
This publication was withdrawn on 16 January 2025.

This publication has been replaced by the Landfill Guidance Group (LGG) Industry Code of Practice LGG 110 'Using bentonite enriched soils in landfill engineering', available from the [Environmental Services Association](#).

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LFE10 - Using bentonite enriched soils in landfill engineering

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The Environment Agency has primary responsibility for the regulations associated with the EU Landfill Directive. This document provides detailed technical guidance you can use to assist you in achieving the EU Landfill Directive's aim of preventing or reducing as far as possible the negative effects of landfilling waste on the environment.

The detail in this document supports our general approach to landfill engineering which is contained in our policy [LFE1 – Our approach to landfill engineering](#).

Executive summary

Bentonite enriched soil (BES) is an effective means of reducing the hydraulic conductivity of sand or silt support materials. Bentonite and water are mixed together with such support materials to form a low hydraulic conductivity barrier suitable for a landfill lining or capping layer. There are several ways to achieve a suitable BES mixture. This document provides guidance on the best practice, quality control and quality assurance of using BES layers. As a landfill operator, you must establish a consistent and auditable quality system, from selecting the support materials to installing and testing the completed liner.

Using mixing and installation methods for BES layers not covered in this document does not preclude their use. However, we advise you contact us early so we can assess whether your proposed techniques are suitable.

1.0 Introduction

The 'Landfill by design' approach (Our approach to landfill engineering) states that technical standards in landfill engineering should be based on site specific risk based criteria supported by technically justified civil and geotechnical engineering calculations founded in sound science.

This document deals specifically with issues relating to designing, constructing and validating of bentonite enriched soil (BES) liners and capping layers whose primary function is to contain pollutants arising from landfilled waste.

Where you use a BES liner as one element of a lining system, you should be aware of the potential interactions with other elements of the system. For example, where you lay a geomembrane over a BES layer the liner may suffer desiccation due to solar heating of the membrane.

1.1 Quality control

As in all landfill engineering applications, a quality approach is essential if your works are to comply with the standards and specifications you agree with us through the environmental permitting process. Quality control in the context of bentonite soil mixing is defined by Edil et al (1990) as 'the actions taken by the designer, mixing plant engineer and installer to ensure their methods, materials and workmanship meet the project specifications'. Table 1 lays out the various stages you should follow in order to ensure you install a high quality liner.

We recommend your designer works closely with your installation contractor to customise the design to the limitations of the mixing machinery and site specific conditions. Further guidance on construction quality assurance (CQA) is provided in later sections.

Figure 1 Stages in the design, construction and validation of a BES basal liner

Stage A Liner design and method statements	
A1	Stage: Regulation 15 Hydrogeological Risk Assessment submitted to and agreed in writing with the Environment Agency
	Details: Suitably qualified, competent and experienced staff should undertake this. Liaison with the Environment Agency is essential at all stages. When the BES liner forms part of a composite lining system the performance specifications must address the BES within this lining system. Any hydrogeological model produced must accurately model the performance specification of the BES element of the lining system.
A2	Stage: Detailed liner design submitted to and agreed in writing with the Environment Agency
	Details: The whole lining system should be technically justified, with care taken to ensure that the BES component of the composite liner is complementary to other elements of the landfill design. This will include the suggested support media and an outline of proposed mixing and installation method.
A3	Stage: Support media source evaluation and laboratory based mixing trials submitted to the Environment Agency and agreed in writing
	Details: The operator should carry out a geotechnical assessment of the intended support media source material. This may take the form of a site investigation or representative production samples from an existing extraction source. This will be in parallel with a comprehensive laboratory-based mixing study using methods as close as possible to that being proposed in the field. This should determine the bentonite dosage rate, mixing procedure and installation requirements.
A4	Stage: Field trial mixing and trial liner report submitted and agreed in writing with the Environment Agency
	Details: The Environment Agency should be invited to attend the field trials of the proposed mixing and placement methods. The trial liner report must provide evidence that the proposed mixing and installation method is capable of achieving the required performance specifications in the field environment.
A5	Stage: Construction and construction quality assurance (CQA) method statement submitted to and agreed in writing with the Environment Agency
	Details: The CQA method statement must include a detailed and systematic programme for checking all elements of the design and construction, the specification and properties of the materials to be used, the mixing method, the methods of installation and the form of reporting and validation.
Stage B Construction and CQA of the main liner	
B1	Stage: Mixing, construction and CQA
	Details: Once the various agreements required in Stage A have been obtained, the mixing and construction of the liner may begin. It is essential that the responsibilities of the various parties involved in the works are clear, and that the CQA engineer maintains liaison with the Environment Agency throughout the construction period.
Stage C Validation	
C1	Stage: Validation report submitted to and agreed with the Environment Agency
	Details: The validation report should include a comprehensive record of the actual construction of the liner, providing a long term record of the works.
C2	Stage: Written acknowledgement from the Environment Agency
	Details: Once the validation report has been reviewed by the Environment Agency the licensee will be informed in writing and subject to other licence conditions being met, land filling can commence.

2.0 Mixing and installation methods

2.1 Introduction

There are two main mixing and installation methods currently in use for BES. These are the rotavation method and the plant based mixing method. Both methods are acceptable, you should normally select your preferred method and contractor early on in the design process. Our primary concern is to ensure we fully scrutinise your proposed methodology to ensure it will comply with this guidance. You or your installation contractor may propose other methods, but we will expect you to present evidence to prove your proposed installation method is capable of achieving a mixing standard equivalent to those outlined below.

2.2 Rotavation methods

There are two main rotavation methods in use, they are in-situ and divorced rotavation. In the in-situ method; the support media, bentonite and water are mixed and compacted at the location of their intended use. For the divorced method, the materials are mixed and then moved to the liner area. If using the divorced method, you must take care to avoid contaminating the lower parts of the mixture. We therefore, recommend you carry out the mixing on a designated area with either a clean sand sub base or concrete hardstanding to reduce the risk of contamination.

2.2.1 Rotavation methodology

In the case of both rotavation methods, the support media is spread out in a controlled manner to achieve a uniform thickness. Spread the bentonite on top of a layer of support material in the quantity and/or rate determined during your laboratory and trial liner stage. The rotovator mixes the BES for the number of runs determined from your trial pad. You may add water to the mixture between rotovator passes. You must put in place measures to control the depth of the rotovator to prevent mixing the underlying layers. After the mixture has been blended, you must immediately profile and compact the layer to prevent changes in the mixture's geotechnical characteristics.

The order of mixing, the rotovators speed, the rotors speed and the number of mixing runs carried out all have significant impacts on the efficiency of the mixing process. Your CQA engineer or inspector must ensure that mixture efficiency is maintained at all stages of mixing. This is likely to involve varying the mixing parameters to ensure mixing. You must support any variation in your mixing procedure with relevant testing.

Figure 2 Recommended performance specification for rotavation methods

Spec-ification	Detail
A	The bentonite spreader must be fitted with an electronically variable mechanical or weight controlled batcher allowing spreading to an accuracy of 0.05Kg/m ² . Measuring the bentonite deposited on a known area of plastic sheeting may check the bentonite application rate.
B	The rotavator must have enough tines or blades to cover the whole axle width of the machinery. The tines or blades must be of sufficient length so as to allow penetration to the total thickness of each lift. The tines or blades must be regularly inspected so as to ensure that they remain intact and clean. Any broken blades should be located and removed from the mixture as they may damage under or overlying liner elements.
C	The rotavator must be capable of maintaining an accuracy of depth control of +/- 50mm. When used in association with a laser depth control instrument much greater levels of accuracy can be achieved.
D	The rotavator must be fitted with a protective guard so as to prevent the loss of excessive bentonite dust during the mixing process.
E	All plant and machinery must be of a design so as to ensure minimal damage to the support media during mixing (low ground pressure plant is considered ideal).
F	Equipment for the application of water to the mixture must be capable of maintaining an
G	The rotavator must be of sufficient power so as to allow the lifting of the support material to ensure complete mixing.
Notes	Accuracy of application of \pm 500ml per square metre of mixture. The support media must be placed in such a way so as to avoid compaction of the soil prior to the addition of bentonite. This can be achieved by working from the prepared sub base or the surface of the previously placed lifts using low ground pressure plant.

You must provide us with the following information about how the mixing plant will operate:

- quantities of support media, bentonite and water added to each batch in Kg and litres;
- the accuracy of all weighing equipment used in the mix in place process;
- the number of passes and speed of each pass including rotor speed;
- the point at which water is added and the number of passes after water is added.

If you use an in-situ support material, you must till it before adding the bentonite to achieve a consistent uniform appearance. The tilled surface must be inspected and signed off by your CQA inspector before you begin placing the bentonite.

2.3 Batch mixing methods

There are two main batch mixing methods; timed and continuous. For the timed method, the materials are mixed and kept in the mixing vessel for a predetermined time. In the continuous method, the materials move through the process continuously. In both processes, the materials are mixed in a controlled manner in a mixing vessel for a set time period. You must fully control the quantity and sequence of the mixture ingredients, preferably by computer. As a general rule the average composition of the output stream when averaged over time, must be equal to the average of the ingredient input stream.

Figure 3 Equipment specifications

Timed batch		Continuous batch	
Spec	Detail	Spec	Detail
A	Equipment controlling the input of water to the mixing chamber must be capable of maintaining an accuracy of application of +/- 5 litres per m ³ of BES.	A	Equipment controlling the input of water to the mixing chamber must be capable of maintaining an accuracy of application of +/- 500ml per m ³ .
B	Support media and bentonite addition rates must be controlled to achieve an accuracy of +/-0.5 Kg/m ³ .	B	Support media and bentonite addition rates must be controlled to achieve an accuracy of +5Kg/m ³ - 0kg/m ³ .
C	All plant and machinery must be of a design so as to minimise damage to the support media during mixing. It is recommended that the rotation speed of the controls is reduced to the minimum when mixing weak support media.	C	All plant and machinery must be of a design so as to minimise damage to the support media during mixing. It is recommended that the rotation speed of the controls be reduced to the minimum when mixing weak support media.
D	The batch mixer must be of sufficient power so as to allow the lifting of support material ensuring complete mixing.	D	The mixing paddles must be of sufficient power so as to allow the lifting of support material ensuring complete mixing.

