducers

A.2 Measurement system using linear variable displacement transducers and rings with strain gages

This system, presented in Figure A.3, uses two linear variable displacement transducers for the measurement of axial strains and two flexible, epoxy resin rings, instrumented with strain gages for the measurement of radial strains. The radial displacement is deduced from the deformations of this flexible ring.

The rings for the measurement of radial strains are attached to the specimen, at 1/4 and 3/4 of its height, using four studs embedded in the specimen during compaction. The axial linear variable displacement transducers are attached to the same studs.



- Key**

 - 1 load piston
 - 2 cell pressure valve
 - 3 triaxial cell wall
 - 4 rings
 - 5 cell pressure sensor
- 6 membranes
 - 7 linear variable displacement transducers
 - 8 studs
 - 9 sample

Figure A.3 — Example of triaxial cell and systems for measuring axial displacements using linear variable displacement transducers and radial displacements using flexible rings

Annex B (informative)

Preparation methods

B.1 General

Different compaction methods can be used for the preparation of the specimens, provided that the method produces specimens of uniform density and water content. Two methods are presented in this annex; others may be applied, for instance Proctor compaction or vibrating hammer.

B.2 Specimen conditions

The water content and density of the specimens should be representative of field conditions. These state conditions of the material should be reported. If the particle size of the material is compatible with the tests for laboratory reference density and water content, then refer state conditions to the reference values.

Generally, the mechanical properties of unbound mixtures vary significantly with the water content and degree of compaction. Table B.1 gives an example of test conditions which can be used for studying the sensitivity of the material with respect to water content and density.

Table B.1 — Example of state conditions for specimen preparation

Water content %			Dry density
W_{OPM-4}	W_{OPM-2}	W_{OPM-1}	$\rho_{d, OPM}$
	1 specimen		100 % $\rho_{d, OPM}$
1 specimen	2 specimens	1 specimen	97 % $\rho_{d, OPM}$
	1 specimen		95 % $\rho_{d, OPM}$
where: W_{OPM} is the optimum water content; $\rho_{d, OPM}$ is the laboratory reference density.			

B.3 Method 1 – Compaction by vibrocompression

This method is based on prEN 13286-52 and applies to mixtures with a maximum particle size less than 31,5 mm.

Select a representative sample of material according to EN 13286-1.

Mix the material with water to obtain the desired initial water content. After mixing, the material should be placed in a plastic bag and stored for 24 h (for materials with water absorption).

Compact the specimen by a vibration process in one layer according to prEN 13286-52 with the following variation:

The material should be compacted in a cylindrical plastic mould, which can receive two caps, covering the ends of the specimen, after compaction to prevent loss of moisture of the specimen during storage. The mould should be modified to support the studs which need to be embedded in the material during the compaction process. The studs are used as reference points/stations for deformation measurements.

The compaction time should not exceed 90 s, as specified in prEN 13286-52. For specimens compacted at low water contents (below the optimum water content w_{OPM}), the compaction time can sometimes exceed this limit. In this case, modify the compaction procedure as follows :

Prepare and compact the material at optimum water content, w_{OPM} . Place the specimen, in its mould, on a rigid, porous base. Place the specimen with its base in upright position in an oven, and dry it at a temperature of $(40 \pm 5)^\circ \text{C}$, until the desired water content is reached (determine the loss of water content by weighing the specimen at regular intervals).

After the compaction of the specimen (and eventually the oven drying), place the caps on both ends of the mould, and seal them with adhesive tape to prevent loss of moisture. Store the specimen in its mould, in vertical position, for at least 24 h before testing, at a temperature of $(20 \pm 3)^\circ \text{C}$.

B.4 Method 2 – Compaction by vibrating hammer

This methods consists of compacting the specimen in several layers, using a vibration process, similar to the vibrating hammer in EN 13286-4

Select a representative sample of material according to EN 13286-1.

