Bundesanstalt für Wasserbau
Kompetenz für die Wasserstraßen

BAWGuideline

on the testing of mineral soft seals and their installation methods in navigable waterway construction (RPW - Guideline for Planning Competitions),

2026 edition

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1 Preliminary remark

The present guidelines (RPW) apply to the testing of the mechanical and hydraulic properties of mineral soft seals (natural clay seals). Natural clay seals are considered the standard solution for waterways. Tests are also listed for sealing designs that are not to be regarded as standard practice but may be used in special cases (geosynthetic clay sealing membranes and duroplastic seals with clay and hydraulic binders). In addition, specifications are described for the testing of mechanised installation methods to be used on waterways when installing sealing materials underwater and during navigation.

Similar guidelines already exist for the testing of hydraulically bound materials used for grouting hydraulic engineering blocks on waterways (RPV (2026)) and for the testing of geosynthetics in navigable waterway construction (RPG (2026)). Together with the Technical Delivery Conditions for Hydraulic Engineering Blocks (TLW (2022)) and the Technical Delivery Conditions for Geotextiles and Geotextile-Related Products for Waterways (TLG (2026)), as well as the Supplementary Technical Contract Conditions – Hydraulic Engineering: Bank and Riverbed Stabilisation (ZTV-W LB 210 (2025)), they form the basis for the tendering and execution of waterway bank and bed stabilisation works.

Soft seals constitute the main part of the surface seals applied today in the field of federal waterways and shipping administration. In addition, alternative sealing materials and installation methods were developed, some of which required test procedures that had not previously been standardised. In order to standardise the inspection standards, it was necessary to compile in a separate guideline the test methods required for these seals, which were partly standardised and partly developed by the BAW for specific requirements on the waterway. For other types of seals (concrete seals, seals made from fully grouted hydraulic engineering blocks and asphalt seals), relevant standards and regulations already exist (e.g. Recommendations for the Execution of Asphalt Works in Hydraulic Engineering (EAAW (2008))).

This Guideline deals with sealants and their installation procedures. Chapters 3 and 4 set out, first and foremost, the requirements and test methods relating to the mechanical and hydraulic properties of mineral-based soft sealing materials, which can be used to demonstrate their general suitability for applications in hydraulic engineering or their suitability for use in accordance with the intended purpose as specified in the building specifications (ZTV-W LB 210 (2025)). For already standardised tests of soil mechanics, the limit values to be complied with are defined and reference is made, where necessary, to the special substance-specific boundary conditions of the tests. In the case of non-standard test methods, the parameters to be tested, the test design, the test procedure and the limit values to be complied with are described in detail in the form of a test regulation. All building-contract-relevant limit values are additionally anchored in ZTV-W LB 210 (2025).

Chapter 5 defines basic requirements for underwater installation procedures for mineral soft seals in navigable waterways (Chapter 5.1). Compliance with these requirements must be demonstrated for each procedure by means of a basic examination in advance, independently of any construction measure (ZTV-W LB 210 (2025)). Boundary conditions and requirements for the execution of these basic tests are set out in Chapter 5.2. By extension, these requirements also apply to other forms of proof of suitability for use (e.g. case-by-case assessment).

Chapter 6 briefly describes, for information purposes, the suitability, control and self-monitoring tests to be carried out as part of the construction project. The requirements and details are set out in ZTV-W LB 210 (2025).

As the development of sealants and installation methods is constantly evolving, it is envisaged that these guidelines will be updated at intervals. It is also necessary to gain experience in practical application with the newly developed test methods and the defined limit values and to incorporate them into further revisions. This version of the RPW (2026) is the first revision of the RPW (2015). The current version is available on the BAW website (www.baw.de).

General subject-specific principles for the application of seals in waterways include the 2002 'Recommendations for the application of surface seals on waterway beds and banks' (EAO (2002)), available on the BAW website.

Products and goods originating from other Member States of the European Union or Turkey, or an EFTA state which is a Contracting Party to the EEA Agreement, which do not meet these technical specifications shall be treated as equivalent, including the testing and inspections performed in the manufacturing country, if the required level of protection - safety, health and suitability for use – is achieved in the long term to the same extent.

2 Scope of application

This document covers test procedures for the following mineral-based soft seals and their installation methods:

- Natural clay seals,
- Geosynthetic clay liners (GCL or GBR-C according to DIN-EN ISO 10318-1 [17]),
- Duroplastic seals with clay and hydraulic binders.

Natural clay is a long-proven sealing material. It is a fine-grained substance found in soil that usually has to be processed in order to meet the corresponding requirements.

Geosynthetic clay liners (GCL) consist of two layers of geotextiles, with a layer of bentonite sandwiched between them. In addition to the pure sealing membranes, there are also combination products in which the GCL is firmly bound to an overlying sand mat. GCLs have been used in landfill construction for a long time. On waterways, this construction method is still considered one of the newer sealing materials. They have not as yet been established as a standard construction method.

A *permanent plastic seal with clay and hydraulic binders* is a mixture of sand, water and a special compound that does not harden. High-speed mixing in a pugmill mixer achieves great erosion resistance. The compound consists of clay minerals, cement and additives. The amount of cement is kept to a minimum so that the mixture remains permanently flexible, acting as a soft seal. On waterways, this construction method is still considered one of the newer sealing materials. They have not as yet been established as a standard construction method.

Detailed information on individual seals can be found in the recommendations on the application of surface seals (EAO (2002)).

3 Basic requirements for sealing materials

The main requirements for soft seals used in waterways for which test procedures are described in these guidelines are briefly summarised below:

Sufficient tightness due to low permeability and low permittivity

The effectiveness of a seal can be assessed by the amount of water passing through per unit of time. This is determined by the hydraulic boundary conditions (water level above the seal), the permeability coefficient of the sealing material and the layer thickness of the seal.

Erosion resistance (internal and external erosion)

The sealing material must be resistant to erosion caused by the hydraulic gradients occurring within the seal (internal erosion). Any potential defects in the seal must not widen when fluid flows through it (external erosion). There must be no erosion of the sealing material on the underside of the seal (external erosion). The erosion stress caused by flowing water on the surface of the seal during installation must not lead to any weakening of the seal. During permanent use, the sealing surfaces must either withstand the hydraulic stresses present or be protected against them.

Deformability

Seals shall not be adversely affected in their function by deformations of the substrate or of components in contact with the seal. Therefore, seals must be sufficiently deformable.

Strength

On the other hand, gaskets must also be of sufficient strength to ensure that mechanical stress does not impair their functioning. Mechanical stresses may, for example, occur as a matter of course during the installation of the seal and the protective layers above it. Shearing stresses of the seal may occur on banks.

Long-term durability

Seals properties must not be altered in a way that is detrimental to their functionality during their planned service life.

4 Methods for testing soft sealing materials

4.1 General information

Annex 1 contains a tabular overview of the test procedures to be carried out for the individual sealing materials in accordance with the requirements set out in point 3. A reference to the individual sections in the text is given. Annex 2 shows a compilation of the respective limit values to be complied with. Annex 3 specifies the parameters and tests that must be determined or carried out for each individual sealing material as part of the testing process to demonstrate their general suitability.

In addition to the tests specified in Annex 1, further material properties may need to be determined for individual sealing materials, depending on the specific application and type of test. Test procedures that are largely standardised will not be discussed in further detail below.

For *natural clay*, the material characteristics are as follows:

- Particle size distribution (DIN EN ISO 17892-4)
  Requirements:
  Grain fraction d20 ≤ 0.002 mm (dry installation)
  Grain fraction d30 ≤ 0.002 mm (underwater installation)
  Grain fraction d80 ≤ 0.06 mm
  Grain fraction d90 ≤ 2.0 mm
- Consistency limits (DIN EN ISO 17892-12)
  Requirements: $W_L > 0.35$, in the plasticity diagram of DIN 18196 above the A-line
- Lime content (DIN 18129) – Index value
- Loss on ignition (DIN EN 17685-1) – index value
- Water content (DIN EN ISO 17892-1) and Proctor density (DIN 18127)
  Requirement: derived from the requirement for undrained shear strength (see Chapter 4.3)
- Water absorption (DIN 18132) – index value
- Mineralogical composition – index value

The RPG (2026) shall also apply mutatis mutandis to the *GCL*. According to DIN EN 13362, the following characteristics may therefore be relevant, depending on the use case and type of test:

- Area-based mass (DIN EN 14196) – with a sand mat where applicable
- Tensile strength/extensibility (DIN EN ISO 10319)
  Requirement: ≥ 12 kN/m
- Water absorption (DIN EN ISO 10769/DIN 18132) – index value
- Bond strength (DIN EN ISO 13426-2)
- Requirement based on previous experience: 60 N/10 cm
- Abrasion resistance (RPG (2026)) when applied with hydraulic engineering blocks or without protective layer
- Puncture resistance (EN ISO 12236) – index value

The tensile strength requirements must also be met by all individual layers of the GCL; in other words, the first peak on the force-strain curve (see DIN EN ISO 10319, Figure 1 [18]) – and thus the failure of the first geotextile component – is the assessment criterion for the tensile strength of the GCL.

Evidence of sufficient friction shall be provided when applying the GCL to banks steeper than 1:3 depending on the corresponding soil and the intended structure of the revetment.

For *duroplastic seal with clay and hydraulic binders,* the

- extent of expansion (DIN EN 12350-5) – index test

must also be determined. It serves as an additional control parameter in self-monitoring and control tests to demonstrate the stability of the selected formulation.

4.2 Determination of permeability coefficient

4.2.1 General

The following must be tested: natural clay seals, duroplastic seals containing clay and hydraulic binders, and GCL.

4.2.2 Special features of test procedure

The water permeability coefficient k_{10} is determined in accordance with DIN EN ISO 17892-11. This value is calculated from the measured flow rate at a constant hydraulic gradient using the following equation:

$$k_{10} = \frac{Q \cdot l}{A \cdot h} \quad (1)$$

k_{10} water permeability coefficient at 10 °C water temperature [m/s]
Q measured flow rate [m^3/s]
A cross-sectional area of the sample [m^2]
h hydraulic height difference [m]
l flow length (layer thickness of the sample) [m]

The permittivity ψ is independent of the layer thickness of the seal and is determined according to the following equation:

$$\psi_{10} = \frac{Q}{A \cdot h} = \frac{k_{10}}{l} \quad (2)$$

ψ_{10} Permittivity at 10 °C water temperature [1/s]

The hydraulic height difference h or the hydraulic gradient i (i = h/l) in the test shall be chosen according to the pressure head provided for in the practical application on waterways. For clay seals and duroplastic seals containing hydraulic binders and clay, the test is usually carried out at a gradient of 30%. The GCL should take into account the usual boundary conditions on waterways corresponding to water columns above the seal of 5 m and 1 m. The greater determined k_{10} value is decisive.

When examining GCL samples, care must be taken to ensure that they remain undisturbed throughout the experiment. Possible changes in the surface structure – such as local indentations caused by hydraulic engineering blocks – must not be eliminated by applying loads or other pressures during the test. The specimen should therefore be carefully placed on both sides in a bed of sand of uniform grain size or fine gravel, so that these areas remain hydraulically effective.

4.2.3 Analysis of test results and limit values

In the test, the flow rate is measured at a certain height of the water column. The permeability parameters k_{10} and ψ_{10} are therefore calculated as an average value for the entire sample. For the calculation of the gradient i and the permeability coefficient, planned thickness of generally 1 cm is assumed for GCL, as a precise determination is difficult, especially if the mat shows thickness fluctuations from the outset or if specimens deformed by stress are examined.

The permissible limit is derived from the maximum permissible seepage water volume specified in ZTV-W LB 210 (2025), which is $2.5 \times 10^{-8} m^3/(s \cdot m^2)$. For clay seals and duroplastic seals with clay and hydraulic binders with a minimum thickness of 20 cm, a k_{10} value of maximum $1 \cdot 10^{-9}$ m/s is required; for GCL with a planned thickness of 1 cm, a value of maximum $5 \cdot 10^{-11}$ m/s. For verification in service condition, e.g. for samples taken from installed seals, an increase of the permitted seepage quantity by a maximum of one order of magnitude is allowed. A comparison of different seals with different thicknesses is possible via permittivity, which can be determined from the tests independently of the layer thickness.

4.3 Determination of undrained shear strength

4.3.1 General information

The tests to be carried out cover natural clay seals and duroplastic seals made from clay and hydraulic binders.

The undrained shear strength c_u can be determined in different ways: Hand-held probe, field vane probe and pocket penetrometer are all suitable for on-site measurements such as monitoring measurements carried out during construction. For laboratory tests, e.g. as part of initial tests or during follow-up tests on samples taken from the seal, the undrained shear strength is determined using a laboratory vane probe or by means of triaxial tests.

The execution and evaluation of field vane probes are regulated in DIN EN ISO 22476-9. By contrast, there are no corresponding standards for laboratory and hand-held probes. If the boundary conditions specified in DIN EN ISO 22476-9 (low rotation speed and vane ratio h/d = 2) are observed, the results of the test methods are comparable within the achievable practical accuracy for construction.

Smaller sample volumes are tested with the laboratory vane and the pocket penetrometer rather than with the hand and field vane. Therefore, to ensure representative shear strength data, at least 5 individual measurements should be taken with the laboratory vane and the pocket penetrometer, and at least 3 individual measurements with the hand and field vane in each test. The pocket penetrometer generally provides lower measurement accuracy than vane probes.

4.3.2 Vane probes

In tests using the laboratory (Figure 1), hand-held (Figure 2) or field vane probe, the maximum torque that can be transmitted into the ground via the vane (max M_D) is determined. From this, the undrained shear strength of the soil is calculated (Chapter 4.3.4).

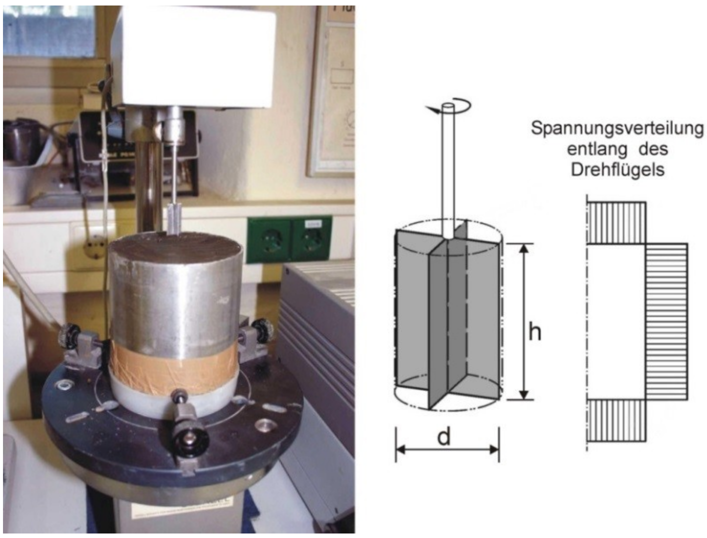

Figure 1: Laboratory vane probe with rotating vane.

Spannungsverteilung entlang des Drehflügels	Stress distribution along the rotary vane

Figure 2: Hand vane probe.