Figure 4 Typical information requirements

Timed batch	Continuous batch
<ul style="list-style-type: none"> ▪ a) Batch quantity in Kg. ▪ b) Quantities of support media, bentonite and water added to each batch in Kg. ▪ c) The accuracy of all weighing equipment used in the batch mixing equipment. ▪ d) The maximum and minimum time for the dry mixing stage in seconds. ▪ e) The maximum and minimum time for the wet mixing stage in seconds. 	<ul style="list-style-type: none"> ▪ a) Daily production rate in Kg. ▪ b) Continuous readouts of the quantities of support media, bentonite and water added (in Kg and litres) during production. ▪ c) The accuracy of all weighing equipment used in the continuous mixing equipment.

3.0 Design issues

3.1 Foundations

If you intend to install 300 mm of BES over weak or poor foundations, you must undertake a geotechnical assessment and present it to us for appraisal. You must receive our approval before proceeding.

3.2 Subgrade

The sub grade you lay for a mineral liner must have a suitable bearing capacity and be free from water ingress or ponding.

3.3 Leachate monitoring and extraction points

Your leachate monitoring points must be designed so they spread loads and don't overstress or punch through the liner. Structure and pipe penetrations through the liner are difficult design problems often causing installation difficulties and potential points of weakness, you should avoid them at all costs. A successful design requires a detailed knowledge of the available techniques and the practical aspects of installation.

3.4 Desiccation under geomembrane liners

Evidence is emerging of a process where a diurnal cycle of moisture evaporation from the mineral liner, which condenses on the lower surface of the geomembrane and runs downslope. This causes an additional problem of water being trapped between the membrane and the mineral liner. The removal of moisture from the underlying BES caused in this way can be severe, resulting in permanent damage and the need to the mineral liner and geomembrane. One proposed solution to this problem is to immediately cover of laid geomembranes to ensure it is in intimate contact with the mineral liner and that temperature variations are minimised.

4.0 Minimum standards

A number of minimum standards are currently being used with regard to BES. We recommend you consider these standards as the minimum we will accept for the construction of BES liners or caps. This is irrespective of a site's risk context. You should bear in mind however, that these standards are not fixed and where you can provide a suitable justification, we can vary these standards. The current minimum criteria are outlined in table 5:

Figure 5 Installed BES as a landfill liner or capping layer is typically required to meet the following criteria

Primary properties	Secondary properties
<ul style="list-style-type: none"> ▪ Very low hydraulic conductivity and low gas permittivity. ▪ Moderate to high shear strength (sufficient to ensure minimum deformation under the design loading with a factor of safety) ▪ Density >95% of maximum dry density with a 4.5 Kg hammer. ▪ Homogeneity ▪ The BES shall be physically and chemically suitable for its proposed end use. 	<ul style="list-style-type: none"> ▪ Good plasticity and workability. ▪ Low shrinkage. ▪ Low frost susceptibility. ▪ Chemical resistance and compatibility with many site-specific leachates. ▪ Low dispersivity and erosion susceptibility. ▪ Appropriate actuation capacity. ▪ Some resistance to settlement damage. ▪ The minimum bentonite dosage rate applied to the mixture is 1.5 % by weight. ▪ An additional bentonite dosage of 0.5% for batch mixed BES (1.5% for the rotavation mixed BES) by weight is added to the results of the laboratory testing to provide a factor of safety for all mixture designs.

Due to the site specific nature of each BES mixture, you must carry out detailed testing of your proposed mix. Your installation contractor will normally do this for you by using trial pads to ensure the required environmental protection performance is achieved.

5.0 Recommended minimum information requirements

As a minimum, you must accompany your design submission with the following information. However, please bear in mind this list is not exhaustive. Your liner design must also be covered in sufficient detail within your working plan and method statement to allow us to make an informed judgement on the performance capabilities of the BES liner.

- a. The design engineer's name, qualifications and relevant experience.
- b. The quality assurance procedures applied to the design process.
- c. The concepts underpinning each design element.
- d. Calculations and factor of safety used in all aspects of the design including mixture dosage calculations.
- e. Side slope stability calculations and factors of safety. (In particular the BES/FML interface)
- f. Surface water management measures within and around the cell during ingredient mixing and construction, to include provisions for control of particulate pollution of surface waters.
- g. Basal and side gradients of the completed lining system for leachate management.
- h. The location, function and stability of permanent and temporary bunds to include construction specification.
- i. Construction details of the joints between phases of working.
- j. Measures to prevent dust generation. (Health and safety risk assessment to be produced by the installation contractor)
- k. Environmental protection measures and the method statements to show how these will be met.
- l. Details of any interaction between other lining elements such as surface preparation for the placement of flexible membranes above or below the BES liner.

5.1 Recommended additional requirements for using BES for landfill caps

You must also present the following additional information to us for any project involving using BES as a low hydraulic component within a capping system.

- a. Anticipated gross settlement and settlement rates of the waste body together with calculations proving the integrity of the capping system during and after anticipated settlement. Resistance to settlement can be approximately calculated using the BES's geotechnical parameters and models.
- b. The maximum slope angle anticipated together with slope stability calculations and factors of safety.
- c. Drawings showing gradients of the completed capping system.
- d. Details of any penetrations of the cap and any infrastructure in close proximity to the capping layer.
- e. Details of the measures to ensure the compatibility of the BES component to other elements of the capping system above and below the BES. In particular granular or high porosity gas collection media.
- f. Details of any design measures to reduce the impact of desiccation of the BES.

6.0 Trial pad

Prior to constructing the liner, a trial pad must be constructed using the intended mixing, placement and compaction machinery.

Before commencing, you must submit a method statement detailing how you will construct the trial pad, and what type and frequency of tests you will use. This allows us to know what materials and methods you plan to use, it also gives us an opportunity to attend your site during construction of your trial pad. This is beneficial to both you and us, and can help prevent problems later on.

One of the objectives of your trial pad is to assess the efficiency of the mixing plant with your site specific materials. Often, batching or mixing plant may not be available on your site for operational reasons. In these cases, you can carry out the mixing trial off-site or as soon as the plant arrives at your site.

Your test pad must be designed to provide the following information:

- a. The suitability of the mixing method and mix ingredients under site conditions.
- b. The ability of the mixture to achieve the geotechnical design criteria.
- c. The suitability of the method of placement and compaction methods to achieve the geotechnical design criteria.
- d. Recommendations for the operation and management of the chosen mixing technique.
- e. Recommendations for the compaction of the liner including the thickness of each lift, the weight and type of compaction equipment and minimum number of passes required to achieve specification compaction.
- f. The information needed to prepare the detailed construction method statement for the liner/capping layer.

You should base your layer thicknesses and number of compactor passes on the Department of Transport's Code for Highway Construction, Part 2, series 600, while still taking account of your site specific conditions.

The dimensions of the trial pad must relate to and be designed to take account of the following factors:

- a. The type of mixing plant employed.
- b. The operational parameters of the mixing plant employed.
- c. The design of the liner.
- d. The earthworks and compaction equipment.
- e. The requirements for sample measurements and observations of equipment performance.
- f. The test pad must be of sufficient length so as to allow the mixing and spreading plant to reach full operational speed.
- g. The test pad should be at least three construction machine widths wide and three to five construction machine widths long.

You should use the same subgrade material for your trial pad as you intend to use on the actual liner or cap. Where your design includes significantly different gradients, you should carry out a number of trials to reflect the differing field conditions.

Your trial pad must be supervised by a suitably qualified and experienced engineer (geotechnical engineer or engineering geologist). Ideally you should use the same engineer to quality assure both the trial pad and the main. We expect you to invite us to observe your mixing trials and trial pad construction.

You should normally take at least three samples from each lift. You should then determine the hydraulic conductivity, density, moisture content, classification properties and bentonite content of each sample. On completing the test pad, you should destructively test your trial pad to investigate the adequacy of inter-lift bonding and to observe the macro homogeneity of the mixture.

Your trial pad is an ideal opportunity to assess the performance of your chosen mixing method. You should use at least twelve random samples from the completed mixture to determine the bentonite dosage rate. This will allow your CQA engineer to determine the actual performance of the mixing method and design your method statement to take account of this.

6.1 Trial liner report

Your trial liner report must include as a minimum, the following measurements and records:

- a. A detailed level survey of the subgrade prior to the liner or cap placement and a description of the sub grade.
- b. Records of the quantities of mixture ingredients, mixing times, mixing plant operational parameters, mixed material standing time, and condition of ingredients and finished material and semi-hydrated state of the material.
- c. The type, dimensions, weight and operating speed of the plant, together with the frequency and energy of vibrating rollers or cross sectional area and arrangements of the studs of sheep foot rollers.
- d. The number of passes of the roller, or of each type of roller if more than one is used.
- e. The method of measuring moisture content and density of each sample.
- f. All field tests and samples, including failures.
- g. Photographs of the trial (particularly the destructive testing).

When complete, your CQA engineer must forward your report to us for written approval. Your report must include an assessment by a suitably qualified and experienced engineer confirming the raw materials, mixing and placement methods employed are suitable for your proposed use. You must also incorporate the findings of the trial liner report into your construction method statement, particularly the operating parameters of the mixing plant.

7.0 Materials

This section deals with the various elements of a BES mix and the appropriate laboratory testing. There are four subsections dealing with bentonite, the support media, the mixing water and the characteristics of the mixture.

7.1 Bentonite

Bentonite grade is defined as the particle size distribution of the raw bentonite clay (used in the BES mixture).

A wide variety of bentonite grades are available, from coarse pellets to fine powders. In general, the finer the grain size, the better coating of the support media and more active the cation exchange capacity and immediate swelling potential. Therefore, you should use fine powders (which may increase the effectiveness of the mixture) wherever possible.