Mix the material with water to obtain the desired initial water content. After mixing, the material should be placed in a plastic bag and stored for 24 h (for materials with water absorption).

Compact the specimen as follows :

Place the latex rubber membrane on the bottom plate of the triaxial cell; place a porous stone on the bottom plate;

secure an O-ring over the latex rubber membrane to seal it against the bottom plate;

place a split mould over the bottom plate with the latex rubber membrane extending up through it;

stretch the latex rubber membrane lightly over the interior surface of the split mould and over its upper lip;

apply a vacuum to the split mould to hold the membrane tightly against the mould during the compaction process. Other suitable techniques may also be used for this purpose;

place the studs used as reference points for deformation measurements in their positions inside the mould;

compact the moist unbound mixture in layers, typically six to seven layers, in the membrane-lined split mould attached to the bottom of the triaxial cell;

determine the height of each layer. For each layer, introduce in the mould the required mass of material, to obtain the required density, when the layer will be compacted to its final height. Compact each lift by vibration, until the final height of the layer is reached. Scarify the material surface between lifts. It should be noted that to obtain uniform density, the bottom layers have to be slightly undercompacted, since compaction of each succeeding layer densifies the aggregate in layers below it. After the last layer is partially compacted, put the top cap in place and continue vibration until the final height of the specimen is obtained;

after the specimen has been formed, place the top porous stone and the specimen cap on the surface of the specimen, place the membrane ends over the cap and base and seal the specimen with O-rings or rubber bands;

apply a partial vacuum of 10 kPa to the specimen and remove the split mould.

Annex C (informative)

Guidance on test procedures and ranking of materials

C.1 Purpose

This informative annex gives additional information on permanent deformation testing, and describes two approaches for ranking of granular materials on the basis of their mechanical properties.

C.2 Experimental stress levels for permanent deformation tests

The objective of permanent deformation tests (single stage tests) is to study the development of permanent deformations under the application of one repeated stress path, without prior conditioning. Permanent deformation tests may be used for different purposes (ranking, evaluation of maximum allowable stress levels, modelling of permanent deformations), and the number of tests to perform and stress paths depend on the application.

Concerning the suitable stress levels the following recommendations can be made:

Tests can be performed using variable confining pressure (method A) or constant confining pressure (method B).

Maximum stress levels should be similar to those used for resilient testing (high stress level or low stress level, depending on the position of the material in the pavement). The “high stress level” corresponds to stresses usually found at the top of the base layer, under a thin bituminous wearing course (less than 80 mm). The “low stress level” corresponds to stresses obtained under thicker bituminous layers, or in a granular subbase, (under a first granular base layer).

Stress paths to apply in each test can be selected from those used for the resilient behaviour tests, presented in Tables 3 and 5. The most appropriate stress paths are those with the highest stress amplitudes, leading to the highest permanent deformations.

C.3 Ranking of materials based on resilient behaviour tests

The approach described here is suitable for ranking of materials used for base layers of low traffic pavements. It consists in performing one resilient behaviour test with variable confining pressure and high stress level, following the procedure described in 7.2. From the results of the test, two parameters are determined:

A characteristic permanent axial strain, ε_1^c , which defines the resistance of the material to permanent deformations. The value of ε_1^c is determined from the results of the conditioning and calculated as follows:

$$\varepsilon_1^c = \frac{\varepsilon_1^p(20\,000) - \varepsilon_1^p(100)}{\ln(20\,000) - \ln(100)} \quad (1)$$

where

$\varepsilon_1^p(20\,000)$ is the permanent axial strain at the end of the conditioning (after 20 000 cycles).

$\varepsilon_1^p(100)$ is the permanent axial strain after the first 100 cycles.

A characteristic value of resilient modulus, E_c , defined as the resilient modulus determined for stress values $p = 250$ kPa and $q = 500$ kPa.