When conducting the vane probes, the dimensions and geometrical ratios between the rotary vane and the sample container Figure 3must be observed accordingly. The standardised ratio of height to diameter of the rotary vane is h/d = 2.

For the laboratory vane probe, a vane with h = 2.5 cm and d = 1.25 cm is used. The rotational speed is 6°/min. The dimensions of the handheld vane probe are h = 5.08 cm and d = 2.54 cm. The vane probes are pressed into Figure 3 the ground according to the specifications and rotated clockwise. There are no specific requirements for the rotation speed; the rotation should be very slow. Once the maximum torque has been reached, the test shall be terminated.

In the case of the handheld vane probe, the torque is measured by a deflection pointer, which stops rising once the breaking torque is exceeded. The maximum torque can be read from a fixed marker. The undrained shear strength is calculated from the measured torque using the equation (3) or (4).

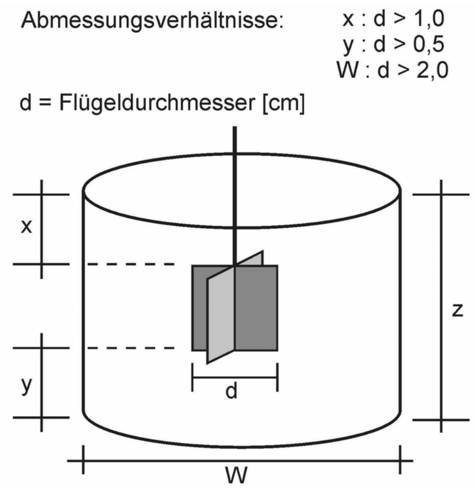

Figure 3: Minimum size of the sample container for a given rotor blade diameter.

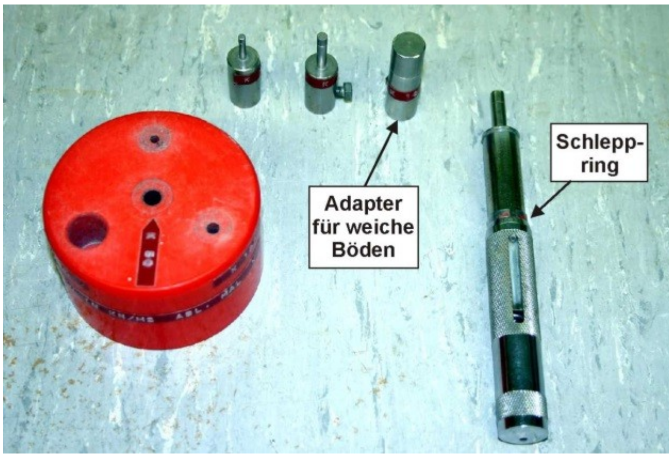

Figure 4: Pocket penetrometer with various adaptors.

Abmessungsverhältnisse	*Dimension ratios*
Flügeldurchmesser	*Vane diameter*

Adapter für weiche Böden	Adapter for soft soils
Schleppring	Towing ring

4.3.3 Pocket penetrometer

A rapid test to determine the undrained shear strength is carried out with the pocket penetrometer (Figure 4). To do this, the penetrometer is pressed vertically into the sample, slowly and with light pressure, against the soil resistance and the spring resistance of the penetrometer. The force required for this is displayed on a scale on the penetrometer via a towing ring. Depending on the adapter used (attachment tip), this force is converted into a stress or strength specification. In the case of the strengths to be examined in seal construction, an adapter for soft floors is generally used.

4.3.4 Analysis of test results and limit values

For vane soundings, the undrained shear strength c_u is calculated from the measured maximum torque max M_D as follows:

$$c_u = \frac{max\, M_D}{\frac{\pi}{2} \cdot d^2 \cdot h \left(1 + \left(d/3h\right)\right)} \tag{3}$$

h Height of the vane [m]
d Diameter of the vane [m]
max M_D maximum torque [Nm]
c_u undrained shear strength [$N/m^2 = 10^{-3}$ kPa]

A rectangular stress distribution along the rotary vane is assumed in accordance with DIN EN ISO 22476-9. For the predetermined aspect ratio of the vane of h/d = 2, this results in:

$$c_u = \frac{6 \cdot max\, M_D}{7 \cdot \pi \cdot d^3} \tag{4}$$

A reduction in the shear strength determined in accordance with Annex C to DIN EN ISO 22476-9 is not permitted for soft seals.

As undrained shear strength is highly dependent on water content, the soil-specific characteristic curve of the sealing material, $c_u = f(w)$, is determined for natural clay seals as part of the preliminary testing. The undrained shear strength c_u is determined for this purpose at different water levels w with the laboratory vane probe. The graph (Figure 5) shows the water content at the installation limits specified in ZTV-W LB 210 (2025)

for underwater installation: $15 \text{ kPa} \leq c_u \leq 25 \text{ kPa}$
for dry installation: $c_u \leq 50 \text{ kPa}$

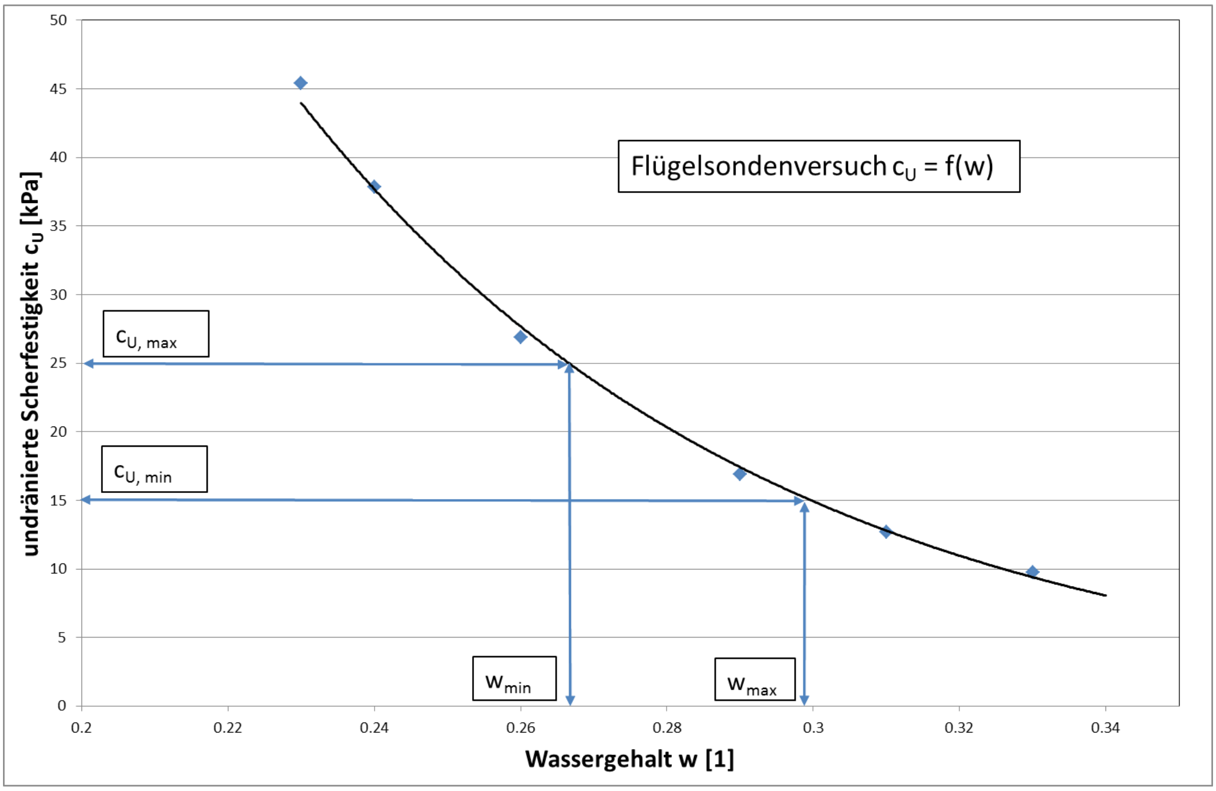

Figure 5: Sample graphical representation of dependence $c_u = f(w)$ for natural clay.

undränierte Scherfestigkeit C_U [kPa]	undrained shear strength C_U [kPa]
Wassergehalt w [1]	water content w [1]
Flügelsondenversuch C_U = f(w)	vane probe test C_U = f(w)

The limit water contents w_{min} and w_{max} (see Figure 5) provide an indication of how much water must be added to or removed from the naturally extracted clay material during processing and homogenisation in order to achieve the above-mentioned installation strengths. In the case of sensitive clay materials, different processing may result in different parameters c_u = f(w) for the status before and after the processing of the material. The decisive installation criterion is therefore the strength and not the water content.

For duroplastic seals with clay and hydraulic binders, the installation strength limits to be complied with shall be laid down in accordance with the required material characteristics in the preliminary test or suitability test.

4.4 Decay test according to Endell

4.4.1 General information

Natural clay thicknesses must be tested.

The test to determine the decay rate developed by Endell (1941) assesses the stability of a test specimen when stored in water. This method assesses the nature and rate of disintegration or swelling of cohesive soils in qualitative terms. Sealing materials with increased disintegration are more susceptible to erosion. This poses a risk to the seal, which is not yet protected, particularly during the construction phase. In conjunction with the results of the hole erosion test (HET, see Section 4.5), determination of the disintegration index is used to assess, on a qualitative basis, the susceptibility of a sealing material to erosion.

4.4.2 Project design and procedure

Determination of decay resistance is carried out using the test apparatus shown on the right in Figure 6. A measuring cylinder 60 cm high and 7 cm in diameter is filled almost to the brim with distilled water, and a hydrometer 50 cm long and 2 cm in diameter is immersed in it. The hydrometer, which has a measuring scale, is weighted at the bottom with lead balls to ensure a stable floating position. A wire basket is attached to the lower end of the hydrometer, in which the cylindrical specimen body (diameter d = 2 cm, height h = 4 cm) is located. When the hydrometer containing the soil sample is placed in the measuring cylinder filled with water, water displacement, together with the weight of the hydrometer and the soil sample, results in a specific immersion depth, which must be recorded as reading A1 at the start of the test. During the test run, care must be taken to ensure that the temperature of the measuring environment remains as constant as possible.

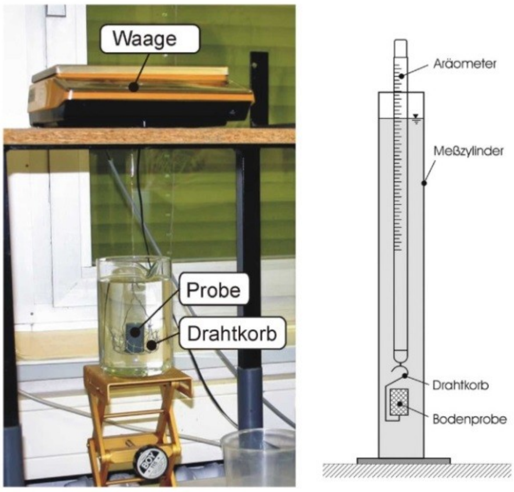

Figure 6: Test apparatus for determining resistance to decay; left: automatic data logging; right: hydrometer measurement.

Waage	Scale
Probe	Sample
Drahtkorb	Wire basket
Aräometer	Hydrometer
Meßzylinder	Graduated cylinder
Drahtkorb	Wire basket
Bodenprobe	Soil sample

As the soil sample decays, when relevant, causing soil particles to settle within the measuring cylinder, the weight of the sample decreases. At the same time, the hydrometer moves slowly upwards and gradually reduces its immersion depth. The immersion depths measured at different times (readings A(t)) shall be recorded until buoyancy is constant, but at least until 24 hours after the start of the test. At the end of the test, the immersion depth of the hydrometer – without the test specimen but including the wire basket – is recorded (reading A2).

The test rig was further developed at the BAW and fitted with an automatic data-logging system (Figure 6, left). The sample body is immersed in a coarse mesh wire basket in a water container. The basket is suspended from a precision balance with a measurement accuracy of 0.01 g, and the initial weight is recorded whilst the basket is buoyant. Similar to reading a hydrometer, the buoyant weight of the residual sample on the wire basket is measured at intervals. Documentation of the reading times, the logging of measured values and the evaluation are carried out automatically.

4.4.3 Analysis of test results and limit values

The measured values are analysed and the decay factor Z is calculated using a simple ratio equation. Here the variables are:

$$Z = \frac{A1 - A(t)}{A1 - A2} \tag{5}$$

Z Decay coefficient [-]
A1 Immersion depth of the hydrometer [mm] or buoyant weight of the specimen including the wire basket [g] at the start of the test
A(t) Immersion depth of the hydrometer [mm] or buoyant weight of the specimen including the wire basket [g] at time t after the start of the test
A2 Immersion depth of the hydrometer [mm] or buoyant weight of the wire basket without the specimen [g]

Qualitative information on the temporal course of decay can be derived from a graphical representation of the value pairs Z and t in the form Z = f(t).

The test yields decay numbers that are too low if the soil particles that detach do not sink to the bottom of the water container but remain on the wire mesh. In this case, the result cannot be assessed; the test must be repeated.

To facilitate better comparison of the resistance to decay of different seal samples, the decay index after 8 hours of testing, Z(8), is used. According to Endell (1941), every soil has a specific water content at which the most severe decay is to be expected. Therefore, the decay number Z(8) shall be determined for at least five different water contents or installation strengths, e.g. c_u values between 10 and 70 kPa for clay. Experience shows that very little decay is to be expected in the range of the flow limit w_L due to high water saturation.

At present, it is not yet possible to specify a reliable and reproducible limit value for the decay rate of sealing clays. Experience to date shows that when decay rates are above Z(8) = 0.05, susceptibility of the sealing material to erosion increases. In the event of a negative result for the decay test and an ambiguous result for the hole erosion test, the sealing material cannot be used in the waterway without additional measures (e.g. sand equalisation layer for relatively coarse-grained substrate or application of a geotextile for soil type 4 according to TLG (2026)).

4.5 Erosion test (hole erosion test, HET)

4.5.1 General information

The following are to be tested: sealing materials made from natural clay and seals containing hydraulic binders and clay.

The pinhole test described to date in the RPW (2015) for assessing the erosion stability of mineral sealing materials has often failed to produce reproducible and plausible results. The search for an alternative, better and therefore more reproducible test method led to the discovery of the hole erosion test (HET), as described by Wan and Fell (2004). Modifications developed at the BAW (Hark (2018); Zaid et al. (2022))

led to the experimental procedure and analysis described in the following sections. Classification of soil materials with regard to their risk of erosion follows that proposed by Briaud et al. (2017).

4.5.2 Principle of the test

Similar to the pinhole test, the hole erosion test begins with the preparation of a cylindrical soil sample (d = 10 cm, h = 12.5 cm) made from processed and uniformly compacted sealing material. A central hole 8 mm in diameter is then drilled along the entire longitudinal axis of the sample. The sample body, or this opening, is then flushed through under constant pressure. The increasing enlargement of the opening over time and the corresponding mean shear stresses along the hole wall are determined. Both parameters form the basis for the evaluation of sealing clay.