7.1.1 Bentonite quality.

To be sure it's suitable, you must assess any bentonite product against the following criteria:

- a. The content of materials other than montmorillonite.
- b. The montmorillonite content.
- c. The presence or absence of polymers or additives.
- d. The type and origin of the bentonite component (Natural sodium, sodium enriched bentonite, or calcium bentonite)

Your designer must ensure the chosen raw bentonite has the following minimum properties to be used in any landfill environment:

- a. Able to mix well with the support media ensuring an equal distribution of bentonite throughout the support matrix.
- b. Able to bond well to or be retained by the support media matrix.
- c. Able to hydrate in a controlled manner producing uniform moisture content throughout the mixed material.
- d. Does not react with common leachate components.
- e. Does not react with site specific leachate components.
- f. Retains performance over the design life of the landfill.
- g. Able to provide in association with the support media, a liner which is able to act as a suitable foundation onto which other lining components or waste may be placed.
- h. The mixture must be designed in such a way so as to allow the bentonite component to hydrate with uncontaminated mixture water so as to ensure that the maximum swelling potential and minimum hydraulic conductivity of the bentonite is achieved.

7.1.2 Percentage of bentonite

Whenever you refer to bentonite content, you must express it as a percentage of dry bentonite with respect to the dry support material.

The bentonite content must be determined from laboratory measured values and rounded upwards to the nearest whole number.

Your laboratory will advise you of an appropriate factor of safety to account for varying mixing efficiency, you must add this factor when calculating the required percentage of bentonite. Our experience has shown laboratory mixing methods to be superior to those you will likely achieve in a field environment. You should also expect variation in mixing efficiency between the main installation methods. You must calculate the minimum bentonite content required in accordance with the method set out in Appendix 3. The bentonite dosage rate you use must be based on the hydraulic conductivity and other performance based specifications required for the capping or basal lining layer.

Due to the variation of bentonite dosage rate inherent with all mixing processes, it is essential you establish a minimum bentonite dosage target. You should allow no variation below this dosage rate.

Your eventual mixture design must take account of the efficiency of the field mixing process you adopt.

You should consider the effect of leachate on the hydraulic conductivity of the BES, your bentonite dosage rate should reflect this consideration. We recommend you prepare a series of mixtures; replacing the water component with a sample of the sites leachate free from suspended solids. Use these samples to determine the additional bentonite dosage required to account for the effect of leachate percolate on the BES's performance. This process is **essential** where BES is not in composite with an FML.

7.2 Support media

You must send a source testing report and testing method statement to us for our written agreement. These documents should fully detail the support media you plan to use and clearly demonstrate its suitability. You may incorporate this report into the mix design report you also send us if you wish. Your report must include the following:

- a. The location of the source (address, national grid reference, location plan and suppliers name).
- b. The anticipated quantity of material available compared with the volume required for the works.

- c. The results of the site investigation, including detailed logs and plans for all trial pits and/or boreholes. All aspects of the investigation should follow the guidelines outlined in BS 5930:1981.
- d. The laboratory test sheets for all tests (including failures). These would typically include particle size distribution testing (BS1377 Part 2 Method 9), natural moisture content (BS 1377 Part 2 Method 3.2) hydraulic conductivity (BS 1377 Part 6 Method 6), soil water pH and conductivity (BS 1377 Part 3 Test 7).
- e. The results of all field tests including failures.
- f. Expert geotechnical opinion on the suitability of the material for the proposed use.
- g. If the source is from a stockpile, the original location of the material and period over which the material has been stockpiled.

You must incorporate the information derived from the source investigation report into the laboratory based mixture design process.

It is important the support media is able to maintain its stability throughout the mixing and placement process. A support media with a low bearing capacity may result in problems in achieving the required degree of compaction. You can determine the bearing capacity of the support media at the source evaluation stage by compaction, plate bearing or aggregate quality assessment tests.

7.2.1 Soil water chemistry of the support media

You should subject a sample of soil moisture extracted from the support media to chemical analysis to ensure it is free of substances that may affect the bentonite's performance (for example, humic acid). All different support media sources used during your project must have their soil water tested.

The swelling capacity of bentonite may be affected by ions present in limestone type support media. You must not use limestone and calcium rich support media (or indeed any support mixture which may impact on the efficiency of the BES) for BES liners.

Your mixing contractor and CQA engineer must jointly ensure the support material is free of the following:

- a. peat or bulk organic material;
- b. logs or tree stumps;
- c. any industrial, commercial or domestic waste material;
- d. materials susceptible to spontaneous combustion;
- e. material in a frozen condition;
- f. any material likely to have a detrimental effect on the performance of the BES mixture;
- g. any other material outside the agreed specification.

7.2.2 Mixing water chemistry

You must also record the chemical characteristics of the intended source water, whether the source is mains or non-mains water. This testing should confirm the water will not affect the swelling potential of the bentonite, compared to the laboratory tests results. If you plan to use mains water for mixing, you must consider its consistency. If instead you plan to use non-mains water for mixing, you should continue testing its chemical properties throughout the mixing process at a rate of one test per thousand gallons you use. The tests you use must cover any properties that may reduce the effectiveness of the bentonite.

7.2.3 Particle size distribution of the support media

Ideally the particle size distribution (PSD) of a support media would remain constant, but natural variation means the PSD will vary depending on which part of the source quarry the material comes from. It is essential therefore you ensure during the source assessment stage that the source material is fully characterised. You must also carry out confirmatory

testing during the mixing process. The number of tests you need will depend on the variation in the source media and its expected impact on the BES's quality.

The fines content of the support media must not be so great as to prevent the homogenous mixing of the bentonite throughout the mixture. A high clay and silt content will reduce the efficiency of many types of mixing machinery. The level at which the fines content becomes problematic depends on the type of mixing machinery you use. It is essential the mixing method you adopt is able to mix the BES without clogging because of a high fines contents. This is particularly important when using mine and quarry waste as a support media.

Your CQA engineer must ensure the support media doesn't contain particles greater than 20mm diameter or 4cm³ volume. You must reject any material exceeding these criteria.

8.0 The mixture

8.1 Mixture design report

Your mixture design report must include:

- a. The full PSD curve and source location of the support media used in the design tests, with enough tests to cover the full range of likely particle size distribution variations for the source material.
- b. Full laboratory mixing procedures for the BES, including equipment used, sampling method, mixing times and any preparations undertaken.
- c. Bentonite content/hydraulic conductivity correlation graph, with at least five differing bentonite dosage rates.
- d. Measurements of the theoretical and actual void space at 95% compaction efficiency at each of the tested bentonite dosage rate.
- e. Site specific laboratory derived methylene blue calibration curve using at least five points (1 point for each bentonite dosage).
- f. Calculated application rate including a factor of safety. The factor of safety must be stated. Design dosage rate must be presented as a percentage bentonite by dry weight.
- g. Full specification and technical details on the intended grade of bentonite. To include specifications for:
 - i) bentonite swelling capacity, (free swell or Enslin values)
 - ii) full PSD specification including the coarse and fine content specifications.(maximum 5% >125 mm)
 - iii) full chemical composition (without additives) including montmorillonite content.
 - iv) identification of any additives.
- h. A full density/moisture content calibration graph at a range of moisture contents around the optimum and the intended installation moisture content. Good BES mixtures typically have moisture contents of at least 2% above the optimum moisture content to allow the plastic deformation of clods, which results in a more homogenous as-placed macro structure.
- i. The source of the water (tap, surface or ground water) its chemistry including pH and resistivity and an assessment of the likely impact of the source water on the swelling capacity of the bentonite being used in the project. (Using where necessary, the bentonite free swell test ASTM D 5890)

9.0 Laboratory testing

9.1 Hydraulic conductivity

We recommend you use the British Standard (BS 1377:1990: Part 6: method 6) test for source testing quality assurance purposes. There is an important factor to consider when carrying out hydraulic conductivity tests on BES samples. You must allow the samples to hydrate and achieve equilibrium for a sufficient length of time to take account of the hydration characteristics of the bentonite component. Significantly lower hydraulic conductivities will be achieved when a sample is fully hydrated.

If the geochemical nature of the mixture water or support media soil water is thought to have an impact on the swelling characteristics of the bentonite or the BES mixture, then hydraulic conductivity testing must be carried out using the liquids to be used in the main works.

Your CQA engineer must ensure the testing laboratory undertaking the hydraulic conductivity measurements is fully aware of the hydration characteristics of the BES.

9.2 The Methylene blue test.

You should carry out a series of methylene blue tests using your intended support media and bentonite source over a range of bentonite concentrations. Use the results of these tests to produce a site specific calibration curve. You may then use this calibration curve in the bentonite quality assurance program. A standard test methodology is detailed in Appendix 1.

You can also use Methylene blue testing to assess the quality of the raw bentonite clay.

10 Quality control and assurance

Your CQA system must ensure that source materials are visually assessed before and during the mixing process at minimum defined intervals throughout the project. Any contamination identified, must be removed immediately and logged in the CQA engineers recording system. The record must include identification of changes in the nature and appearance of the source material.

10.1 Construction quality assurance

Where you are using a BES liner to fulfil the requirements of an environmental permit, we will require an independent third party CQA programme for the works. We therefore recommend you do the following:

- a.** Prepare a quality assurance statement, including full details of staff and their relevant experience, which should be submitted to us for approval. All personnel responsible for producing a BES mixture must be fully conversant with the specifications and the design mix requirements for the project.
- b.** Review the supply of raw materials (bentonite, support media and mixture water), mixing process, installation, quality control and quality assurance specifications and method statements prepared by your contractor.
- c.** Ensure that all materials tested in the laboratory design mixture and source report are representative of the materials to be used on site. All testing and calculations carried out in the design of the BES mixture must be presented at the design acceptance stage.
- d.** Provide supervision and quality assurance of the mixing and placement of the BES in accordance with the method statement agreed with us.
- e.** Ensure up-to-date calibration certificates are available for all equipment used for the measurement of support media, bentonite and water in the mixing process.
- f.** Keep records of all site operations, site conditions and testing. The records shall be made available for inspection by us. All records (including failed tests and areas of remediation) shall be included in the final validation report.
- g.** Prepare and submit to the licensee/operator a certification report on completion of the works.

During the construction of the liner or capping layer, you must follow the construction method statement as closely as possible. You must agree any amendments or variations in writing with us before proceeding.