ϵ_1^c and E

For ranking, the parameters ϵ_1^c and E_c are determined at a water content $w = w_{OPM} - 2\%$ (w_{OPM} being the optimum water content) and a dry density $\rho_d = 0,97 \rho_{dOPM}$, (ρ_{dOPM} being the laboratory reference density). On the basis of these parameters, three classes of mechanical performance C1 to C3 are defined, as follows:

Table C.1 — Classification of unbound granular materials based on mechanical performance

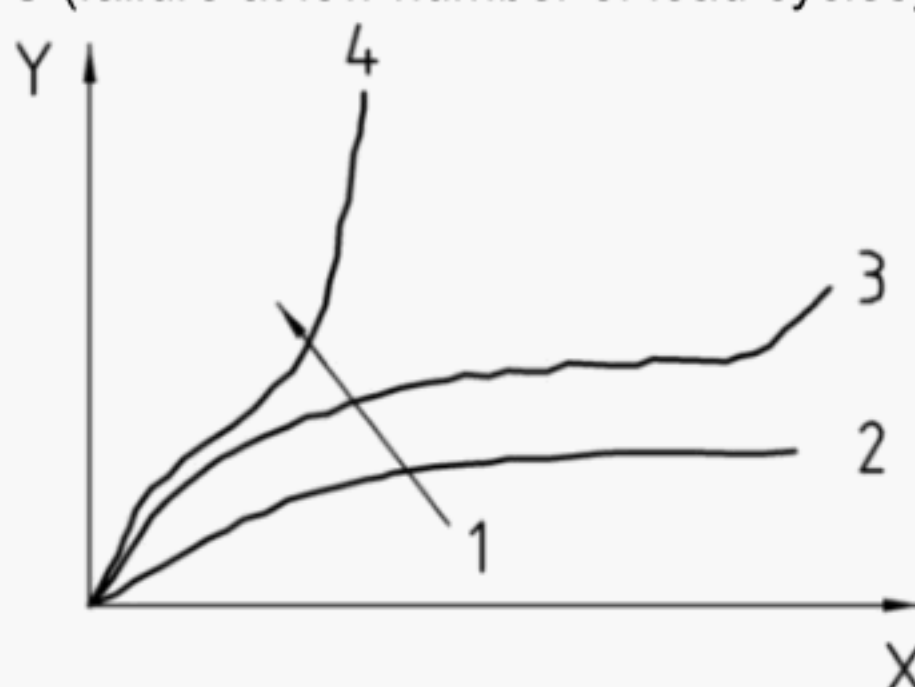
parameters E_c and ϵ_1^c		
Class	Characteristic Elastic modulus, E_c	Characteristic permanent strain, ϵ_1^c
C1	$500 \text{ MPa} \leq E_c$	$\epsilon_1^c \leq 2,5 \times 10^{-3}$
C2	$500 \text{ MPa} \leq E_c$	$2,5 \times 10^{-3} < \epsilon_1^c \leq 6 \times 10^{-3}$
	$250 \text{ MPa} \leq E_c < 500 \text{ MPa}$	$\epsilon_1^c \leq 6 \times 10^{-3}$
C3	$250 \text{ MPa} \leq E_c$	$6 \times 10^{-3} < \epsilon_1^c$

C.4 Ranking of materials based on permanent deformation tests

The procedure described below may be used for ranking materials on the basis of their plastic deformability.

Permanent deformation tests can lead to three ranges of behavior as shown in Figure C.1:

- Plastic shakedown – range A (stable deformation behavior);
- Plastic creep – range B (failure at high number of load cycles);
- Incremental collapse – range C (failure at low number of load cycles).



Key

- | | |
|--------------------------------|--------------------------|
| 1 increasing deviator strength | 4 range C |
| 2 range A | X number of load cycles |
| 3 range B | Y permanent strain range |

Figure C.1 — Deformation behavior of unbound granular materials

Two critical stress levels can be defined. One is at the limit of range A behaviour (and is known as 'the Plastic Shakedown Limit') and the second at the upper limit of range B behaviour (known as 'the Plastic Creep Limit').