4.5.3 Test design

The system consists of a three-part test cell. It comprises an upper inlet cylinder, a middle sample cylinder, on which the sample to be examined is mounted, and an outlet cylinder. There is a sealing ring between each of these parts. All three parts are clamped together by threaded rods. The test cell is rounded off by an inlet and a collection container (Figure 7), which are arranged in front of and behind the cell. With these containers, different pressure levels can be set to flow through the sample (as the starting height, a height difference of h = 2.9 m is recommended). The collection tank also serves to allow dislodged soil particles to settle. The water flowing through drains from the collection container into a circulation tank, where a pump returns it to the inlet container. In order to keep the water level in the inflow container constant, an overflow is installed to feed excess water from the inflow container into the circulation container.

A differential pressure transducer measures the pressure difference between the inlet and outlet of the sample. Flow meters measure the amount of water flowing through the flow channel per time unit. Both measuring devices thus provide the key values for evaluation and interpretation of the test data. An example of the measurement data is shown in Figure 8. Table 1 shows the measurement range and measurement error for both measuring devices.

Table 1: Measuring range and measurement errors of measuring devices with HET.

	Flow meter	**Differential pressure transducer**
Measuring range	0 – 2.778 l/s	0 – 0.5 bar
Measurement errors	0.2% of measured value + 1.96 ml/s	±0.1% FS (FS = full scale, i.e. ±0.1% of 0.5 bar)

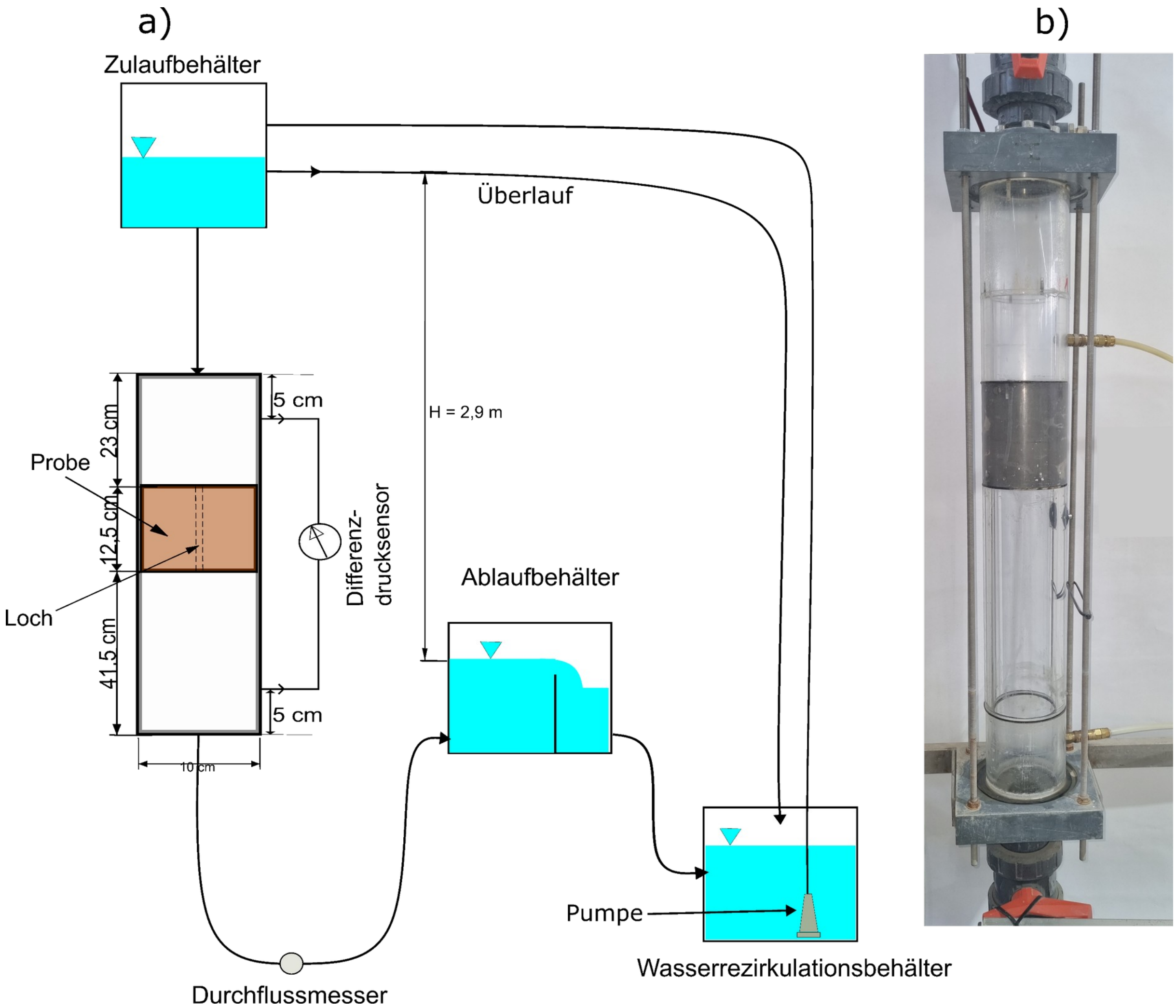

Figure 7: Modified HET. (a) sketch of the test system (b) photo of the test cell with mounted sample.

Zulaufbehälter	Feed tank
Überlauf	Overflow
Ablaufbehälter	Drainage tank
Pumpe	Pump
Wasserrezirkulationsbehälter	Water recirculation tank
Durchflussmesser	Flow meter
Probe	Sample
Loch	Hole
Differenzdrucksensor	Differential pressure sensor

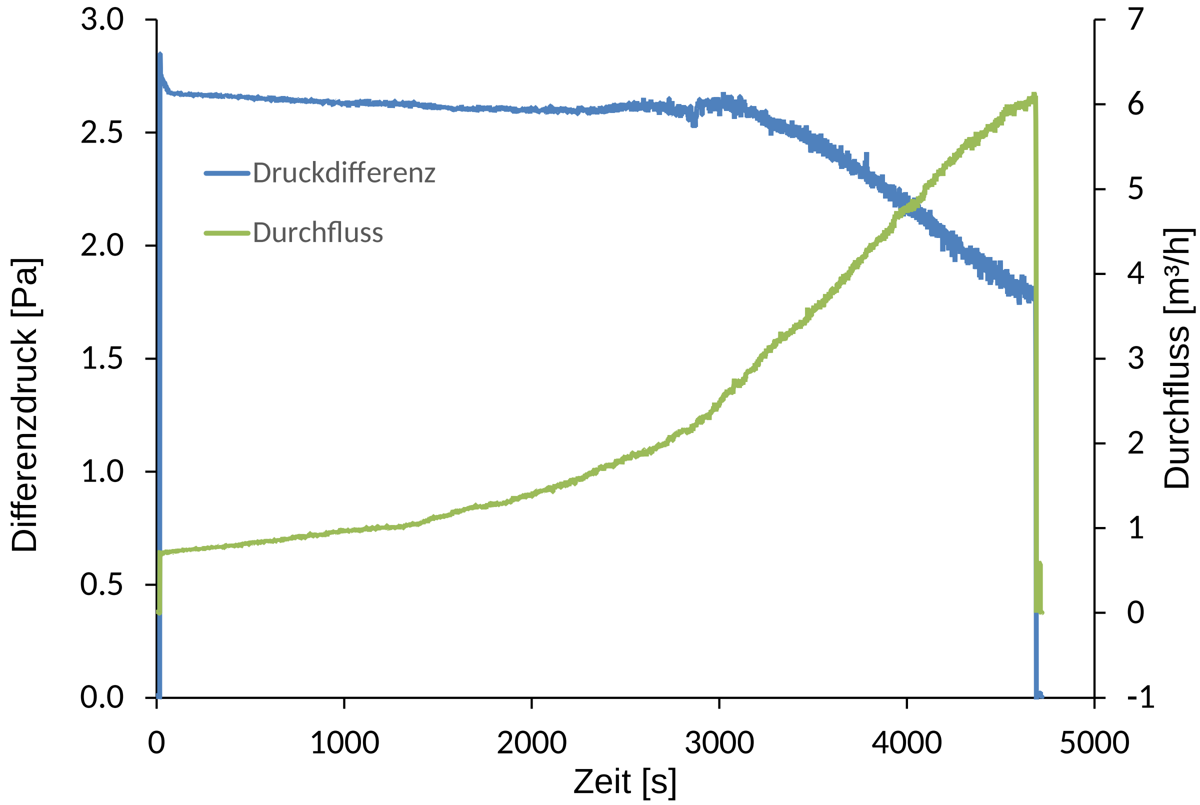

Figure 8: Measurement data from a HET on a tested sealing clay.

Differenzdruck [Pa]	Differential pressure [Pa]
Zeit [s]	Time [s]
Durchfluss [m^3/h]	Flow rate (m^3/h)
Druckdifferenz	Pressure difference
Durchfluss	Flow

4.5.4 Sample preparation

Before the test specimen is produced, the sealing material must be prepared in accordance with the conditions that will prevail during subsequent seal installation and in accordance with the requirements of ZTV-W LB 210 (2025) for undrained shear strength. This is c_u = 15–25 kPa for underwater construction and $c_u \leq 50$ kPa for dry construction. The HET-tests should be carried out at shear strengths of approximately $c_{,u}$= 20 kPa and approximately $c_{,u}$= 50 kPa. Three HET test specimens per shear strength shall be prepared and tested.

The sample is installed in three layers, which are compacted in the sample cylinder with the help of the Proctor hammer (a).Figure 9 After compaction, a continuous opening with a diameter of 8 mm is created. For this purpose, a copper tube guided with two PVC plates, as shown in Figure 9b, is pressed into the sample. A plexiglass ring is then placed on the underside of the sample to support the sample (Figure 9c). This ring sits on the sealing of the test cell, preventing the sample from slipping (Figure 9d).

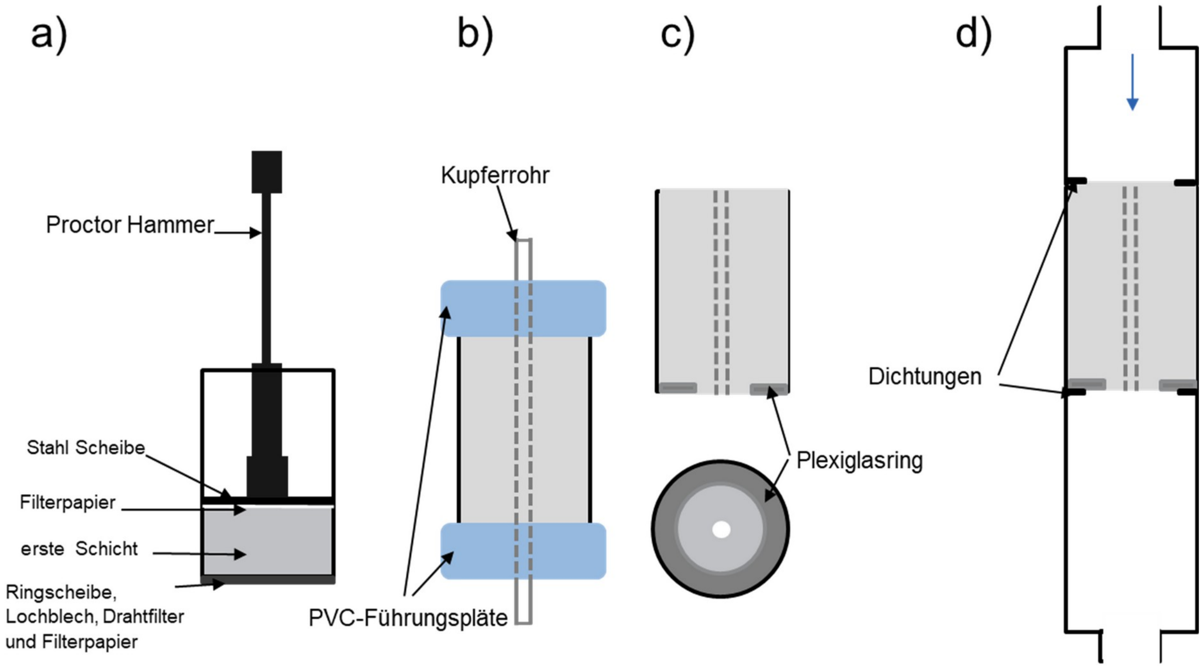

Figure 9: *Sample mounting: (a) compaction, (b) hole making, (c) plexiglass ring insertion and (d) mounting of the sample cylinders on the test cell (modified by Zaid et al. 2022).*

Proctor Hamme	Proctor hammer
Stahl Scheibe	Steel disc
Filterpapier	Filter paper
Ringscheibe, Lochblech, Drahtfilter und Filterpapier	Ring disc, perforated plate, wire filter and filter paper
Kupferrohr	Copper tube
PVC-Führungspläte	PVC guide rails
Plexiglasring	Plexiglass ring
Dichtungen	Seals

4.5.5 Test procedure

After the sample is mounted, the test cell is slowly and gently filled with water to avoid damage to the sample body. After this, the test, i.e. the flow, can be started. During the test, both the flow rate and the pressure difference between above and below the sample body shall be continuously measured. To this end, the pressure measurement points must be positioned at a sufficient distance from the specimen so that uniform flow can be established within the test cell across the entire cross-section. In the test design chosen in the BAW, this occurs at about 18 cm above the inlet and about 35 cm below the outlet of the sample body. Where possible, flow should be maintained until a flow rate of 6 m^3/h is reached to achieve sufficient widening (approx. d = 2–3 cm) of the flow channel without the specimen breaking down completely.