You should carry out all testing as the work progresses. Where test results indicate poor mixing quality or placement, you must mark the affected area and take the appropriate remedial measures.

Your construction method statement must ensure the following actions are recorded and collated by the CQA engineer;

- a. The method of subgrade preparation, and acceptance criteria.
- b. The method of liner construction, including the plant to be used, lift thickness, minimum number of passes of compaction equipment and the methods for keying in individual lifts.
- c. The method to be adopted for the mixing of the BES including the tolerance values of all the ingredient control and measurement systems. This must be in the form of a clear and comprehensive process description.
- d. The allowable working ranges of classification indices, moisture content and density.
- e. The type, dimensions, weight and operating speed of the compaction plant, together with the frequency and energy of vibrating rollers or cross sectional area and arrangements of any studs or sheeps foot rollers (if applicable).
- f. The number of passes of the roller, or of each type of roller if more than one is used.
- g. The proposed method of determining the liner and lift thickness and the tolerance values of these measurements for the determination of thickness, gradient and extent.
- h. The differences in construction and testing techniques between base and side slopes (if any).
- i. Remedial action to repair damage to the liner resulting from the CQA sampling.
- j. Remedial action to be taken in the event of non compliance with any part of the specified criteria.
- k. Procedures for dealing with inclement weather, including frost damage, desiccation, ponding, water erosion and wetting during construction.
- l. The method for protecting the completed liner, including any temporary protection.
- m. Stability calculation for structures and slopes. This should include stability assessments, subsidence and settlement calculations including factors of safety, to show that the liner will be stable over the predicted lifespan.
- n. The specification for the preparation of the top surface of the liner if a flexible membrane is to be placed above it.

10.2 Documentation and reporting

Your CQA engineer must maintain a daily record of the work's progress, including:

- | | |
|--|---|
| a. Date | i. Material stockpiled or stored |
| b. Weather conditions | j. Visual inspections carried out of placed and mixed materials |
| c. Delivery of materials | k. Quality assurance installation checklist |
| d. Plant and labour | l. Placed material (number of lifts and spatial extent) |
| e. Materials used (source and quantity) | m. Site meetings |
| f. Batch or mix numbers | n. Progress photographs |
| g. Non-conforming materials | o. In -situ testing carried out (location and type) |
| h. Non-conforming areas of placed material | |

Your CQA engineer must provide us a brief, written weekly progress report outlining the following points.

- a. Progress in the last week.
- b. The support media source being used.
- c. Testing undertaken.
- d. The amount of BES produced.
- e. Any problems encountered.
- f. The work programme for the following week.
- g. Weather conditions.

10.3 Field quality control systems

Table 7 gives an indication of the scope of testing normally required during construction of a BES liner or cap. You should decide the actual methods and frequencies on a site and material specific basis, based on sound statistical assessment. Your method statement must also specify the accredited (NAMAS or equivalent) and risk based testing laboratory to be used.

10.3.1 Bentonite quality control

Your CQA engineer or inspector must maintain records of all deliveries of bentonite. For each bentonite batch delivered to site, you must record the following information:

- a. All relevant quality specifications set out in table 11 of this document.
- b. Supplier's compositional analysis.
- c. Batch number, date of production and source.
- d. The name of the supplier and the product name.
- e. The type of bentonite (Natural sodium, calcium, sodium activated).

A test certificate containing the information outlined above must accompany each delivery. You must not use any bentonite until it's properties have been fully verified and accepted by your CQA engineer or inspector.

Bentonite must be stored in a clean and dry environment. If the delivery is in bags, store the bags in separate locations to prevent the mixing of batches and deliveries.

10.3.2 Support media quality control

Your CQA engineer or inspector must clearly define all stockpiles of mixed BES. They must also give each batch a unique reference and record their position. Your CQA engineer or inspector must inspect all stockpiles of support media on a daily basis, this also provides a good opportunity to collect samples for compliance testing.

10.3.4 Rotor condition

Your CQA engineer or inspector must ensure at the start of each day that all mixing plant is in good working order.

It is important that the condition of any plant used for mixing BES is inspected at regular intervals during the mixing process. Your CQA inspector should carry out these inspections, looking for missing tines, blockages or waste entanglement.

10.3.5 Edges and beginning of mixing runs

For both the in-situ and divorced mixing methods, your CQA engineer or inspector should visually assess the efficiency of mixing at the beginning and end of each rotovator run when it is not operating at maximum speed. If full mixing efficiency is not achieved at the beginning of the mixing run, you must accurately define the extent of sub specification mixture during the construction of the trial pad.

Your CQA engineer must visually assess material from the edges of the test pad before inclusion in the liner to assess the completeness of mixing. The edges of each lift should be horizontally offset to avoid alignment with joints of lower layers.

10.3.6 Storing mixed BES

Any support media and mixed BES which is stored prior to placement must not be contaminated with topsoil. We recommend you avoid using the lowest 250mm of the stockpile if you've stored mixed BES on areas which are not concrete or hardstanding.

You must store the completed BES mixture in such a way to prevent wetting by rain or desiccation. We recommend you use mixed material within four weeks. If the mixture is stored for more than 24 hours, your CQA inspector must inspect it before use.

10.3.7 Immediacy of mixing process

If using either the in-situ or divorced mixing method, you must ensure the mixture is not exposed to:

- any rainfall.
- high winds.
- unmixed surface exposure for more than two hours. All bentonite must be mixed by the end of the day.

10.3.7 Position of stockpiles

Your CQA inspector must record the position of each batch of mixed BES using drawings and records. Your CQA inspector must ensure your contractor is kept informed of the position of each batch of BES.

10.3.8 Production rates

Your CQA inspector must ensure that only material worked in one day or shift is included in a particular stockpile or defined area of liner. Your records must show the placed extent of each stockpile, run or batch of mixed BES.

11 Overlapping

For divorced and in-situ installation methods, your CQA inspector must check the overlapping of the spread bentonite with areas of support media previously spread.

For mix in place installation, your CQA inspector must ensure at least three metres overlap at the start and end of each run. Similarly, an overlap of half a meter is required at the edge of each run. These overlaps ensure full integration of each panel. Where possible, your contractor should leave the leading edge of the previous panel uncompacted to allow the integration of the following panel. Where the previous panel has been compacted, your CQA engineer must ensure that adequate bonding is achieved between the panels. This includes checking the adequacy of mixing, bentonite and water dosage and presence of visual macro structures such as cracks or clods.

11.1 Surface regularity

The finished surface must be firm and smooth. In this context, firm means that indentations can't easily be made in the surface. For BES, shear strength should be $>50\text{kN/m}^2$. (Although this parameter will be design specific). For other materials such as sand the material should be $>90\%$ of its maximum dry density (using the 4.5kg rammer) to ensure no movement will occur during or after placement of the waste.

Smooth in this context means there should be no sharp angles in the subgrade which exceed + 10mm under a 1000mm lath (for example, at changes of grade due to rutting), and no large rounded irregularity may exceed + 50mm under a 3000mm lath).

11.2 Placement and compaction

The subgrade must be compact (see glossary of terms) and free of all standing water. We recommend using a smooth vibrating roller because of the lack of macro structure within the BES and the reduced thickness of the completed barrier.

11.3 Moisture content

The moisture content of mixed and placed material must not differ by more than +2% (w/w) from that used in the design mixture and trial pad. If the moisture content varies in excess of 2%, you must regard this as a failure. Your CQA engineer must then provide evidence that the BES is capable of attaining specification compaction, shear strength, bearing capacity and hydraulic conductivity.

11.4 Weather

You must not allow any kind of material placement during periods of heavy rain. Similarly, care is required to avoid losing bentonite during strong winds. If the BES mixture sticks to the compaction roller at any point, then work must stop. You must remove any placed and compacted BES which has become desiccated and either rework it with additional water or disposed of it.

11.5 Health and safety

As bentonite is a very fine dry material which is easily blown away, you must take care to prevent people from inhaling it. Bentonite can also cause irritation to the nose and eyes. When working with bentonite, staff must take suitable protective measures such as appropriate dust masks and goggles. Bentonite is not toxic, and may be washed from the skin with soap and water. For full health and safety information and a risk assessment on using and installing BES, please consult an appropriate health and safety authority, such as the HSE.

11.6 Depth control

The primary objective of assessing the depth of the BES is to provide assurance you have achieved the layer thickness you agreed with us. Where this is not the case, you must add further material to the layer to bring it up to the design specification. There two following methods are acceptable. Thickness measurements must be taken on a 10m grid.

Method 1.

A hole is made in the completed and compacted BES layer at the point where core samples are taken to check density or hydraulic conductivity or at the designated sampling frequency. This hole is extended to the top of the previous lift and the depth of the penetrated lift measured using a flexible steel rod. Measurement should be repeated at 90o intervals around the circumference of the hole, so that four measurements are obtained.

The hole must be repaired using an identical mixture compacted carefully into the hole or using pure bentonite identical to that used in the mixture. The CQA engineer must record all penetrations and the associated repair of the penetration.

Method 2.

Laser levelling may be used to control the thickness of the compacted BES lift. An accuracy of +5mm must be achievable. Measurements must either be on a continuous basis or on a 10 m grid.

11.7 Inter-lift bonding

Where you are placing more than one lift, you must scarify the surface of the previous lift prior to placing the subsequent lift. The scarifying should be sufficiently disruptive to ensure adequate bonding of each lift and the removal of any potential discontinuity and planes of weaknesses at the lift interface.

11.8 Covering and protection

You must protect the surface of the completed lift to avoid excessive wetting or desiccation. You must remove and discard any BES material affected by frost, this applies to both stockpiles and the liner itself. . You must offer us an opportunity to view the completed cap or liner before you cover it.

12 Validation report

You should include as a minimum the following information in your validation report.