C.4.1 Procedure

To find the "Plastic Shakedown Limit" it is necessary to conduct permanent deformation tests at a minimum of three different confining stresses. For each confining stress, subject a specimen to the lowest deviatoric stress given in Table C.2 according to the permanent deformation test procedures described in this European Standard. Then increase the deviatoric stress (Multi-Stage Test) or select a new specimen and apply the next higher deviatoric stress level to it (Single Stage Tests). Continue testing the specimen(s) at increasing deviatoric stress levels until

$$\epsilon_{p\ 5\ 000}^1 - \epsilon_{p\ 3\ 000}^1 > 0,4 \times 10^{-3}$$

(2)

strain is reached

where

- $\epsilon_{p\ 5\ 000}^1$ is the accumulated vertical permanent strain at 5 000 load cycles of the current deviatoric stress;
- $\epsilon_{p\ 3\ 000}^1$ is the accumulated vertical permanent strain at 3 000 load cycles of the current deviatoric stress.

Each test consists of applying 5 000 cycles of one of the stress paths according to Table C.2 without prior conditioning.

Table C.2 — Possible stress levels for the permanent behaviour ranking test (Single-Stage Tests / Multi-Stage Test)

Confining stress, σ_c kPa	Deviator stress, σ_d kPa	Stress ratio, σ_d/σ_c (–)
constant	min	max
20	0	1; 2; 3; 4; 5; 6; 7 ... n
50	0	1; 1,5; 2; 2,5; 3 ... n
70	0	1; 1,5; 2; 2,5; 3 ... n
150	0	1; 1,5; 2; 2,5; 3 ... n

In the absence of failure, interrupt the test if the specimen experiences large strains ("failure") before 5 000 cycles are completed at the current deviatoric stress level and recognize that the current deviatoric stress level is too high.

The test is then repeated but using the next confining stress. If the Multi-stage test procedure is in use, a new specimen is used for this repetition. Finally, the sequence is, again, repeated at the third confining stress level.

When the stress paths are completed, remove the measuring system and membrane and determine the water content using the totality of the specimen.

C.4.2 Interpretation

C.4.2.1 Limits

$\epsilon_{p\ 5\ 000}^1 - \epsilon_{p\ 3\ 000}^1 > 0,4 \times 10^{-3}$ strain

On the basis of experience in Germany it is suggested that a value of $\{\epsilon_{p\ 5\ 000}^1 - \epsilon_{p\ 3\ 000}^1\} = 0,045 \times 10^{-3}$ defines the "Plastic Shakedown Limit" for unbound granular materials as used in the unbound layers of pavement constructions and that a value of $\{\epsilon_{p\ 5\ 000}^1 - \epsilon_{p\ 3\ 000}^1\} = 0,4 \times 10^{-3}$ strain defines the "Plastic Creep

Limit". Subjecting a specimen to stress levels which generate strains a little larger than these values will allow the exact "Plastic Shakedown and Plastic Creep Limits" to be interpolated.

C.4.2.2 Model

With appropriate selection of the material constants in the following equation it is possible to define the "Plastic Shakedown Limit" as shown in Figure C.2:

$$\sigma = \frac{\sigma_{1\max}}{1 + \left(\frac{\sigma_{1\max}}{\sigma_3} \right)^\beta} + \alpha \quad (3)$$