To determine the final hole diameter, the test specimen must be removed from the test cell. The flow channel is then filled with plaster (Figure 10a). A 3D model is then created from the plaster impression using a 3D scanner (b).Figure 10 Using this model, horizontal cross-sections are determined for different depths, and the corresponding areas (A_h) are calculated from these. The respective hole diameter $\varnothing_h$ is given by the equation (6). The final hole diameter $\varnothing_f$ is derived from the mean value of all calculated hole diameters $\varnothing_h$ from the cross-sections examined.

$$\varnothing_h = \sqrt{\frac{4\,A_h}{\pi}} \tag{6}$$

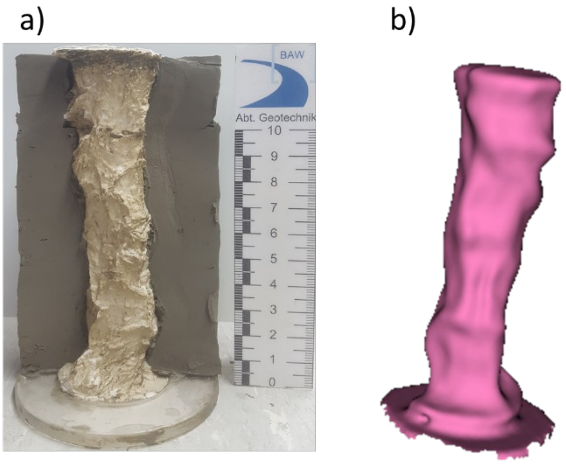

Figure 10: *Determining the hole diameter (a) photo of plaster cast, (b) 3D model of hole (Zaid and Stelzer 2023).*

4.5.6 Test evaluation

The criterion for assessing erosion resistance is the relationship between the wall shear stress at the flow channel (hole wall) and the erosion rate (hole enlargement) during the flow process. Both parameters are determined by the variable hole diameter $\varnothing_t$ during the test. As part of the investigations carried out at the BAW by Zaid et al. (2022), it was demonstrated that a linear correlation between the hole diameter and the flow rate can be assumed (Figure 11). The diameter $\varnothing_t$ is therefore calculated according to equation (7). The relationship between the two variables is shown in Figure 12.

$$\varnothing_t = \varnothing_i \left(\frac{\varnothing_f - \varnothing_i}{Q_f - Q_i} \right) \left(Q_t - Q_i \right) \tag{7}$$

$\varnothing_t$ hole diameter at time t
$\varnothing_t$ initial hole diameter (0.08 m)
$\varnothing_f$ final hole diameter (m)
Q_t flow rate at time t (m^3/s)
Q_i initial flow (m^3/s)
Q_f final flow (m^3/s)

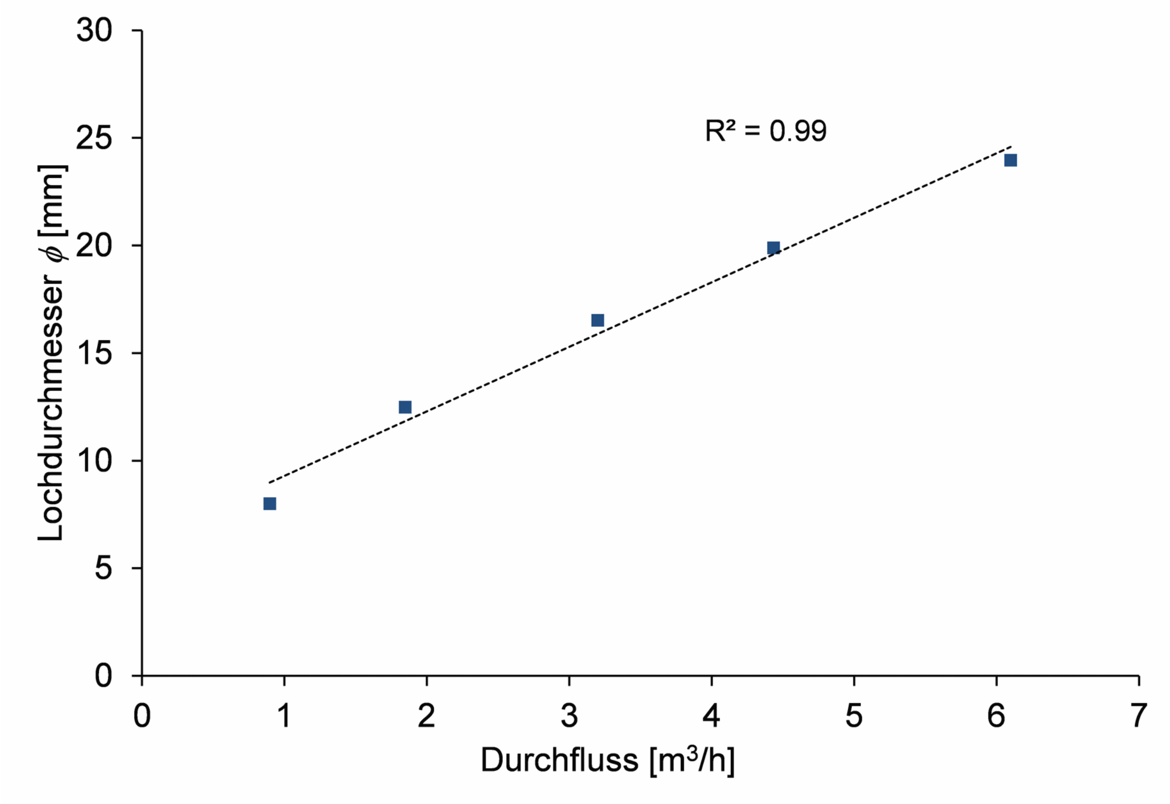

Figure 11: *Hole diameter Ø = f(Q) (from Zaid et al. 2022).*

Lochdurchmesser Ø [mm]	Hole diameter Ø [mm]
Durchfluss [m^3/h]	Flow rate (m^3/h)
Zeit [s]	Time [s]

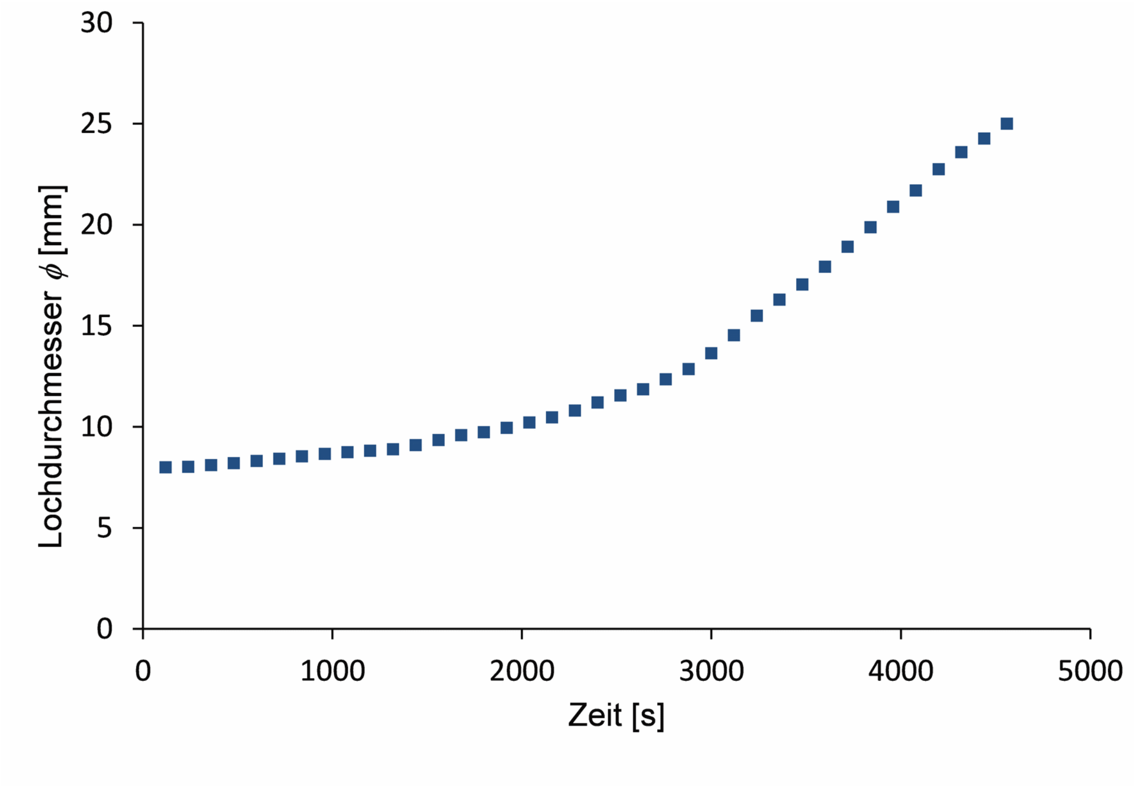

Figure 12: *Hole diameter Ø = f(t) of a tested sealing clay.*

After determining the temporal course of the hole diameter, the temporally variable erosion rate $\dot{\varepsilon}$ in mm/h can be (8) calculated according to equation (Figure 13).

$$\dot{\varepsilon} = \frac{d\varnothing}{dt} \tag{8}$$

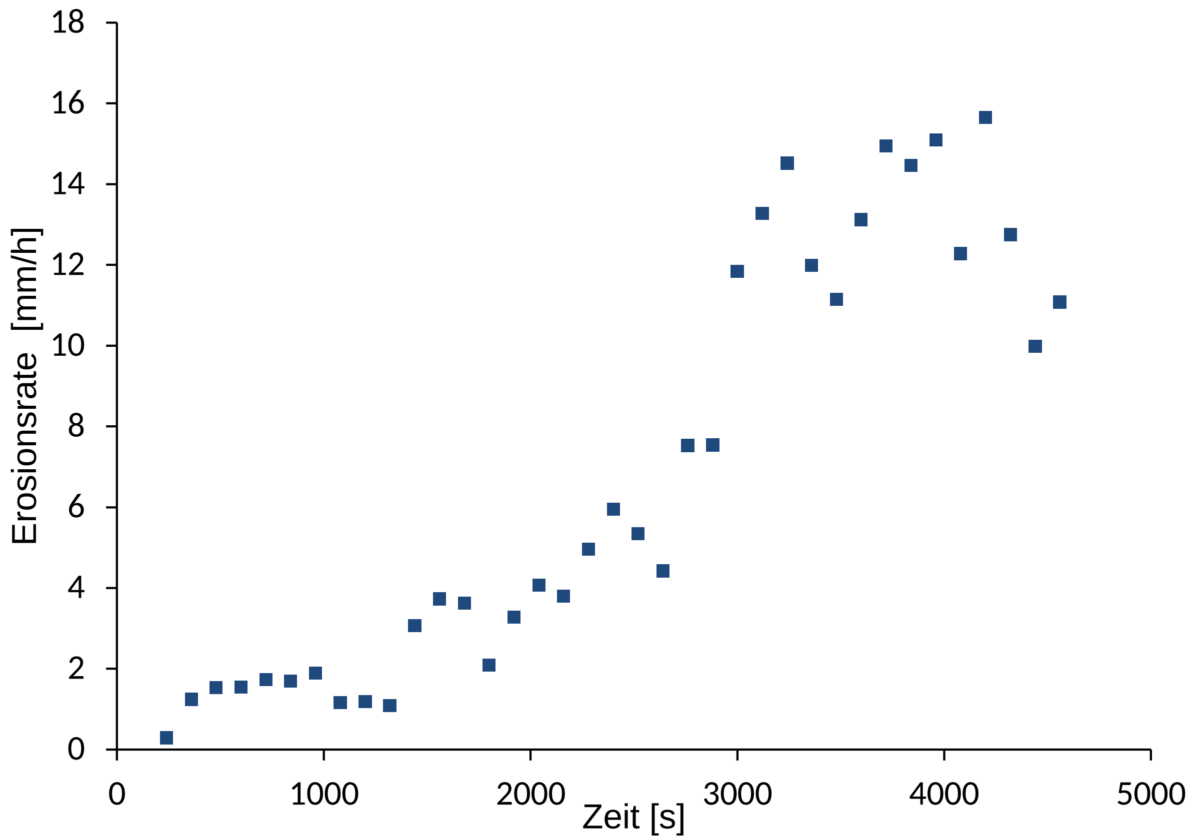

Figure 13: Erosion rate $\dot{\varepsilon}$ = f(t) of a tested sealing clay.

Erosionsrate [mm/h]	Erosion rate [mm/h]
Zeit [s]	Time [s]

The wall shear stress τ_t at time t is calculated according to equation (9) (Figure 14).

$$\tau_t = \rho_w \cdot g \cdot \frac{\varnothing_t}{4} \cdot \frac{\Delta H_{eff,t}}{L} \tag{9}$$

ρ_w Water density (kg/m^3)
g Acceleration due to gravity (m/s^2)
$\varnothing_t$ Hole diameter at time t (m)
L Sample length (m)
$\Delta H_{eff,t}$ is the effective pressure difference between above and below the sample

The effective pressure difference is calculated taking into account the local hydraulic losses that occur at the inlet and outlet of the flow channel (m). These are calculated using the equation (10).

$$\Delta H_{eff} = h_t - \left[K_{On} \frac{v_t^2}{2 \cdot g} + K_{Off,t} \frac{v_t^2}{2 \cdot g} \right] \tag{10}$$

h_t measured pressure difference between above and below the sample at time t (m)
K_{Ein} Loss coefficient at inlet
$K_{Aus,t}$ Loss coefficient on outlet
g Acceleration due to gravity (m/s^2)
v Average velocity at time t , in m/s, according to the equation (11)

$$v_t = \frac{4 . Q_t}{\pi . \varnothing_t^2} \tag{11}$$

Q_t Flow rate at time t (m^3/s)
$\varnothing_t$ Hole diameter at time t (m)

Since the inlet opening is usually rounded a few minutes after the start of the test, the inlet loss coefficient (K_{Ein}) according to White (2011) can be set at K_{Ein} = 0.05. The losses at the outlet are significantly greater and can be estimated using White's (2011) equation (12) (Zaid et al. (2023)) as follows:

$$K_{Off,t} = \left[1 - \frac{\varnothing_t^2}{\varnothing_{Cyl}^2} \right]^2 \tag{12}$$

Where $\varnothing_t$ = hole diameter at time t (m),
$\varnothing_{Cyl}$ = diameter of test cell below the sample (m).

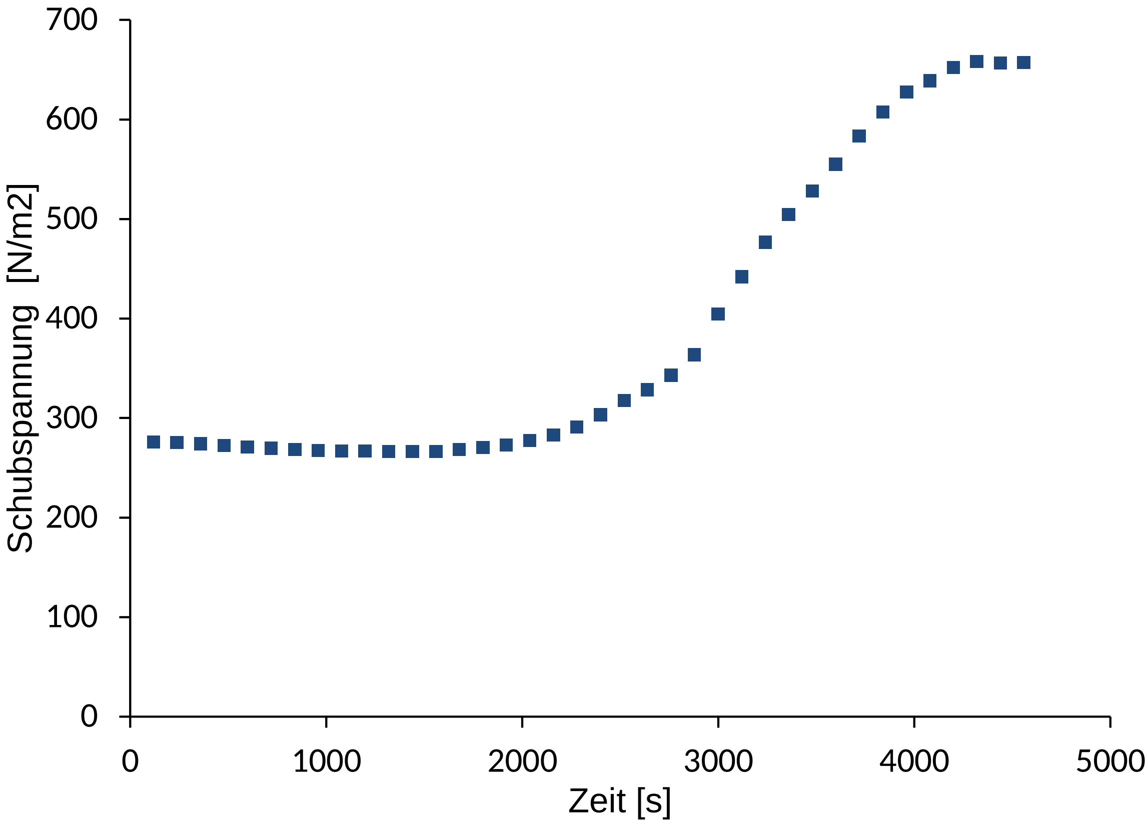

Figure 14: Shear stress τ = f(t) on the perforated wall of a tested sealing clay.