- The results of all testing. This must include field and laboratory tests and the records of any failed tests with the details of the remedial action taken referred to the appropriate secondary testing. Any test results which fail due to poor sampling, specimen preparation or defective testing must be accompanied by a written explanation from the testing laboratory or Quality Assurance engineer. The results must be clearly presented and graphs and tables should be used where necessary.
- Records made of the quantities of mixture ingredients, mixing times, mixing plant operational parameters, mixed material standing time, condition of ingredients and finished material and semi hydrated state of the material.
- Plans showing the location of all tests.
- 'As built' plans and sections of the works.
- Copies of the site engineer's and/or QA inspectors daily record (including for example plant in use, work done, problems experienced and weather conditions)
- Records of any problems or non-compliance and the solution applied.
- Any other site-specific information considered relevant to proving the integrity of the liner by the Quality Assurance engineer or the Environment Agency.
- Validation by the Quality Assurance engineer that all of the works subject to QA and CQA procedures have been carried out in accordance with the method statement, designs and specifications agreed in writing with the Environment Agency.
- Drawings shall be provided showing the following:
 - construction details including pre installation levels, completed levels, and slope angles;
 - locations of each batch of material;
 - the location of all in -situ and destructive tests;
 - locations of failed and repaired materials;
 - details of as built overlaps with existing and future lining/capping elements;
 - details all other lining/capping system components;
 - photographs of the liner placement.

13 Conclusions

A high quality, consistently low hydraulic conductivity barrier may be produced with the careful application and enforcement of good practice and construction quality assurance across the whole of the BES production and installation process. A consistent and auditable quality system must be created from the selection of the support media to the installation and testing of the completed liner.

Variations in efficiency and performance can occur in any of the mixing methods if the production process is not closely monitored. It is with this in mind that we don't promote any one production method over another.

Figure 6 Performance specification and testing frequencies for the bentonite clay component of the BES mixture

Property	Test method	Limiting value	Frequency of testing	Comments
Montmorillonite content	XRD or Methylene Blue: CUR Recommendation 33 (see appendix 2)	>75% or >250mg MB per gram of bentonite.	Every batch (5000 tonnes or at least 1 per project which ever is less)	This test is to assess the quality of the bentonite ingredient component and is separate to the testing carried out on the completed BES mixture.
Moisture content (maximum)	ASTM D4643	At delivery: 9-14% At mixing:<15%	Every 250 tonnes	If the bentonite has a moisture content of >15% as a result of atmospheric conditions, measures must be taken to adjust the mixture to take account of the additional moisture content within the bentonite.
Particle size distribution (PSD)	BS1377 (1990) Part 2 method 9.	95% passing a 125µm screen	Every 250 tonnes	
Free swell index	ASTM D5890	±25 ml	Every 50 tonnes	
Fluid loss	ASTM		Every 250 tonnes	

Figure 7 Support media test types and their frequency for the quality control of a BES mixture design

Property	Test method	Limiting value	Frequency of test	Comments
Moisture content	BS1377 1990, Part 2 Method 3.2 or plant specific method with accuracy of +/-1%	Design specific	Every 500 m ³ or continuous measurement.	Where a site specific moisture content is used this must correspond to the moisture content used for the trial mix and field trials.
Methylene blue absorption	CUR Recommendation 33 (see appendix 2)	Design specific	Every 500m ³	The support media's methylene blue value is used in the mixture calibration curve to assess methylene blue value at zero added bentonite.
pH	BS1377 Part 3 Method 9	5.5. - 8.5	Every 5000m ³	This parameter must also be measured at any significant change in the nature of the support media.
Conductivity		1000	Every 5000m ³	This parameter must also be measured at any significant change in the nature of the support media.
Chloride content	BS1377 Part 3 Method 7	600ppm maximum	Every 5000m ³	This parameter must also be measured at any significant change in the nature of the support media.
Visual inspection	1.Before Mixing 2. During mixing 3. At Placement	Any significant variation from normal visual appearance of the support material.	Continuous or designated inspection frequency.	Any significant variation in the appearance of the support media must be backed by other characterisation tests.
Fines content (Mineral particles <63microns)	BS1377 1990, Part 2, Method 9	<10% <63microns	Every 500m ³	
Maximum particle size	BS1377 1990, Part 2, Method 9 or visual assessment by the CQA Inspector.	<20mm with a volume greater than 4cm ³	Every 500m ³	
Carbonate content	BS1377 Part 3 Method 6	5%w/w Maximum	Every 1500m ³	This parameter must also be measured at any significant change in the nature of the support media.
Organic content	BS1377 Part 3 Method 3	3%w/w Maximum	Every 5000m ³ and Continuous visual assessment by CQA Inspector.	This parameter must also be measured at any significant change in the nature of the support media.
Support media contamination	visual	see text definitions	Continuous	

Figure 8 Water component test types and their frequency for the quality control of a BES mixture design

Property	Test method	Limiting value	Frequency of test
Conductivity	To be agreed with the Environment Agency	1500 μ sv	At each significant change of water source.
pH	BS1377 Part 3 Method 9	>5 and <9	At each significant change of water source.
Chloride content	BS1377 Part 3 Method 7	600mg/l maximum	At each significant change of water source.
Hydraulic conductivity	BS1377 Part 6 Method 6	Design specific.	At each significant change of water source.

Note: significant is defined as for example as a change from mains to groundwater supplies or from one groundwater source to another.

Figure 9 Construction quality assurance testing during the construction phase

Test type	Test standard	Test frequency (divorced)	Test frequency (batch/continuous)	Test frequency (mix in place)
Moisture content of mixture.	BS1377 1990, Part 2 Method 3.2 or Mixing Method Specific	1/100m ³	1/100m ³	1/100m ³
Water added(l/m³)	Mixing Method specific. (To be agreed with the Agency)	Complete records presented in litre/m ³ and litres	Continuous measurement (with printout) as litre/m ³ and litres	Complete records in litres with extrapolation to litres/m ³
Support media added	Mixing Method specific.	Complete record presented in Kg	Continuous measurement (with printout) in kg	Weigh bridge records of support media used.
Bentonite added	Mixing Method Specific.	Complete record presented in kg and as a %w/w	Continuous recording in kg and as a %w/w	Complete record presented in kg and as a %w/w
Moisture content (as placed)	BS1377 1990, Part 2 Method 3.2	1/250m ³	1/250m ³	1/250m ³
Liquid limit (as placed)	BS1377 1990, Part 2 Method 4.3	1/250m ³	1/250m ³	1/250m ³
Plastic limit and plasticity index (as placed)	BS1377 1990, Part 2 Method 5.3	1/250m ³	1/250m ³	1/250m ³
Particle density	BS1377 1990, Part 2 Method 8	1/500m ³	1/500m ³	1/500m ³
Hydraulic conductivity (as placed)	BS1377 1990, Part 6, Method 6	1/500m ³	1/500m ³	1/500m ³
Particle size distribution (of mixed BES)	BS1377 1990, Part 2, Method 9	1/500m ³	1/500m ³	1/500m ³
Lift thickness	Method 1(see text) Method 2 (see text)	1/250m ² /lift 10 metre intervals	1/250m ² /lift 10 metre intervals	1/250m ² /lift 10 metre intervals

Test standard	Test frequency (divorced)	Test frequency (batch/continuous)	Test frequency (mix in place)	Test standard
Compacted surface evenness	See text	1/500m ² /lift	1/500m ² /lift	1/500m ² /lift
Density (in-situ)	BS1377 1990, Part 9, Methods 2.1,2.2,2.4 or 2.5	1/250m ³	1/250m ³	1/250m ³
Bentonite spreading rate.	Designer specified (usually over a 1 metre square area.)	Not Applicable	Not applicable	One every 5 mixing runs and at the beginning of each shift.
Bentonite content of mixed BES	Methylene blue test CUR Recommendation 3 (see appendix 4)	1/500m ³	1/500m ³	1/250m ³
Visual homogeneity (of placed material)	Designer specified	1/250m ³ or were modifications are made to the mixing or installation process.	1/250m ³ or were modifications are made to the mixing or installation process.	1/250m ³ or were modifications are made to the mixing or installation process.
Mixing quality of BES	CUR Recommendation 33 (see appendix 5)	Three per project or were modifications are made to the mixing or installation process.	Three per project or were modifications are made to the mixing or installation process.	Three per project or were modifications are made to the mixing installation process.

Note: The method and format of presentation of the continuous recording data should be agreed with the installer prior to the commencement of works. It is also important all data from continuous measurement of mixing parameters is kept for record purposes.

Glossary of terms

The following definitions have been used throughout the document. (Different terms may be used throughout literature and the industry to refer to the same items)

Batch mixer

Mixing carried out in batching plant, this may be continuous or timed. Support material, water and bentonite are mixed together in a chamber. The mixed material is transported from the mixer to the liner where it is compacted.

Bentonite

Bentonite is a soft rock consisting of clay minerals of colloidal nature and is a product of the weathering of volcanic tuff or ash. Its main constituent is the clay mineral montmorillonite together with associated minerals such as quartz, tridymite, cristobalite, mica, feldspar, pyrite and calcite. The mineral is mined from various locations across the world before it is ground to form to a powder. Various additives may be added to the bentonite to enhance its performance.

There is a wide range of bentonite available on the market for a variety of uses ranging from drilling muds through to moulding sands. They can be natural, chemically treated and/or have polymers to enhance certain properties.

Sodium bentonite has the greatest swelling capacity, but its unit cost in Europe is high. Calcium bentonite is an absorbing but relatively low swelling clay. Measurements of high cation swelling capacity (CEC) generally indicate whether it is a sodium or calcium bentonite.

Natural calcium bentonite may be treated with sodium salts to produce sodium activated bentonite. Sodium ions are exchanged for the calcium ions to enhance the materials swelling capacity.

Various polymers are used to alter properties for specific uses but these are generally proprietary additives and their identity is commercially confidential. Adequate information is required from the suppliers on the long term performance and ideally the mixture should be tested with anticipated leachate or individual solutions that could pose potential leaching problems when in contact with the BES mixture.

Bentonite enriched soils (BES)

BES may be defined as a processed mixture of powdered bentonite clay with a support material together with the contemporaneous addition of water to produce a material with enhanced low permeability characteristics.