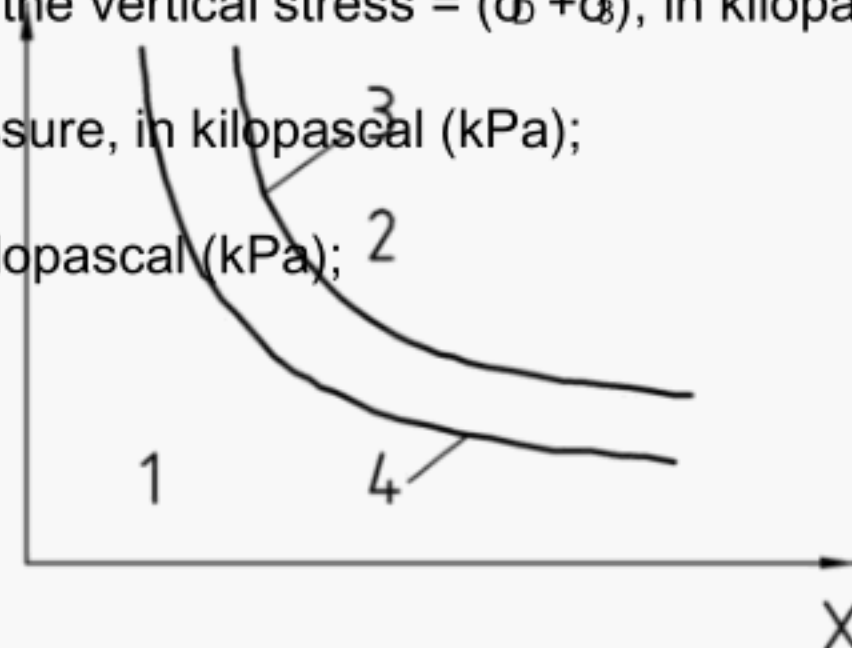
where

$\sigma_{1\max}$ is the maximum value of the vertical stress = $(\sigma + \alpha)$, in kilopascal (kPa);

σ_3 is the (constant) cell pressure, in kilopascal (kPa);

α is a model constant, in kilopascal (kPa);

β is a model constant.



Key

- | | | | |
|---|--------------------------------|---|--|
| 1 | range A | 4 | shakedown limit for material Y |
| 2 | range B | X | stress ratio $\frac{\sigma_{1\max}}{\sigma_3}$ |
| 3 | shakedown limit for material X | Y | vertical stress $\sigma_{1\max}$ |

Figure C.2 — Ranking of materials

If desired, the same approach may be used to plot the "Plastic Creep Limits".

C.4.3 Ranking

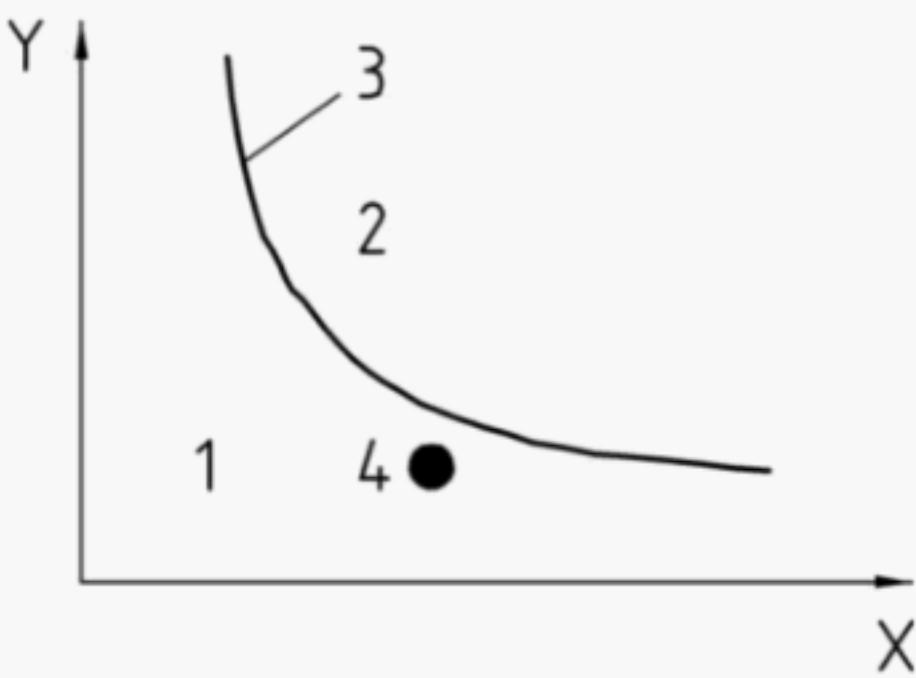
If the "Plastic Shakedown Limits" of different materials are available, then ranking of the materials (comparison of different materials) is possible by comparing the "Plastic Shakedown Limit" curves of the different materials (Figure C.2).