Schubspannung [N/m2]	Shear stress [N/m2]
Zeit [s]	Time [s]

4.5.7 Evaluation of erosion stability

To assess the erosion stability and classify the sealing material under investigation, the erosion rates determined as a function of the corresponding wall shear stresses over time should be plotted on the classification diagram in a double-logarithmic scale, as described by Briaud et al. (2017). Six zones are defined within this diagram, each representing a different degree of susceptibility to erosion (zones I to VI). The BAW has stipulated that only clays corresponding to classes IV–VI in Figure 15 (zones highlighted in green) are permitted.

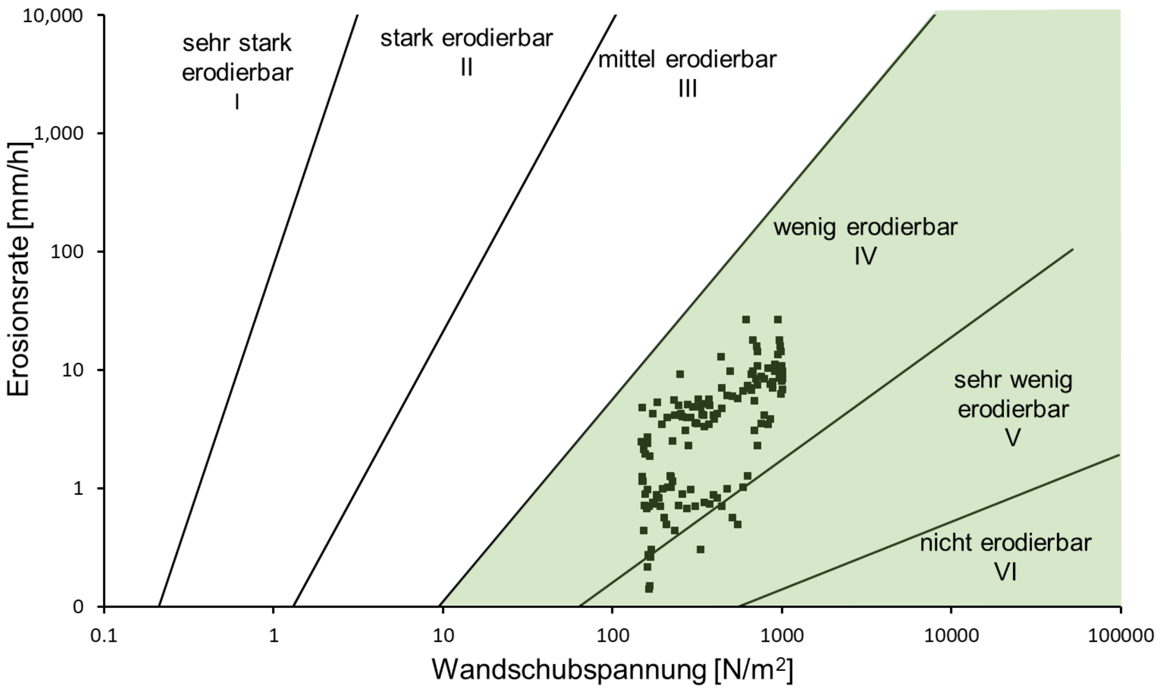

Figure 15: Erosion diagram for classifying clays according to their erosion susceptibility (adapted from Briaud et al. 2017) with an example of a tested sealing clay.

Erosionsrate [mm/h]	Erosion rate [mm/h]
sehr stark erodierbar	very highly erodible
stark erodierbar	highly erodible
mittel erodierbar	moderately erodible
wenig erodierbar	slightly erodible
sehr wenig erodierbar	very resistant to erosion
nicht erodiebar	not erodible

4.6 Flexibility test (beam bending test)

4.6.1 General

Sealing materials made from natural clay and duroplastic seals composed of clay and hydraulic binders are to be tested. For the latter, the test shall be carried out after a setting time of 28 days. The beam bending test is used to assess the flexibility of sealing materials. For GCL, it can be assumed that there is sufficient flexibility without the need for evidence.

4.6.2 Project design and procedure

A test specimen measuring 50 cm × 10 cm × 10 cm is produced in a rectangular mould, with a consistency and density corresponding to the conditions under which it will subsequently be installed. The finished test specimen must not have any inhomogeneities or cracks on its underside; otherwise, the specimen must be rejected.

The test specimen (bending beam) is removed from the mould and placed on a test frame (see Figure 17), the support points of which are 40 cm apart. Beforehand, a non-woven fabric is placed on the underside of the beam and several thin, highly flexible sheets (d = 0.7 mm) are laid over the support points in order to 'impose' a controlled bending line on the beam during the subsequent bending process and to minimise the risk of cracks forming at the support points.

To prevent the beam from sagging under its own weight before the test actually begins, it is first supported at the centre by an adjustable lifting platform.

A pressure cushion is placed on the top of the beam and fixed to the frame with screws. The pressure cushion can be inflated by hand with air and is used to apply a uniform distributed load to the bending beam. Figure 16 and Figure 17 show the structure of the measuring apparatus.

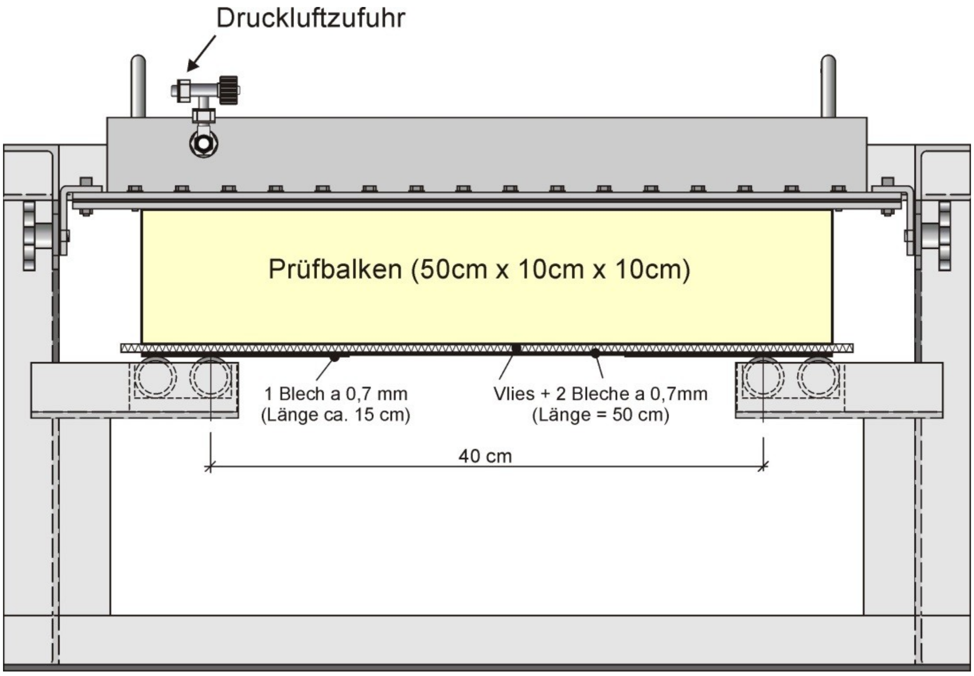

Figure 16: Construction of the measuring apparatus – dimensional sketch.

Prüfbalken	Test beam
Blech	Plate
Vlies + Bleche	non-woven + plates
Länge	Length

Figure 17: Design of the measuring apparatus (without pressure pad) – photo.

Once a dial gauge has been fitted in the centre of the beam, it is set to zero. The test begins by removing the support at the centre of the beam by slowly lowering the lifting platform. As a result of the now effective net weight of the specimen, the beam begins to bend. Once a quasi-stable state has been reached (slight creepage of the beam is neglected), the deformation is photographically documented and any cracking is recorded. To increase the deflection of the beam, compressed air is carefully applied to the air cushion on the top of the beam using a hand pump. The pumping should be completed within 60 s. The deformation of the underside of the beam should be monitored with the dial gauge. Once the sample has been lowered to a position in the centre of the beam at f = 20 mm, the beam must be inspected again for cracks (on both the front and rear sides). The condition of the beam must be documented; any cracks that may have formed must be recorded, along with their depth and length.

4.6.3 Analysis of test results and limit values

A material is considered sufficiently flexible for a soft seal if it can accommodate a substrate deformation with a flank slope of 1:10 or steeper without harmful cracking (EAO 2002). For the bending test, this means that the specimen (support span 40 cm) must accommodate a deformation of f = 20 mm at the centre of the beam. Any cracks occurring on the tension side must not extend into the material to a depth of more than one-third of the beam’s height. Figure 18 shows an example of an inadmissible crack formation at 20 mm deflection.

If no cracks are detected at the bottom of the sample after the deformation of f = 20 mm, the lowering in the centre of the beam can be continued for further qualitative estimation of the deformation behaviour until the maximum possible deflection or the maximum permissible crack depth is reached.

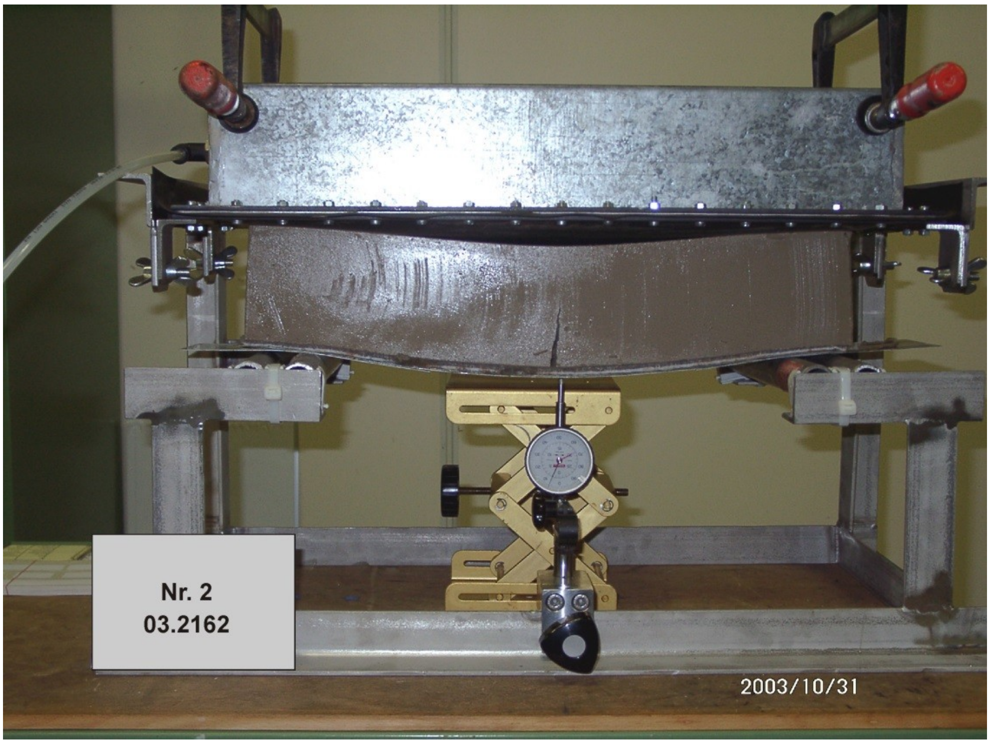

Figure 18: Material sample after 20 mm deformation: unallowable cracking.

4.7 Rinse-off test

4.7.1 General information

Duroplastic seals with clay and hydraulic binders installed under water are to be tested. If the sealing material falls freely through the water during mounting, it must be sufficiently resistant to the erosion that occurs as a result. This is checked with the rinse test. During the test, the sealant is passed three times through a 1 m high water column in a sieve basket, and the mass loss of the sample is then determined.

4.7.2 Project design and procedure

The test device (Figure 19) corresponds to the one according to RPV (2026) and consists of a 120 cm high plexiglass cylinder (Ø = 20 cm), which is filled with water up to a height of 100 cm. The sieve basket with lid has a diameter and height of 13 cm and is made of perforated sheet metal with a hole diameter of 3 mm. The basket is fitted with a 2.7 kg weight that can be detached. The sieve basket can be pulled completely out of the water cylinder by the weight using two pulleys.

2000 g of sealant is poured into the sieve basket in accordance with the installation conditions, compacted by tapping lightly, and weighed. The sieve basket is then attached, placed on the water surface and released so that it falls through the 1 m high water column in free fall. The weight is then attached, and the sieve basket is raised evenly by the weight. This process is repeated twice. The mass of the sealing mass remaining in the sieve basket is then determined.

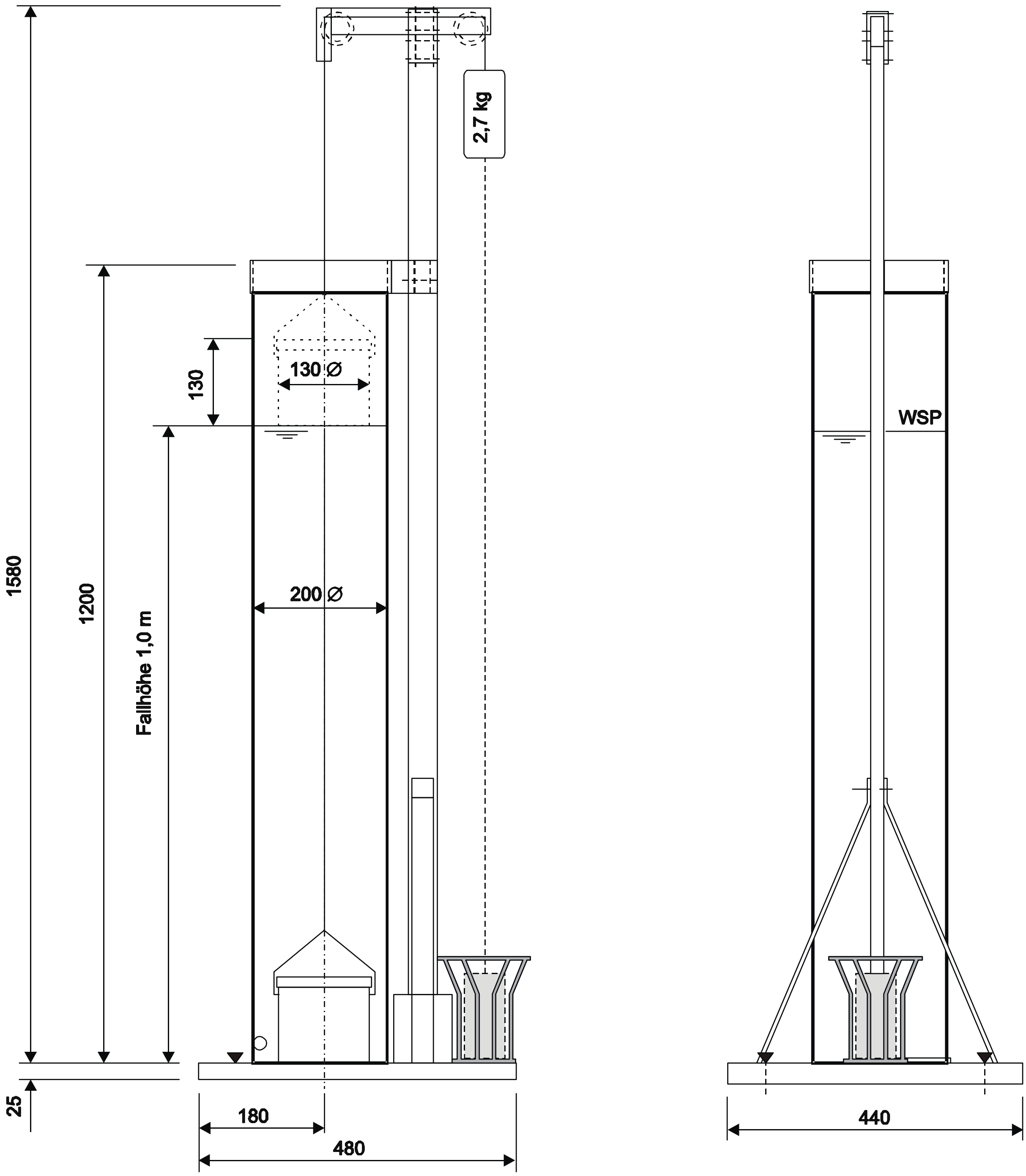

Figure 19: Test device for the rinsing test (graphic representation).