BES may be used to create a low permeability barrier suitable for use as a landfill capping or lining layer. Bentonite Enriched Soil is manufactured by mixing a granular support media (typically of sand sized particles) with a powdered bentonite clay with the addition of moisture to produce a very low permeability mineral liner.

BES liners have been used as a primary single liner or a secondary liner as part of a composite or multi-barrier system. The design context of the BES element of the lining system is very much determined by the specific performance requirements of each site. However a number of minimum performance specifications are applicable for every lining and capping application.

Cation exchange capacity

Variations in charge and size of the montmorillonite platelets will occur, depending on their source. These variations affect the swelling characteristics of the material and thus the quality. The thickness of the montmorillonite platelets varies between 1-8nm and the surface charge is given by the cationic exchange capacity (CEC), the amount of the platelets. Values can range from 80 to 150 meq/100g.

Divorced mixing

As for the mix in place method only carried out a location away from the liner.

Homogeneity

The degree of perceptible uniformity achieved in a BES mixture.

Mix in place

Mixing is carried in -situ using a rotovator. Bentonite is spread over the support media and mixed with or without the addition of water. The mixed material is then compacted.

Mixing quality

The degree to which the bentonite component is mixed homogeneously throughout the support media.

Mixing water

The water required to bring the moisture content of the mixture to the required level. The mixture water may be ground, surface or tap water.

Mixture

The mixture of a granular support material with bentonite, mixing water and any adjutants.

Polymer additives

Polymers are long chain molecules that attach themselves to the plate like structure of the clays and stabilise the structure. Long term tests carried out to date suggest no significant changes in these properties with time.

Support media

The granular material, which is mixed with powdered Bentonite clay to produce when compacted a material with enhanced low hydraulic conductivity characteristics. The existing permeability of the support media determines the quantity of bentonite clay required to bring about the ultimate specification permeability.

Support media may be natural sand or a mine or quarry waste with a suitable particle size distribution.

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Appendix 1: Quantitatively determining the amount of active clay within geosynthetic products and bentonite enriched soils by X-ray diffraction

Swelling clays are utilised in geosynthetic clay liners (GCL) and bentonite enriched sands (BES) to provide an impermeable barrier for use in construction of containment landfill sites. The permeability and hence efficiency of the barrier will be affected by the amount and type of clay used. Quantitative X-Ray diffraction provides a method of determining this.

1.1 Scope of method

This method identifies and quantifies the physical properties of the active clay. It provides a method to quality assure the clay component of a GCL or BES.

1.2 Definitions and terminology

Polymer: Any additive introduced to a clay product that will act when hydrated to change the expected performance of the CGL.

1.3 Principle

The active clays bentonite may be accompanied by amorphous material and other fine clay grade mineral fragments that make up the plastic mass. X-ray diffraction provides a method of identifying the mineral phases. When placed in a diffracting position the crystalline components will produce a series of characteristic peaks and background according to their individual crystal lattice setting. Using a combination of bulk analysis and narrow particle extraction it is possible to identify the active clay type, its abundance, and other accompanying crystalline phases, together with an inferred amorphous content. The peak position indicates the type of phase present, movement upon ethanediol solvation indicates the maximum expansion, phase abundance is determined using peak height calibrated by integral width. If the active clay is interstratified its degree of interstratification can also be recorded. The moisture content as supplied can be calculated using this method.

1.4 Apparatus and reagents

1.4.1 X-ray powder diffractometer system, capable of recording the diffracted X-ray pattern (profile) onto paper.

Note: This X-ray equipment should conform with the appropriate statutory safety regulation for ionising radiation.

The output produced on paper shall be such that:

- the linear distance equivalent to an angular range of 34\AA to 2.23\AA is recorded at a step size of 0.04 and a count time of 60 seconds per step;
- the data collected are achieved by exposing a constant sample area to the radiation source utilising an auto-divergence slit or similar device;
- the radiation used is sourced from a normal or broad focus tube to maximise area saturation and increase peak to background ratio; if fine or long-fine tubes are to be used the analysis parameters shall be adjusted to give identical performance to a normal focus tube;
- the pattern shall be free of $K\alpha_2$ radiation and secondary fluorescence by adjustment of pulse height selection and the use of an appropriate form of monochromation;
- particle statistical factors shall be considered prior to and during analysis;
- Sample spinning and the use of a fine and narrow particle range will reduce statistical errors during sampling;

- a means of peak measurement is required so that position, height and width of each diagnostic peak can be recorded.

1.4.2 Sample preparation equipment.

- Grinding mill capable of reducing all particles in the sample to less than 20 mm when used as described in this method; without inducing additional amorphous components and without detectable contamination from the grinding media. It is recommended that agate media be used.
- Balance capable of weighing to an accuracy of 0.0001g (validated).
- Bulk sample holder capable of holding >1.5 grams of dry powder randomly.
- Clay sample holder capable of holding a 25 mm diameter silver filter.
- Silver filters 25 mm diameter, 0.45 mm pore size, 25 mm diameter, 0.26 mm thick with 1.2m retention or equivalent.
- Filtration apparatus that will give an even coating of clay beyond the illumination area of the incident X-ray beam and to a depth that all radiation is used up by extinction before it penetrates the filter substrate.
- Volumetric flask grade A, 5ml glass.
- Graduated pipette, 0 to 5ml.
- Temperature controlled high capacity ultra centrifuge and vials capable of sustaining 9000 rpm at constant temperature.
- Drying apparatus capable of collecting particles of clay in the range of 0.1 to 0.15 mm. Freeze drier recommended.

1.4.3 Reagents

- Ethanediol AR;
- Water HPLC grade;
- Propan-2-ol AR.

1.5 Procedure

1.5.1 Preliminary sample preparation:

1.5.1.1 Dry the bentonite at 60°C to constant weight (to remove inter-layer water only).

1.5.1.2 Weigh out 50g by difference - standard analytical procedure (of supplied bentonite) to the nearest 0.01 g into a watch glass and dry for 15 hours. Record supplied and dried weight and label difference as "moisture content".

1.5.1.3 Weigh (standard analytical procedure) into the grinding mill container a representative sub-sample as recommended by the mill manufacturer.

1.5.1.4 Add an appropriate amount of propan-2-ol and grind for such a time as is necessary to reduce the maximum diameter of all particles to less than 20mm.

1.5.1.5 Dry again at 60°C in a fume cupboard to remove propan-2-ol.

1.5.2 Mounting bulk sample:

1.5.2.1 Pack a sub-sample of the fine homogeneous dry powder into a specimen solder (back fill recommended) to produce a random powder mount.

1.5.2.2 Using only hand pressure for consolidation, mount the sample into the X-ray diffractometer.

1.5.2.3 Generate the diffractogram and record required information (label "prehydrate"). This will give the bulk mineralogical weight percents of all phases in sample.

1.5.3 Hydration of bulk sample

1.5.3.1 Remove the powder from the sample holder (plus the remainder of dry powder) and place in 50ml of pure water for 6 hours and then dry at 60°C as before.

1.5.3.2 Regrind the sample and mount the sample into the X-ray diffractometer in the normal way.

1.5.3.3 Generate the diffractogram and record required information (label "hydrate"). This will show if the added polymer (if added) will inter-react with the bulk mineralogical weight percents of the active clay in the sample.

1.5.4 Extraction of active clay component

1.5.4.1 Disaggregation

1.5.4.1.1 Place 20 grams of sample into a large test tube and add 100 ml of purewater HPLC grade, shake well. Allow to stand for 1 hour.

1.5.4.1.2 Shake the sample and quickly decant the obvious fine fraction and transfer it to a plastic container for ultrasonic treatment. Ultrasonic disaggregation is a crucial contributor to good preparations. The best instruments are the horn type devices that produce 100 or more acoustical watts at the transducer tip. Irradiate the sample for a few minutes (3 min at 100w), allow it to settle for a minute or so and decant the fines to a centrifuge tube.

1.5.4.2 Particle size separation

1.5.4.2.1 At this point ideally the suspension has particles of single crystals. Remove any excess salts or added polymer by washing and centrifugation with pure water.

1.5.4.2.2 The next step is the separation of the clay size fraction which we take here to be 15µm equivalent spherical (esd). Particle size separations are based on Stoke's law and it applies strictly to spherical particles which platy clay minerals (bentonite) are not. So using Stoke's law, which is a numerical expression that describes a particle being pulled by gravity but whose fall is restricted by a viscous fluid. The balance between these two forces results in a terminal velocity V_T that is conversely proportional to viscosity of the liquids and proportional to the force of gravity g (in cm.s^{-2}). It is also directly proportional to the difference in density between the particle and the liquid ($d_p - d_l$) and the particle diameter squared D^2 in square centimetres. The equation for Stoke's law is:

$$V_T = \frac{g(d_p - d_l)D^2}{18\eta}$$

1.7. Calculations and expression of results

The intensity (energy per second) of a reflection (hkl) in a powder diffraction pattern is given by the complete formula below:

$$I(hkl) = \frac{(1 + \cos^2 2\theta) I_0 e^4 \lambda^3 dN^2 p F^2 T A V}{32\pi m^2 c^4 r (\sin^2 \theta \cos \theta)}$$

Where:

I	Intensity of X-rays diffracted by (hkl) plane
I_0	Intensity of primary X-ray
e	Charge of electron
m	Mass of electron
λ	X-ray wavelength
D	Slit width of detector
c	Velocity of light
r	Specimen to detector distance
N	Number of unit cells per unit volume
P	Multiplicity factor
F	Structure factor
θ	Bragg angle
T	Temperature factor
A	Absorption factor
V	Volume of powder in the beam

Formula (1) can be considered as two main factors affecting intensity of a given (hkl) reflection: a) diffractometer factor and b) sampling factor:

$$I = T \left(\frac{(1 + \cos^2 2\theta) e^4 \lambda^3 dI_0}{32\pi m^2 c^4 r (\sin^2 \theta \cos \theta)} \right) (N^2 A V p F^2)$$

Let nabla (∇) represent the diffractometer factor which is a constant for a given diffractometer provided that tube decay and atmospheric conditions are a constant:

$$\nabla = T \left(\frac{(1 + \cos^2 2\theta) e^4 \lambda^3 dI_0}{32\pi m^2 c^4 r (\sin^2 \theta \cos \theta)} \right) \text{ equation (3)}$$