C.4.4 Application

If the suitability of an unbound granular material for a layer in the pavement is to be checked, a comparison of the shakedown limit with the maximum stresses in the unbound pavement layer may be performed (see Figure C.3). In principle, if the calculated maximum stress is within the range A there should be little risk of rutting within the unbound layers. If the calculated stress is within the range B, there would be a risk of rutting

within the unbound layer and it might be necessary to use another unbound granular material. Any behaviour in range C (see Figure C.1) would, certainly, be inadmissible. However, insufficient experience is currently

available to confirm the reliability of this deduced linkage between range boundaries defined via the triaxial test and in-situ performance types. For this reason, users should confirm predictions made by the above approach by using alternative means.



- Key**
1 range A
2 range B
3 shakedown limit for material X
- 4 calculated maximum stress within the unbound layer
X stress ratio 1_{max3}
Y vertical stress 1_{max}

Figure C.3 — Application of ranking

Annex D (informative)

Suggested tables for presentation of test results

Table D.1 — Presentation of the results of the conditioning

N Cycles	σ_3 kPa		σ_d kPa		Resilient strain 10^{-3}		Permanent strain 10^{-3}		Resilient modulus MPa
	min	max	min	max	ϵ_{1r}	ϵ_{3r}	ϵ_{1p}	ϵ_{3p}	E_r
10									
20									
50									
100									
200									
400									
1 000									
2 500									
5 000									
7 500									
10 000									
12 500									
15 000									
20 000									

For each series of measurements (10 consecutive cycles), give the average values of the stresses and strains.

Table D.2 — Presentation of resilient behaviour results

σ_3 kPa		σ_d kPa		Resilient strain 10^{-3}		Resilient modulus MPa
min	max	min	max	ϵ_{1r}	ϵ_{3r}	E_r
0	0	0	0	0,0	0,0	0

For each of the stress paths applied, give the average values of stresses and strains measured in the last 10 load cycles.

Table D.3 — Presentation of permanent behaviour results

<i>N</i> Cycles									Resilient modulus MPa
	σ_3		σ_d						
					Resilient strain		Permanent strain		
						ϵ_3^r		ϵ_3^p	
	kPa								
			kPa						
					10			10	
	min	max	min	max	ϵ_1^r	ϵ_3^r	ϵ_1^p	ϵ_3^p	E_r
1	0	0	0	0	0,0	0,0	0,0	0,0	0
10									
20									
50									
100									
200									
400									
1 000									
2 500									
5 000									
7 500									
10 000									
12 500									
15 000									
20 000									
30 000									
40 000									
50 000									
60 000									

For each series of measurements (10 consecutive cycles), give the average values of the stresses and strains.

Table D.4 — Presentation of the multi-stage test results

	σ_3		σ_d		Average resilient strain		Accumulated permanent strain		Resilient modulus
N	kPa		kPa		ϵ_3^r		ϵ_3^p		MPa
Cycles					10 ⁻³		10 ⁻³		
	min	max	min	max	ϵ_1^r	ϵ_3^r	ϵ_1^p	ϵ_3^p	E_r
10 000	0	0	0	0	0,0	0,0	0,0	0,0	0
10 000									
:									
5 243									
10 000									

:

For each of the stress levels applied average values for stresses and resilient strains are given in one row of the table. The accumulated permanent strains from the beginning of the stress path to stress pulse $N = 10\,000$ are also given in the same row.

If the test is interrupted this should be noted by indicating the number of cycles applied for that stress level ($<10\,000$). Indicate the start of a new sequence by a bold line.

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