4.7.3 Analysis of test results and limit values

Based on the mass difference, the mass loss of the sealing mass is calculated in percent. The sealing compound has a sufficiently high resistance to erosion if the mass loss is less than 6 per cent.

4.8 Turbulence test

4.8.1 General information

Geosynthetic clay liners (GCL) shall be tested.

The test is designed to assess the erosion resistance of bentonite enclosed within geotextiles when subjected to turbulent external flow condition.

The test procedure simulates the turbulent flow around the GCL, such as that caused by ship waves or a propeller wake. However, as the GCL specimen is installed upside down in the test – contrary to natural conditions – and is subjected to stress from that position, the test procedure yields results that err on the side of caution.

4.8.2 Project design and procedure

The test equipment (see Figure 20) corresponds to that for the turbulence test according to RPG (2026), where the detailed test design is shown and described. The sample containers are firmly connected to the test frame via the brass tube screwed centrally into the Plexiglas lid, and the pipe is used to vent or equalise pressure in the sample container during the test. The static water level in the water tank is adjusted using the millimetre scale on the Plexiglas front panel. The 4-blade turbulence vane generates a turbulent flow around the GCL probe at 260 rpm.

Three test specimens, each with a diameter of 168 mm, are punched out of the sample to be tested and installed in separate specimen containers, with the top surface facing downwards. The test specimen is then sealed with the top cover and left to saturate for 48 hours in drinking water at a temperature of 20±5 °C, with a water depth of 20 cm. The test specimen should be immersed at an angle to prevent air pockets forming beneath the GCL. After this swelling process of the GCL without load, the test specimen is reopened, and 1,500 g of 5/8 aggregate is loosely poured and evenly distributed within the specimen using an adjustable installation gauge.

A brass disc weighing 2130 g and measuring 151 mm in diameter is applied as a load, so that the GCL is subjected to a surface pressure of 2 kN/m^2. The test specimen is then closed again.

The test container is filled with drinking water to a height of 20.5 cm. The water temperature of the test containers is measured at the beginning and end of the test. The sample container is transferred directly from water storage into the test container. To do this, air must be prevented from becoming trapped under the test surface by immersing it at an angle. Using a spacer 3 cm high between the lower edge of the sample container and the upper edge of the vane, the sample container is positioned at the correct height and clamped to the test frame. The spacer shall be removed for testing.

Turbulent flow over the samples is maintained for 96 hours. The samples are then carefully removed, samples of 10 cm diameter are punched out and the water permeability of the GCL is tested in accordance with Section 4.2.

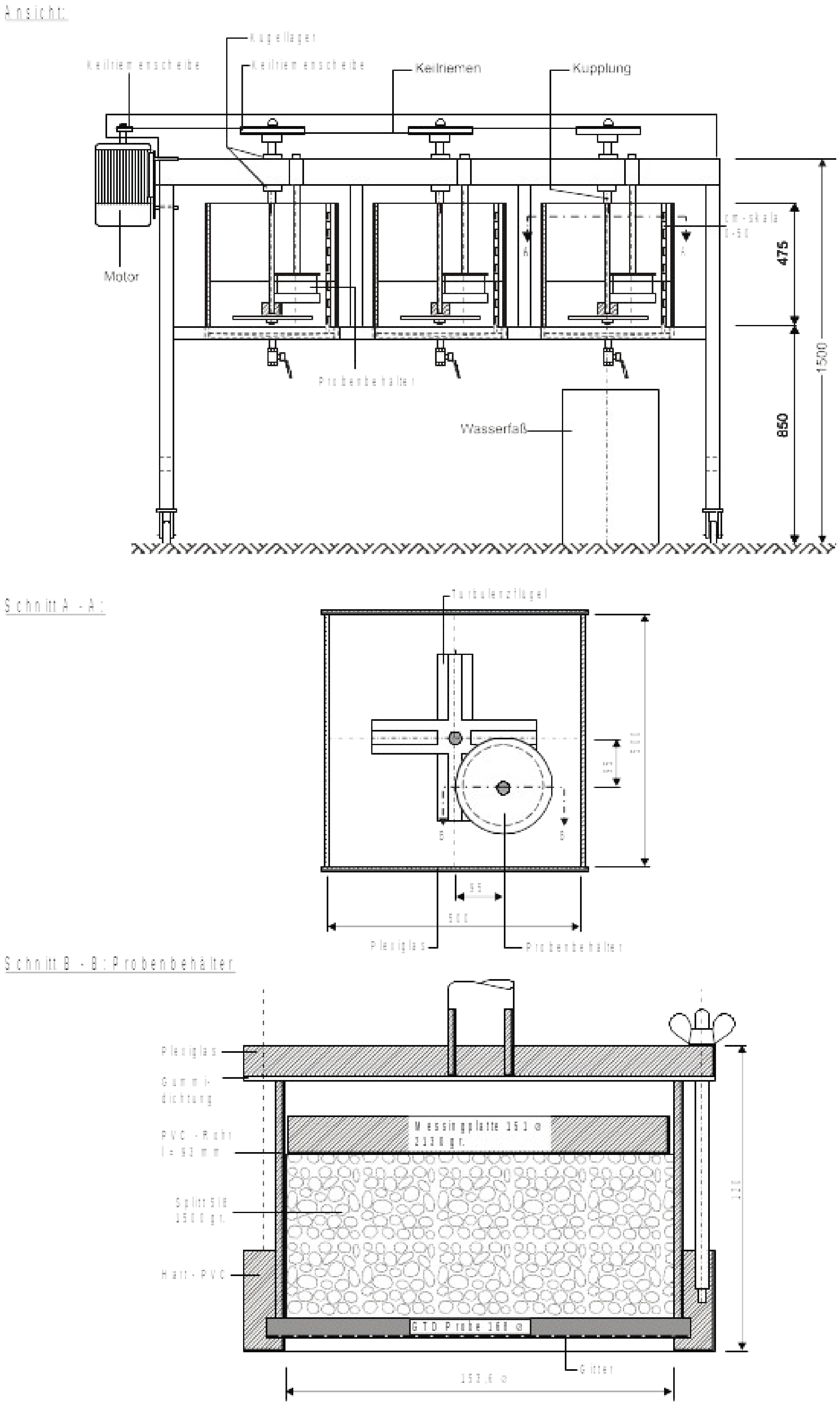

Figure 20: Test device according to RPG (2026) or DIN EN ISO 10772:2012-12)) for the determination of erosion stability of a GCL (graphic representation).

Ansicht	View
Keilriemenscheibe	V-belt pulley
Motor	Engine
Kugellager	Ball bearings
Keilriemen	V-belts
Kupplung	Coupler
Probenbehälter	Sample containers
Wasserfaß	Water barrel
cm-skala	cm scale
Schnitt A-A	Cross-section A-A
Turbulenzflügel	Turbulence vane
Plexiglas	Plexiglass
Schnitt B-B Probenbehälter	Cross-section B-B sample container
Gummidichtung	Rubber sealing
PVC – Rohr	PVC – tube
Splitt 5/8	Grits 5/ 8
Hart – PVC	Hard – PVC
Messingplatte	Brass plate
GTD Probe	GCL sample

4.8.3 Analysis of test results and limit values

The water permeability of the GCL samples must not exceed, following exposure to turbulence, the maximum permissible increase under service conditions as specified in point 4.2.3. With a potential difference of 5 m relative to 1 cm sample thickness, this results in a maximum permissible water permeability of the GCL samples after the turbulence test of $k_{10} = 5 \cdot 10^{-10}$ m/s or a maximum permittivity of $\psi_{10} = 5 \cdot 10^{-8}$ 1/s.

4.9 Puncture resistance test

4.9.1 General information

Geosynthetic clay liners (GCL) shall be tested. The test method determines the puncture resistance of seals against shock or impact loads, as can occur in type and magnitude during placement of hydraulic engineering blocks.

Based on experience, proof of resistance to dynamic perforation for natural clay seals with undrained shear strength is not required when installing c_u = 15 to 25 kN/m^2 and an installation thickness of at least 20 cm. For duroplastic seals with clay and hydraulic binders, the penetration test may also be waived with a normal and drained internal shear strength of c_u = 5 to 10 kN/m^2 and an internal thickness of at least 20 cm. This presupposes that the seal is protected by a geotextile or a granular filter (a filter made of rock aggregates) during the installation of the hydraulic structures.

The test procedure described below for the GCL shall be applied by analogy to other sealing materials, as appropriate.

When testing GCL, it is necessary to distinguish whether the seal is to be installed in dry or wet conditions.

<u>Dry installation of the GCL means</u>: The bentonite mat is not laid under water. It remains dry during installation and when covered with hydraulic engineering blocks; the bentonite has not swollen. It must be protected from adverse weather conditions (e.g. heavy rain).

In this case, only the puncture resistance of the geotextiles enclosing the bentonite is decisive for the GCL. Redistribution of the bentonite stored between layers is minimal whilst it is unswollen, and is largely offset when the bentonite swells. To test puncture resistance, in the same way as for testing geotextiles in accordance with RPG (2026), the rammer is dropped onto the test specimen with a defined impact energy in accordance with Table 2; the specimen rests on a defined test base and is secured at its edge with a defined clamping force. The test provides a yes/no statement on the puncture resistance of GCL by visual inspection for damage to the geotextiles enclosing the bentonite at the end of the test.

Underwater installation of the GCL means: installation and backfilling with hydraulic engineering blocks take place underwater; the GCL has already swollen by the time the backfilling begins, which is carried out from the backfilling scaffold at the water's surface. In this case, the behaviour of the GCL with swollen bentonite filling is examined in the test during backfilling. The bentonite filling must not be pushed aside laterally by the impact of the hydraulic blocks (or, in the case of the drop test, by the rammer) to such an extent that its sealing function is significantly impaired. In order to assess this, following the loading of the GCL with the rammer, the water permeability of the test specimen is tested by visual inspection in accordance with Section 4.2, in addition to a visual inspection for damage to the geotextiles enclosing the bentonite.

In the case of underwater installation ('installation in wet conditions') of the GCL, the hydraulic blocks in the water exchange area are generally laid from land using excavators. The results of the penetration test with the fall energies according to Table 2 for installation in wet conditions can only be transferred to the water change area if the hydraulic engineering blocks are placed on the GCL and are not ejected from 2 m height. Otherwise, the penetration test must be carried out using the drop weights specified for installation in dry conditions.

4.9.2 Project design and procedure

The test facility – shown in Figure 21 – consists of

- a 4-column tubular steel frame with a central 2-column rammer guide,
- a steel rammer with a defined cutting edge,
- an electric motor for lifting the rammer,
- an electromagnet for attaching and disconnecting the rammer,
- a hydraulic system for lifting the 4-column tubular frame to allow the installation and removal of test specimens,
- a hydraulic system for clamping the test specimen with a defined clamping pressure of 12.2 N/cm^2 during the test,
- a trolley for holding the sand bed and the test sample, with a base area of 80 cm by 80 cm and a depth of 31 cm.

The fall energy relevant to the test procedure depends on the size, mass and installation method of the hydraulic engineering blocks used. Depending on the stone class as defined in TLW (2022), a different reference stone size or stone mass applies, which must form the basis of the test. In the light weight classes (LMB) according to TLW (2022), an oversize grain content of up to 30 per cent is permitted, where individual oversize stones may weigh twice as much as a stone at the upper class limit. For this reason, in the lighter weight classes, twice the mass of the upper class limit is taken as the standard stone mass.

For the drop energy approach, two cases are distinguished depending on the type of installation:

- For installation in dry conditions, the impact energy is calculated as that generated by the representative stone of the relevant stone class when it falls freely through the air from a height of 2 metres and strikes the GCL.
- For underwater installation, the potential energy is taken to be that possessed by the representative stone of the stone class used when backfilling the GCL from the water's surface. This fall energy is determined by the maximum sinking velocity of the respective stone, as established by Knieß (1981).