Substitution of expression 3 into equation 2 gives:

$$I = \nabla N^2 A V P F^2 \quad \text{equation (4)}$$

Under ideal conditions with perfect trigonometric design let $\rho = 1$

$$I = N^2 A V \rho F^2 \quad (5)$$

For a given sample(s) let the collective factors ($N^2 A \rho F^2$) of absorption be a constant for that sample K_s therefore:

$$I = K_s V \quad (6)$$

This is only true under two conditions: a) if the sample is always a reproducible uniform thickness or b) if the sample has infinite thickness. This is because as the radiation penetrates deeper into subsequent atomic planes more atoms are irradiated. The resulting wave front is constructive when X-rays are in phase. This amplification of radiation is proportional to the amount of reflecting nodes or atoms exposed to the X-ray beam. It is therefore possible to deduce that abundance of atoms (X) is proportional to radiation intensity (4) and is expressed in equation (7):

$$I \propto X \quad (7)$$

Let K_s be the constant for proportionality of equation (7) where K_s is a factor containing the mass absorption coefficient of the total sample. Expression (8) is the same as formula (6) when the factor for density of the component is 1.

$$I = K_s X \quad (8)$$

where K_s is the absorption constant of component s, I_s is the corrected intensity and X_s the weight fraction of component s.

$$X_s = \frac{I_s}{K_s} X_c = \frac{I_s}{K_c} \quad (9)$$

where c is a calibration standard of known properties. For a binary system the following formula is resolved by equating equation (9).

$$\frac{I_c}{X_c K_c} = \frac{I_s}{X_s K_s} \quad (10)$$

Equation (10) is in the form of $Y = mX$ with three ratios: I_c/I_s corrected intensity of component s with respect to a standard intensity c; X_s/X_c is the ratio of the weight fractions of component s and calibration c in a binary mixture; K_s/K_c is the ratio of the correction intensities for that binary system and related directly to Berry (1972). This relationship is always a straight line passing through the origin (Chung 1974).

$$\frac{I_c K_s X_s}{I_s X_c K_c} = 1 \quad \frac{I_s}{I_c} = \left(\frac{K_s}{K_c} \right) \left(\frac{X_s}{X_c} \right) \quad (11)$$

The relationship observed in equation (11) holds true for each derivation of equation (1) whether the assumption is made that the volume of an irradiated sample is a constant irrespective of Bragg angle or probability of orientation, texture and particle statistics are considered.

Transposition of equation (11) gives the standard working formula for the addition method (Chung 1974) where I_c and I_i are the observed intensity from the addition of a weight fraction of calibration standard X_c :

$$X_i \frac{X_c I_i}{K_i I_c} \quad (12)$$

If this formula is expanded to take into account the crystallinity index of the reflection the observed intensity I_i becomes I_s which takes into account peak shape and is free of overlap errors experienced by estimation of area. Any errors are systematic and are flushed out by K_s

$$X_s = \left(\frac{X_c}{K_s} \right) \left(\frac{I_s \alpha_s}{I_c \alpha_c} \right) \quad K_s = \left(\frac{I_{i50} : 50 \alpha_{ii50} : 50}{I_{i50} : 50 \alpha_{cc50} : 50} \right) \quad (13)$$

In addition to this each diffractometer has its own unique trigonometric design tailor made for the particular user's requirements. This would indicate that as nabla is a constant for a particular diffractometer it is not a constant for all diffractometers. Treating the diffractometer in the same way as the sample, variation between diffractometers can be corrected by the use of an internal standard which would give a correction factor for that diffractometer ∇ . Re-integration of nabla into equation (13) gives the working formula for quantitative X-ray diffraction, equation (14). Notice that the formula presented here produces data unnormalised and is not affected by errors associated with undetected and amorphous phases.

$$X_s = \nabla \left(\frac{X_c}{\left(\frac{I_\delta \alpha_\delta}{I_\gamma \alpha_\gamma} \right)} \right) \left(\frac{I_s \alpha_{ss}}{I_c \alpha_{cc}} \right) \quad (14)$$

Where:

X_s = weight fraction of phase s

X_c = weight fraction of the calibration spike c

I_δ = observed intensity in counts at peak maxima of phase s when mixed with calibration spike c in a 1:1 ratio

α_δ = the corrected full width at half peak maxima after peak deconvolution for phase s

I_γ = observed intensity in counts at peak maxima of calibration spike c when mixed with phase s in a 1:1 ratio

α_γ = the corrected full width at half peak maxima after peak deconvolution for phase c

I_c = observed intensity in counts at peak maxima of phase s within the mixture

α_c = the corrected full width at half peak maxima after peak deconvolution for phase s within the mixture

∇ = diffractometer calibration factor

1.8 Report

The test report shall contain the following information:

- a) The number and year of publication of this standard;
- b) The test laboratory and, if required, the test operator; the date of the test;
- c) A description of the product tested;
- d) Details on the equipment used;
- e) The experimental data and calculations for each specimen, their average and standard deviation;
- g) Any deviation from the standard.

2. Method for determining of methylene blue value of bentonite

Purpose and application

2.1 Scope

This methodology describes how the absorption of methylene blue by bentonite is determined. The test has been developed for landfill engineering applications where it is required to assess the montmorillonite content of clays used in geosynthetic clay liners and bentonite enhanced soils.

2.2 Principle

A bentonite sample dispersed in water is titrated with a methylene blue solution until a light blue "halo" appears round a dark blue coloured drop of bentonite suspension on filter paper.

2.3 Equipment and reagents

2.3.1 Equipment

- analytical balance with a measurement accuracy of 0.01g
- combined magnetic stirrer and hot plate
- drying oven (93±3)°C and (1 10±5)°C
- burette
- tripod
- 300 ml wide necked Erlenmeyer
- plastic rod
- 1000ml measuring flask
- magnetic stirrer rod
- 1 litre polyethylene bottle with screw closure
- 10ml sampling pipette
- 5ml sampling pipette
- round paper filter with a centre line of 150mm
- drying scales

2.3.2 Reagents

- - distilled water;
- - methylene blue ($C_{16}H_{18}C1N_3S \cdot x H_2O$ ($x = 4$ to 5)) p.a., 0.5 %
- - 0.5% methylene blue solution
- - sulphuric acid 2.5 mol/l
- - peptisator (saturated solution of tetrasodium diphosphate $Na_4P_2O_7 \cdot H_2O$).

2.4 Preparation

2.4.1 Methylene Blue Solution

Weigh 5g of undried methylene blue to an accuracy of 1 mg (A). Dissolve this quantity in 600ml lukewarm distilled water. Decant the solution after 24 hours into a one litre measuring flask. Boil the residue in 100ml water and after it has cooled add to the remainder of the solution in the measuring flask. Then fill the measuring flask to one litre with distilled water.

Dry around one gram methylene blue (Bv) to constant weight at $93 \pm 3^\circ C$ (Bd). Then calculate the strength of the methylene blue solution in mg $C_{16}H_{18}C1N_3S \cdot 3H_2O$ per ml, to an accuracy of 0.001 mg MB/ml. Keep the methylene blue solution in a dark room.

Note: Because of the strong colouring effect of methylene blue this substance shall be used with care.

2.4.2 Bentonite

Weigh the dry weighing scale (F). Take a representative part sample of the bentonite of around 500g and determine the weight of the scale with the sample (G). Keep the remaining part of the bentonite sample. Dry the part sample for at least 24 hours to constant weight in an oven of $110 \pm 5^\circ C$. Then determine the weight of the scale and the dried sample (H). The mass determinations must be carried out to an accuracy of 0.1g. the moisture content (D) of the bentonite must be calculated accurately to 0.1 %.

2.5 Procedure

2.5.1 Weigh 500mg (E) of undried bentonite and transfer this to an Erlenmeyer. Add to this 50ml of water and 5ml of peptisator. Place the Erlenmeyer on the hot plate and stir the contents for 10 minutes. Heat until the suspension boils.

2.5.2 Turn off the hot plate when the liquid is boiling. The bentonite shall be fully in suspension. Wait until the liquid has cooled to room temperature and add 2 ml H_2SO_4 (2.5 mol) and stir the suspension for half a minute. Then add 80 to 90% of the anticipated final use to methylene blue solution and stir the suspension for 120 ± 10 seconds.

2.5.3 Place two pieces of filter paper on top of each other, onto which the liquid must be dotted. Titrate the cooled bentonite suspension with the methylene blue solution and stir the liquid regularly. Because of the accuracy required titration shall not be carried out in steps of more than 1 ml. Every 2 minutes dot a drop from the suspension onto the filter paper using a plastic rod. To determine the end point of the titration add 1 ml of the methylene blue solution each time, stir the suspension for 120 ± 10 seconds and dot again.

2.5.4 Do not add any more methylene blue solution to the suspension when the first halo is seen (the light blue coloration around the dark blue dot). Stir the suspension for (120 ± 10) seconds and then dot a drop of the suspension onto the

filter paper. If the halo remains then the end point has been reached. Otherwise add another 1 ml of methylene blue solution and repeat the procedure until the end point is reached.

Note: The quantity of methylene blue solution used as the number of ml added at the point when the halo is not quite visible (V).

During the gradual addition of the methylene blue solution the colour of the liquid circle (halo) on the filter paper changes as follows:

1. colourless when the bentonite is not saturated with methylene blue;
2. light blue when the bentonite is just saturated (end point);
3. blue when free methylene blue is present.

For a better recognition of the end point it is recommended that the same point be dotted a few more times.

2.6 Calculations and expression of test results

Calculate the concentration of the MB solution in mg MB/ml, from:

$$C = \frac{A}{K} \times \frac{B_d}{B_v} \times \frac{mMB.3H_2O}{mMB.0H_2O}$$

where:

- C is the concentration of the MB solution, in mg MB/ml;
- A is the quantity of methylene blue weighed, in mg (solution);
- B_v is the quantity of methylene blue weighed, in mg (before drying);
- B_d is the weight of the methylene blue after drying, in mg;
- mMB. 3H₂O is the molecular weight of MB with 3 molecules of water of crystallisation (= 373.90);
- mMB. 0H₂O is the molecular weight of MB with 0 molecules water of crystallisation (= 319.85);
- K is the volume of the measuring flask, in ml (1000 ml).