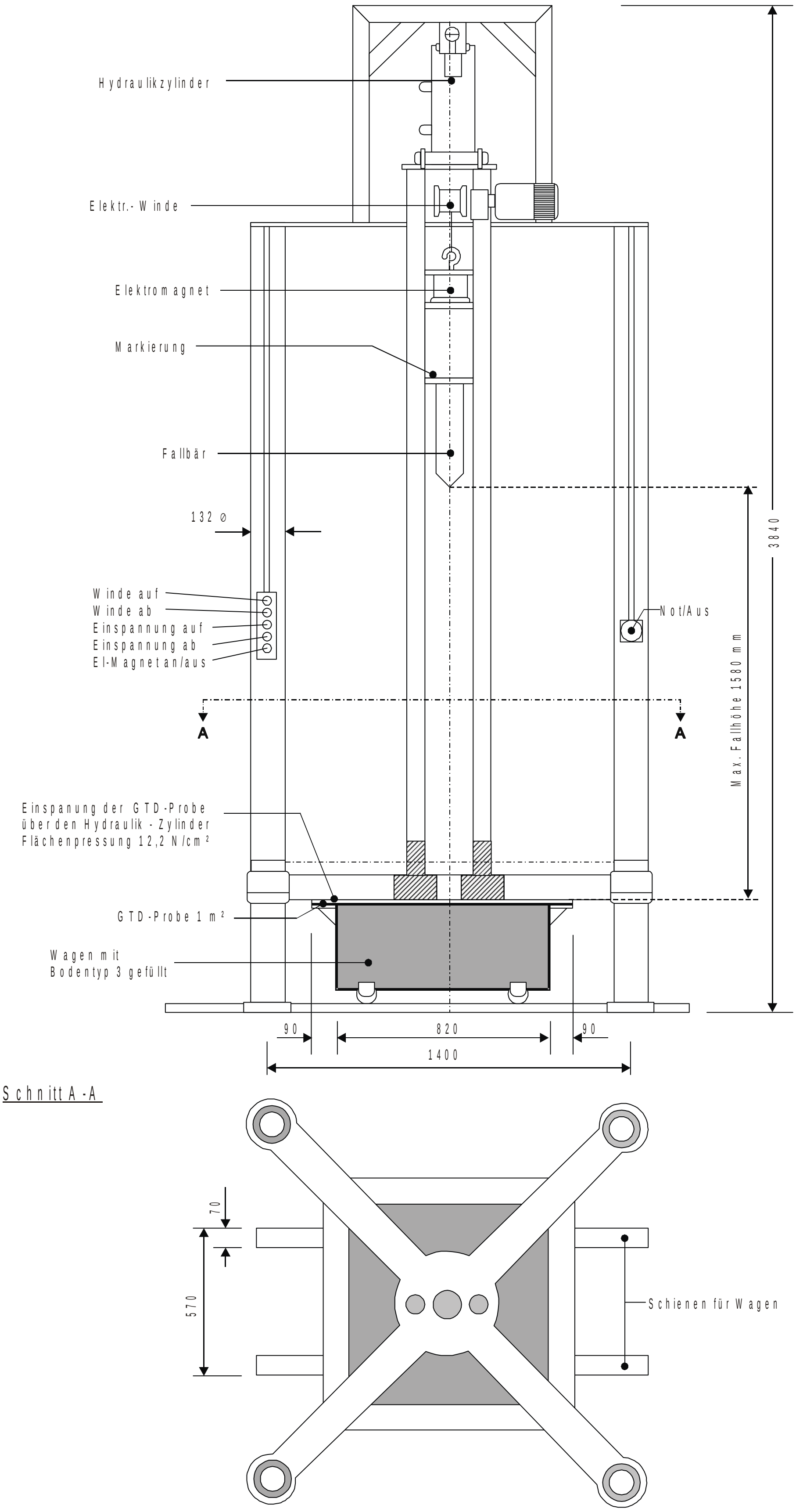

Figure 21: Testing apparatus for determining resistance to dynamic perforation in accordance with RPG (schematic diagram).

Hydraulikzynlinder	Hydraulic cylinder

Elektr.- Winde	Electric winch
Elektromagnet	Electromagnet
Markierung	Marking
Fallbär	Rammer
Winde auf	Hoist the winch
Winde ab	Lower the winch
Einspannung auf	Clamp engaged
Einspannung ab	Clamp released
El/Magnet an/aus	El/Magnet on/off
Einspannung der GTD-Probe über den Hydraulik-Zylinder Flächenpressung 12,2 N/cm^2	Clamping of the GCL probe via the hydraulic cylinder; surface pressure 12.2 N/cm^2
Wagen mit Bodentyp 3 gefüllt	Wagon filled with soil type 3
Not/Aus	Emergency shut-down
Max. Fallhöhe	Maximum drop height
Schnitt A-A	Cross-section A-A
Schienen für Wagen	Rails for wagons

For the most common stone classes according to TLW (2022), the corresponding fall energy is set out in Table 2. Unlike the testing of geotextiles in accordance with RPG (2026), when testing GCL, the largest or heaviest stone in the relevant stone class – taking into account the proportion of oversized particles – is the determining factor for the test, as any unacceptable damage to the GCL can lead to local failure of the seal. The decisive fall energy for a larger stone class may have to be calculated analogously to this procedure.

The dynamic perforation resistance test shall be carried out at room temperature on at least 3 (for dry installation) or at least 5 (for wet installation) square samples with an edge length of 100 cm each. When testing for installation in wet conditions, the samples must be stored under water for 24 hours before the test is carried out.

For the standard test, a dry soil of soil type 3, as defined in the technical note ‘Application of geotextile filters on waterways’ (MAG (2021)), is used as the test substrate. The test result cannot be extrapolated to soils that are significantly coarser-grained or firmer; however, as an alternative to the standard procedure, a representative soil sample may be placed in the cart. The test soil is placed into the trolley outside the test frame, compacted to a medium density by tamping, and finally levelled off so that it is flush with the top edge of the trolley. The dry or swollen specimen is placed on the test base with the designated underside facing downwards, such that the direction of the determined lower maximum tensile force (longitudinal or transverse) forms a right angle with the longitudinal axis of the cutting edge of the rammer.

The prepared sample trolley is positioned under the test frame in the test position, and the sample’s edge clamping is secured. The rammer is driven up to the required drop height, activated for testing and then secured in a resting position.

When testing for installation in wet conditions, where the bentonite has already swelled by the time the hydraulic engineering blocks are laid, an additional assessment is carried out to check for any unacceptable crushing of the soft bentonite in the impact area. To this end, two samples, each 10 cm in diameter, are punched out from the point on the rammer with the smallest radius of curvature (Figure 22) and the water permeability is tested in accordance with Section 4.2.

Table 2: Required impact energies for the perforation test.

Stone class according to TLW 2022	Rock density	Maximum sieve diameter	Maximum stone mass	Longest edge length of the largest stone	Required impact energy for the installation test	
	ρ_s	D	G	L	in dry conditions	in wet conditions
CP $_{90/250}$	2650 kg/m³	36 cm	80 kg	56 cm	1600 Nm	510 Nm
	3000 kg/m³	36 cm	90 kg*	56 cm	1800 Nm	710 Nm
CP$_{90/250}$ without oversize particles	2650 kg/m³	25 cm	30 kg*	39 cm	600 Nm	120 Nm
	3000 kg/m³	25 cm	30 kg*	39 cm	600 Nm	170 Nm
LMB $_{5/40}$	2650 kg/m³		80 kg	56 cm	1600 Nm	510 Nm
	3000 kg/m³		80 kg	54 cm		610 Nm
LMB$_{5/40}$ without oversize particles	2650 kg/m³		40 kg	45 cm	800 Nm	210 Nm
	3000 kg/m³		40 kg	43 cm	800 Nm	250 Nm

**Values after rounding*

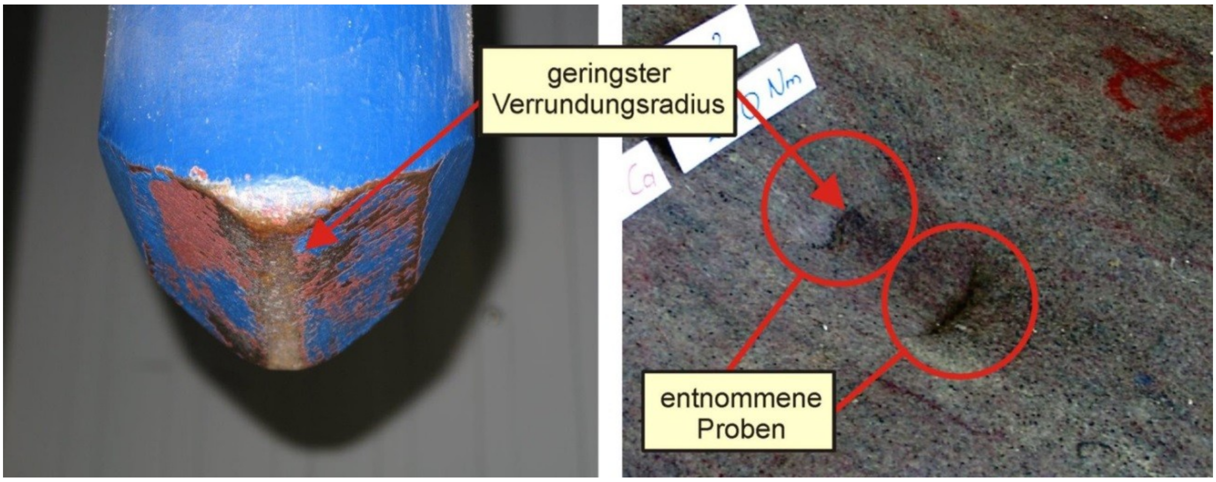

Figure 22: Edge of rammer and location of sample taken at the point on the rammer with the smallest radius of curvature.

geringster Verrundungsradius	smallest radius of curvature
entnommene Proben	samples taken

4.9.3 Analysis of test results and limit values

The sample is inspected for visible damage both before and after mounting. Damages are holes and all changes that indicate a reduction in filter stability and strength (including damage to weft or warp threads, thread shifts, fibre displacements) and to the sealing function (extrusion of bentonite). The stress must only cause a negligible amount of bentonite to be forced through the geotextile.

Furthermore, in tests for underwater installation, the water permeability of the punched GCL samples must not exceed the maximum permissible increase in the required water permeability coefficient, as specified in Section 4.2.3, when the material is in as-used condition. At a potential difference of 5 m relative to 1 cm sample thickness, this results in a maximum permissible water permeability of the GCL samples of $k_{10} = 5 \cdot 10^{-10}$ m/s or a maximum permittivity of $\psi_{10} = 5 \cdot 10^{-8}$ 1/s.

4.10 Determination of the permeability coefficient of GCL at elongation

Geosynthetic clay liners (GCL) shall be tested. The permeability of a stretched GCL is examined.

The GCL must not be designed for load transfer. Nevertheless, it can be stretched locally during installation and when water is poured over it. This elongation must not increase the permeability of the GCL to an unacceptable extent.

Permeability at elongation does not need to be determined separately. It is sufficient to determine the permeability of the GCL (k-value according to Chapter 4.2) in the area stretched during the puncture test (see Chapter 4.9). In the case of tests for underwater installation, the k-value is already determined as part of the perforation test (Chapter 4.9.2). In tests for installation in dry conditions, determination of the k-value following the perforation test is only required to demonstrate permeability under strain. For this purpose, the impact area is marked after the perforation test and the GCL sample is watered 24 hours before the k-value determination. With this result, it is possible to assess, with a high degree of certainty, the influence of strain on the permeability of the GCL in the waterway area. The limit values of the perforation test apply.

4.11 Determination of the permeability coefficient of GCL in overlapping areas

4.11.1 General information

Geosynthetic clay liners (GCL) shall be tested. The permeability in the overlap area of two GCL membranes shall be tested For this purpose, the intended structure of the overlapping areas must be known. The required k-value in the overlap areas can be ensured, for example, by using edges that have already been impregnated with bentonite at the factory (for underwater installation) or by coating the overlap areas with bentonite paste on site during dry installation. The test shall be carried out in accordance with the intended construction.

The general principles for testing permeability in the overlap areas are set out in the Recommendations for the Use of Geosynthetic Clay Liners (EAG-GCL (2002)), whilst the requirements are specified in the EAO (2002). In addition, the special features for testing in navigable waterways are described below. It should be noted that the GCL in the waterway is usually laid transversely to the channel axis and the hydraulic stress takes effect immediately after installation when laying under water at full height.

4.11.2 Project design and procedure

Figure 23 shows the test design for assessing the permeability of overlapping areas of the GCL.

The following boundary conditions shall be observed during mounting of samples and during the test:

- The test is carried out for the overlapping of the longitudinal side of the mat. Sufficient sealing at the transverse edges of the mats (the ends of the mats) must be ensured during mounting.
- The overlap during the test must not exceed 30 cm; smaller overlaps during the test are permitted. The greater overlap widths required in accordance with the regulations for installation in waterways provide a corresponding level of safety.
- The length of the overlapping area shall be at least 25 cm.

- The test should be carried out with pressure heights of 1 m water column and 5 m water column. The higher permeability coefficient is decisive. Depending on the specific project, other pressure levels may also be required.
- The load on the GCL shall not exceed g' = 6 kN/m^2 (under buoyancy).
- Coarse gravel shall be used as the base material on which the GCL is placed in the test cell. Coarse gravel or a coarse aggregate of rock shall be used as surfacing material.
- Any random variations must be systematically eliminated from the test design.
- Hydraulic stress during the test must be applied immediately after installation in the waterway, i.e. without prior swelling.
- In addition, for each test, the water content of the bentonite must be determined before and after the test; furthermore, water absorption must be determined in accordance with the Enslin method (DIN EN ISO 10769, DIN 18132). The installation and removal thickness of the GCL must be documented.
- The test must be continued until constant flow.

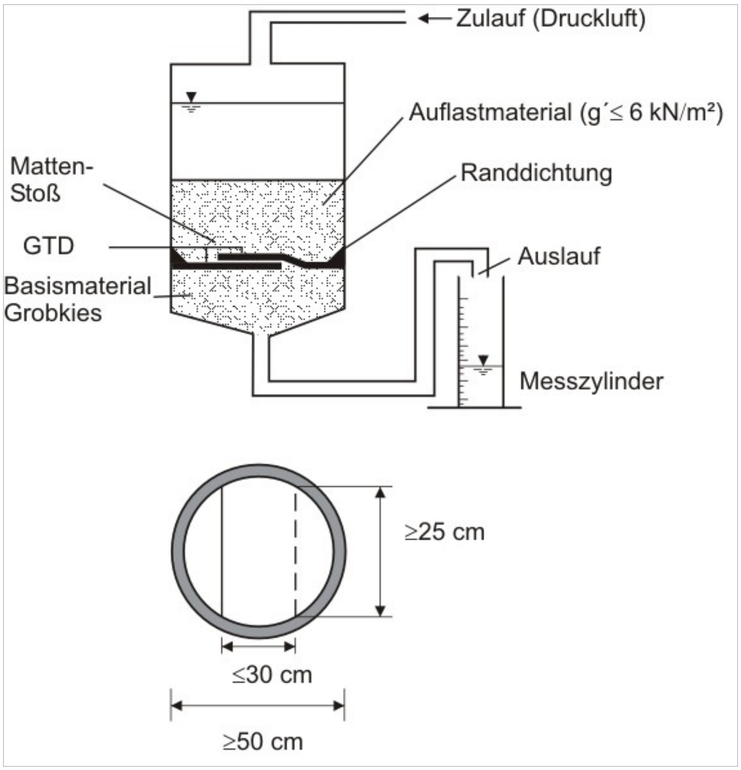

Figure 23: Experimental apparatus for testing the permeability of GCL overlapping areas (sketch).

Matten Stoß	Impact mat
GTD	GCL
Basismaterial Grobkies	coarse gravel base material
Zulauf (Druckluft)	inlet (compressed air)
Auflastmaterial	fill material
Randdichtung	Edge seal
Auslauf	outlet
Messzylinder	graduated cylinder

4.11.3 Analysis of test results and limit values

The permeability coefficient k_{10} of the overlap area is determined from the hydraulic gradient and the flow quantities measured per time unit. As with the calculation of permeability per unit area (see Chapter 4.2), the reference thickness here is the design initial thickness of the single GCL. Permittivity can be determined in the same way.

The permeability coefficient or permittivity must not be higher in the overlap region than in the main area (for limit values, see Section 4.2.3).

5 General suitability of underwater installation methods

5.1 Requirements for installation procedures

5.1.1 General information

The general practice of installing soft seals under water while maintaining navigation imposes particular requirements in terms of installation and laying techniques. The properties of the sealing materials must not be adversely affected by the conditions prevailing during installation and the subsequent construction stages (e.g. due to stretching during laying, settling or pumping caused by water, or backfilling with hydraulic engineering blocks). As the effectiveness of a seal depends not only on the sealing material but also, to a decisive extent, on the design of the connections, joints and seams, as well as overlaps, the installation method must, regardless of the quality of workmanship, provide a system-based safeguard against the occurrence of gaps (e.g. through appropriate overlaps between individual sheets).

In the following chapters 5.1.2 to 5.1.4 the basic requirements for the procedures for underwater installation of various soft seals are presented.

5.1.2 Natural clay seals

The natural clay must be prepared prior to installation so as to form a homogeneous seal that meets the requirements of ZTV-W LB 210 (2025).

The underwater installation procedure must ensure (EAO (2002)) that:

- an unbroken seal is formed,
- construction joints can be executed in a controlled manner,
- the specified layer thickness of the seal is maintained over the surface,
- the execution is not affected by sediment penetration.

To achieve a watertight joint, the installation process must ensure precise positioning of the individual sheets or panels. Overlaps shall be pressed to create a uniform surface. Blunt impacts should be avoided or carried out with great care (EAO (2002)). In addition, the procedure must ensure that no cracks occur (EAO (2002)).

5.1.3 Geosynthetic clay liners (GCLs)

The underwater installation of the GCL must be carried out similarly to the installation of geotextile filters by unrolling onto the bank and bed. Laying a GCL and a sand mat at the same time has proved effective as a means of providing immediate protection and ballast during underwater installation. The mats can either be laid on top of one another individually or firmly joined together, for example by needling. The significantly higher weight per unit area of bentonite and sand mats (around 13 kg/m^2 when dry) limits the range of installation equipment that can be used.

The subgrade must be flat and free of stones. Otherwise, individual sharp-edged stones could become embedded in the GCL laid on top and cause localised damage to the mat when the sealant is poured over it.

The installation equipment must be firmly positioned (e.g. on stilts) to ensure the safe installation of the GCL. It must be possible to lay the individual strips in a single operation using a single piece of equipment. Transferring a rolled mat, for example from a land-based machine to a water-based machine during the laying process, carries the risk of the mats becoming warped, resulting in the overlaps becoming misaligned; it is therefore not permitted.

The bentonite and, where applicable, sand mat must be rolled off directly on the surface of the bank and bed. The roll-off device must guarantee a rigid, firm guide of the bentonite and sand mat when laying to ensure wrinkle-free laying of the GCL. It is also important that the GCL remains free of tension. This usually requires a motorised roll-off device.

'Over-stretching' of the transition area from bank to bed by the GCL can be ruled out with corresponding application and, if needed, by verifications.

No directional corrections may be made during installation, otherwise folds and bulges may occur in the overlap area, which may lead to permanent leaks.

Impacts of GCL may only be carried out as overlaps with a minimum width of 50 cm, in the longitudinal direction of the channel of 1.50 m. Sewing or bonding is currently not permitted.

The individual GCL sheets must be laid in quick succession to minimise, in particular, deposits of any loose, rolling soils present in the overlapping areas of the GCL sheets, as well as sediment deposits on the fine subgrade. After each longer work break (e.g. after 24 h, time must be adapted to the respective local conditions) the overlap areas must be checked by divers and the deposits removed if necessary. This applies in particular to the relatively long longitudinal overlap in the centre of the duct, which remains exposed when the duct is installed half-width.

To protect the GCL from frost damage in the long term, a protective layer of gravelly material – which is filter-stable in relation to the stone fill – must be laid in the water exchange area immediately after the mats have been installed. As a result, the position of the laid mats is already stabilised during the construction phase.

Experience to date has shown that ends left free for longitudinal overlap can turn inwards due to backwash from passing vessels. This leads to improperly formed overlaps. The laid mats must therefore be inspected by divers before being covered with hydraulic stones. Alternatively, structural measures (e.g. local loading with hydraulic engineering blocks) should be put in place to prevent the material from being dislodged during the construction phase.

The covering of the laid bentonite and, where applicable, sand mats with stones must be carried out consistently from bottom to top in the bank area. Dry scaffolding shall be used in which the slats are lowered one by one. If this is not available, the material must be added section by section in 'small steps'. This is particularly important in transition areas where the groundwater level lies only slightly below the channel water level, or where low-permeability soils are present in the channel area. In this case, the residual water under the mat after the installation of the GCL can only flow slowly. The mat's positional stability may initially be reduced, so that improper placement with stones can cause the mat to slip.

Nailing the mat above the bank or other securing measures can cause unacceptable tensile stress on the sealing membranes when backfilling with hydraulic engineering blocks; therefore, such fastenings must not be used.

5.1.4 Permanent plastic sealing with clay and hydraulic binders

The installation of a permanent plastic seal with clay and hydraulic binders is similar to the installation of grouting mortar. The consistency of the sealing material must be such that it flows freely during installation. The flexibility required in the final state results from the requirements for a soft seal (see Chapter 4.6).

The sealing material must be prepared prior to installation so as to produce a homogeneous seal that meets the requirements of ZTV-W LB 210 (2025).

The installation procedures must ensure that

- an unbroken seal is formed,
- uniform density of the sealing material is ensured,
- the specified layer thickness of the seal is maintained over the surface,
- the execution is not affected by sediment penetration.

5.2 Proof of the basic suitability of installation methods

5.2.1 General information

As part of the proof of basic suitability by means of a basic test, the characteristic values Annex 3 listed in the table must be determined and the limit values Annex 2 shown in the table must be complied with. By extension, these requirements also apply to other forms of proof of suitability for use (e.g. case-by-case assessment).

Confirmation of proof of basic competence (see Annex 4 for a sample certificate for a successfully completed basic examination) is issued to a construction company by the BAW or by a testing body recognised for this purpose, in respect of a company-specific method for laying soft seals in federal waterways. This confirms that the installation procedure meets the requirements set out in Chapter 5.1.

The prerequisite for practical implementation of the test is the submission of a detailed description of the procedure and the equipment to be used.

Test boundary conditions (e.g. installation on the bed or in the bank area, installed layer thickness, surface layers to be taken into account) shall be noted in the test certificate. The test certificate is valid for 5 years and must be reapplied for once this period has expired. For procedures that are currently in use without any problems (successful comparable construction projects, successful suitability and verification tests), the test certificate may be renewed without the need for any further tests. For procedures that have not been used, or have not been used successfully, evidence of their fundamental suitability may need to be provided again.

The test is usually carried out in a test basin under conditions similar to those on a construction site (e.g. in terms of the bank gradient). The water depth must be sufficient to allow a substantial part of the seal to be laid underwater. It must be possible to tilt the basin in order to assess whether it has been fitted correctly.

The following chapters 5.2.2 to 5.2.4 explain the boundary conditions and requirements for the tests to be carried out in the context of a usability certificate for the different installation methods.

5.2.2 Natural clay seals

As part of the test, proper preparation of the clay and installation of the clay seal must both be examined. Preparation must ensure that the clay is homogeneous and has the required strength (see Chapter 4.3).

As a general rule, only clay for which basic suitability has been demonstrated may be used (see Annex 3).

After drainage of the test basin, the installed seal is assessed with regard to

- Positioning accuracy of individual sheets, slabs, etc. (depending on the procedure),
- Joint alignment/quality of overlaps,
- Absence of cracks,
- Flatness of the clay surface,
- Layer thickness,
- Material characteristics after installation in accordance with Chapters 3 and4.

The reliability of the installation procedure is assessed on the basis of the installation and system guarantees provided.

5.2.3 Geosynthetic clay liners (GCLs)

As a general rule, only a GCL may be used for which basic suitability or applicability has been demonstrated in accordance with the building specifications (ZTV-W LB 210 (2025)) (see Annex 3).

After drainage of the test basin, the installed seal is assessed with regard to

- Positioning accuracy of individual sheets,
- Quality of overlaps (absence of sediment, overlap width, any open folds in the overlap area),
- Flatness and absence of wrinkles,
- Material characteristics after installation in accordance with Chapters 3 and4.

The reliability of the installation procedure is assessed on the basis of the installation and system guarantees provided.

5.2.4 Permanent plastic sealing with clay and hydraulic binders

As a general rule, only sealing materials for which basic suitability has been demonstrated may be used (see Annex 3). The material properties after installation shall be checked in accordance with Chapters 3 and 4.

As the sealing material is installed underwater in the same way as grout, no separate evidence of its general suitability is required. The company must hold a type-test certificate for the underwater installation of grouting mortar (for the type test, see RPV (2026), Technical Note on the Use of Hydraulically Bound Materials for Grouting Hydraulic Structures on Waterways, MAV (2026)).

6 Tests for installation procedures according to ZTV-W LB 210

In accordance with ZTV-W LB 210 (2025), the following tests must be carried out under the terms of the construction contract:

- Suitability test (to be carried out at the beginning of the construction project under the terms of the construction contract),
- In-house monitoring/inspection tests (to be carried out throughout the construction period under the terms of the construction contract).

Under the terms of the construction contract, a suitability test must be carried out at the start of the construction works in accordance with ZTV-W LB 210 (2025). This involves checking that the seal is laid to the required quality standards under on-site conditions. During the construction operation, inspection tests by the contracting authority and self-monitoring tests by the contractor shall be carried out to demonstrate that the soft seal is continuously installed to the required quality. Further details are laid down in ZTV-W LB 210 (2025).

The characteristic values to be determined as part of these tests relating to the installation procedure for the individual sealing materials, and the corresponding limit values, are set out in ZTV-W LB 210 (2025).

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Annex 1: Overview – Test methods for sealing materials

Requirement	Testing procedures (RPW)	Standard/Regulation/ Special test	Presentation in section	Sealing materials to be tested		
				Clay	GCL	DPTH[2)]
Permeability	Determination of the permeability coefficient k_{10} or permittivity ψ_{10}					
	• Sealing sample	DIN EN ISO 17892-11	4.2	**X**	**X**	**X**
	• Sealing sample under tension	Special experiment	4.10		**X**	
	• Overlap area	Special experiment	4.11		**X**	
Strength/ Shear strength	Determination of undrained shear strength c_u	DIN EN ISO 22476-9	4.3	**X**		**X**
Resistance to decay	Decay test according to Endell	Special experiment	4.4	**X**		
Resistance to erosion	HET test	Special experiment	4.5	**X**		**X**
	Rinse-off test	Special experiment	4.7			**X**
	Turbulence test	Special experiment	4.8		**X**	
Deformability/ Flexibility	Beam bending test	Special experiment	4.6	**X**		**X**
Strength/ perforation resistance	Perforation test	Special experiment	4.9	**(X)**[1)]	**X**	**(X)**[1)]

[1)] Requirement, if applicable, in accordance with point 4.9.1

[2)] DPTH = duroplastic sealing with clay and hydraulic binders

Annex 2: Overview – Limit values to be complied with for sealing materials

Requirement	Test procedure/test value (RPW)	Presentation in section	Limit values		
			Clay	Geosynthetic clay liners (GCL)	Permanent plastic sealing with clay and hydraulic binders
Permeability	Permeability coefficient k_{10} • Sealing sample • Sealing sample under tension • Overlap area	 4.2 4.10 4.11	 $\leq 1 \cdot 10^{-9}$ m/s[1)2)] – –	 $\leq 5 \cdot 10^{-11}$ m/s[1)3)] $\leq 5 \cdot 10^{-11}$ m/s[1)3)] $\leq 5 \cdot 10^{-11}$ m/s[1)3)]	 $\leq 1 \cdot 10^{-9}$ m/s[1)2)] – –
Strength/ Shear strength	undrained shear strength c_u	4.3	≤ 50 kPa *(dry installation)* 15 kPa ≤ c_u ≤ 25 kPa *(underwater installation)*		–
Resistance to decay	Endell decay test (Decay rate after 8 hours)	4.4	≤ 0.05 *(and note HET)*	–	–
Erosion resistance	Hole erosion test Leaching test (mass loss) Turbulence test (k_{10} after test)	4.5 4.7 4.8	Location in Briaud diagram – –	– – $\leq 5 \cdot 10^{-10}$ m/s[3)]	Location in Briaud diagram ≤ 6% –
Deformability/ Flexibility	Beam bending test (cracking depth in the sealing material)	4.6	≤ 1/3 of bar height	–	≤ 1/3 of bar height
Strength/ Dielectric breakdown strength	Penetration test (k_{10} after test) Tensile adhesion strength Bond strength	4.9 4.1 4.1	– – –	$\leq 5 \cdot 10^{-10}$ m/s[3)] ≥ 12 kN/m ≥ 60 N/10 cm	– – –

[1)] *For samples taken from the installed seal, the k-value may not be increased by a factor of more than 10.*
[2)] *K_{10} – decisive for a layer thickness of d = 20 cm*
[3)] *K_{10} – decisive for a layer thickness of d = 1cm*

Annex 3: Overview – Material properties to be determined as part of the assessment of basic suitability

	Natural clay seal	**Geosynthetic clay liners (GCL)**	**Permanent plastic sealing with clay and hydraulic binders**
Material properties, to be determined as part of the assessment of basic suitability	• Water permeability coefficient k_{10} • Natural water content w_n • Yield limit w_L • Particle distribution • Lime content, loss on ignition • Proctor density • undrained shear strength c as a function of water content w_n • Flexibility (flexibility test) • Strength (penetration test) • Erosion resistance (hole erosion test) • Decay resistance (Endell decay test) • Qualitative mineralogical analysis[1)]	• Water permeability coefficient k_{10} (in terms of area, overlaps and elongation) • Tensile adhesion strength • Surface mass • Water absorption • Bond strength • Resistance to erosion (turbulence test) • Resistance to dynamic perforation (puncture test) • Push-through resistance (punch push-through test)[2)] • Abrasion resistance (only when used without a protective coating)	• Water permeability coefficient k_{10} • undrained shear strength c as a function of water content w_n • Flexibility (flexibility test) • Strength (penetration test) • Erosion stability (hole erosion test and washout test) • Extent of expansion

[1)] required when developing new clay deposits or in the event of changes to extraction conditions
[2)] Required only under appropriate boundary conditions

Annex 4: Model certificate for confirmation of proof of fundamental suitability of a method for mechanical installation of soft seals in federal waterways

CONFIRMATION

via the**:**

Demonstration of a process's fundamental suitability

(basic test according to ZTV-W, LB 210)

for mechanical underwater installation of

seals made of treated natural clay

in federal waterways

Executing company: …
…
…

Basis for assessment: Fundamental suitability is confirmed on the basis of the basic test accompanied by the BAW.....

The above-mentioned company has demonstrated the general suitability of the method described below for the installation of clay in federal waterways, subject to the specified conditions and restrictions.

Installation procedures: …

Construction material: …

Installation device: …

Installation boundary conditions: ...

Installation restrictions: …

Further details and conditions relating to the installation procedure are set out in …

Valid until: …

Prepared by: Division: Geo-engineering

Department: Earthworks and shore protection (G4)

Karlsruhe, dated ...

pp