Calculate the moisture content of the bentonite in % (w/w) with respect to the dry weight, from:

$$D = \frac{G - H}{H - F} \times 100 \%$$

where:

- D is the moisture content of the bentonite with respect to the dry weight, in % (w/w);
- F is the weight of the scale, in g;
- G is the weight of the scale and the wet sample, in g;
- H is the weight of the scale and the dry sample, in g.

Calculate the methylene blue value of the bentonite, accurately to 10 mg MB/g, from:

$$MB = \frac{V.C}{\frac{100E}{100 + D}}$$

where:

- MB is the methylene blue value of the bentonite, in mg MB/g;
V is the quantity of MB solution used, in ml;
C is the concentration of the MB solution, in mg MB/ml;
E is the quantity of bentonite weighed, in g;
D is the moisture content of the bentonite with respect to the dry weight, in % (w/w).

2.7 Test report

The test report shall contain the following information:

- a) The number and year of publication of this standard;
- b) The test laboratory and, if required, the test operator; the date of the test;
- c) A description of the product tested;
- d) Details on the equipment used;
- e) The experimental data and calculations for each specimen, their average and standard deviation;
- f) Any deviation from the standard.

Appendix 2: Determining the minimum bentonite content necessary in a BES to meet a hydraulic conductivity specification

Purpose and application

A compacted mixture of BES varies in permeability, partly depending on the bentonite content. The purpose of the test is to check with what minimum bentonite content the specification hydraulic conductivity is met.

Principle

The permeability of a number of mixtures of BES with an increasing bentonite content must be measured with various degrees of compaction, depending on the use of the mixture. One must determine at what bentonite content the specification hydraulic conductivity is met.

Requisites

Apparatus: balance with an accuracy of a maximum of +/-1 g, forced mixer.

Equipment: bins, plastic bags, graph paper.

Preparation

Determine the moisture content of the bentonite and the support material by drying at (110±5) °C to constant weight. Where the support material is too wet, this must be dried in air at room temperature until the moisture content is reduced sufficiently to be able to carry out the tests.

Make at least three mixtures of BES with an increasing bentonite content (in steps of 1 or 2 %). Make at least one mixture with the bentonite content which is thought to be the one required. One mixture must have a 1 or 2 % higher bentonite content and at least one other mixture a 1 or 2 % (w/w) lower bentonite content than the quantity anticipated to be required. Express the bentonite content as the percentage of dry bentonite with respect to the dry support media.

Weigh off:

Step A.

$$Ax \left[\frac{100 + w_z}{100} \right] \text{ Kg undried support material}$$

where

w_z is the moisture content of the support media with respect to the dry weight, in % (w/w);

A is a factor, depending on the required quantity of mixture, which must be at least 10.

Step B.

$$Ax \frac{B}{100} x \left[\frac{100 + w_z}{100} \right] \text{ kg of undried bentonite}$$

where

w_b is the moisture content of the bentonite with respect to the dry weight, in % (w/w);

B is the required bentonite content expressed in dry bentonite with respect to dry support media, in % (w/w).

Add the support media to the bin of the mixer and add the bentonite. Mix the support media and the bentonite for two minutes in a forced mixer. Check whether after mixing a homogenous mixture has been obtained free from lumps. Keep the mixed material in sealed plastic bags or in sealed bins.

Immediately after mixing, determine the maximum Proctor density and the optimum moisture content in accordance with the normal 2.5kg Proctor test as **BS1377 Part 4, Method 3.3**. Provided that the mixture does not have to be dried and that for each moisture content new material is used from the mixing bin.

Starting with a degree of compaction of 95 % make two test specimens for each mixture for measuring the permeability as per **BS1377 Part 6 Method 6**. The moisture content of the test specimens (w) must be 2.0 % (w/w) lower than the optimum moisture content. Weigh a sufficient quantity of mixture for making the test specimens and mix this with the required quantity of water for 2 minutes in a forced mixer. Make the test specimens immediately after mixing and protect the mixture from drying out.

Execution

Measure the permeability of the 6 test specimens (k value) as per BS1377 Part 6 Method 6. Plot the measured k value (Y axis) graphically against the bentonite content (X axis). The Y axis must have a logarithmic scale distribution. Determine on the basis of this graph the bentonite content whereby the k value meets the required permeability criterion based on the degree of compaction used, to 0.1% (w/w) accuracy.

Calculation

Calculate the quantity of water to be added based on Y kg mixture, to 1g accuracy, from:

$$X = 1000xYx \frac{wx \left[1 + \frac{B}{100} \right] \left[w_z + wx \frac{B}{100} x w_b \right]}{100 + w_z + Bx \left[1 + \frac{w_b}{100} \right]}$$

where:

X is the quantity of water to be added, in g;

- w is the required moisture content with respect to the dry weight, in % (w/w);
- B is the bentonite content of the mixture expressed in dry bentonite with respect to the dry granular material, in % (w/w);
- w_z is the moisture content of the granular material, in % (w/w) with respect to the dry weight;
- w_b is the moisture content of the bentonite, in % (w/w) with respect to the dry weight.

The minimum required bentonite content is the bentonite content with which the permeability criterion is met.

Appendix 3: Determining the bentonite content of a BES

Purpose and application

This work regulation describes a fast method for determining the bentonite content in a BES sample. This method is suitable for determining the bentonite content in a field laboratory on site. The bentonite content as described in this method relates to the content expressed as a percentage of dry bentonite with respect to dry support media.

Principle

A sample of BES is dispersed in water is titrated with a methylene blue solution until a light blue 'halo' appears around a drop of dark blue coloured bentonite particles on filter paper. With the help of a blank determination of bentonite and support material the bentonite content of the mixture is calculated.

Requisites

Apparatus: combined magnetic stirrer/hot plate, microwave, balance with an inaccuracy of 0.01g, burette, tripod.

Equipment: 300 ml wide-necked Erlenmeyer flask, small steel scoop, 2 magnetic stirring rods, plastic stirring rod, 2 sampling pipettes (5 ml and 10 ml), filter paper (centre line 150 mm), drying scales, bin with cold water or running water.

Chemicals: methylene blue (MB) solution with known concentration (mg/ml) (see appendix 2), peptisator (a saturated solution of tetrasodium diphosphate $\text{Na}_4\text{P}_2\text{O}_7 \cdot \text{H}_2\text{O}$), 2.5 mol sulphuric acid, distilled water (siphon).

Preparation

Determine the moisture content of the bentonite, support material and BES by drying (in stages) in a microwave oven to constant weight. This is achieved when the weight after 1 minute drying reduces by less than 0.01 g. Make sure that the bentonite does not blow away. First weigh the empty and dry scale (D) and then the scale with the moist sample (E). After drying, determine the weight of the scale with the dry sample (F). Carry out the mass determinations to an accuracy of 0.01 g. Calculate the moisture content of the bentonite (w_b), the support material (w_z) and the BES (W_{zb}). Keep the samples. Do not use the material dried in the microwave for other purposes.

Execution

Blank determination of bentonite

Place the magnetic stirring rod in the Erlenmeyer flask. Add around 0.5 g of moist bentonite (b_v) and calculate to an accuracy of 0.1 g, the dry weight (b), based on the moisture content (w_v). Then add around 50 ml distilled water and 5 ml peptisator using a pipette. Bring the suspension to the boil while stirring and boil for around 1 minute. Then let the suspension cool to around 20°C by placing the Erlenmeyer flask in cold water (the Erlenmeyer must not feel warm any more). Then after cooling add 2 ml 2.5 molar sulphuric acid with the help of a pipette and stir the whole thing on the cold hot plate for 1 minute.

With the help of the burette add an MB solution as follows (cumulative): 5 ml, 10 ml, 20 ml, 21 ml, 22 ml, 23 ml, etc. Stir the suspension after each addition for around 30 seconds. Place two pieces of filter paper on top of each other and dot one drop of the suspension on this using the plastic rod and after 20 seconds a further drop.

While adding the MB solution in stages the colour of the liquid circle around the patch (halo) changes as follows:

- i. colourless, where the bentonite is not saturated with methylene blue;
- ii. light blue, where the bentonite is just saturated (end point);
- iii. blue, where free methylene blue is present.

Where the halo seems to be discolouring, stir the suspension for (120"10) seconds and dot again. Continue to add MB solution in stages (1 ml each time) until a clear halo can be seen. Hold the filter paper against the light to determine the 'turning point'. Note the quantity of MB solution used and the number of ml added at the point where the halo is not yet quite visible (B), to an accuracy of 1 ml.

Blank determination of support media

Determine the consumption of MB solution by the support media in accordance with 4.5.1. Weigh around 10 g moist support media (z_v) to an accuracy of 0.01 g, of which the dry weight (z) is calculated using the moisture content (w_z). Determine the quantity of MB solution (Z) used by adding the MB solution in stages of 1 ml.

Determination of BES mixture

Determine the consumption of MB solution by the BES in accordance with 4.5.1. Weigh around 5 g of moist BES (z_{bv}) to an accuracy of 0.01g, of which the dry weight (z_b) is determined using the moisture content (w_{zb}). Determine the quantity of MB solution (Z_B) used by adding the following cumulative quantities of MB solution: 5 ml, 10 ml, 15 ml, 16 ml, 17 ml, etc.

Calculations

Calculate the moisture content with respect to the dry mass, to an accuracy of 0.1% (w/w):

$$w = \frac{E - F}{F - D} \times 100\%$$

where:

w is the moisture content, in % (w/w) with respect to the dry weight;

D is the weight of the scale, in g;

E is the weight of the scale and the wet sample, in g;

F is the weight of the scale and the dry sample, in g.

Calculate the dry weight to an accuracy of 0.01 g, from:

$$m = \frac{m_v}{100 + w} \times 100$$

where:

m is the dry weight, in g;

m_v is the moist weight, in g;

w is the moisture content, in % (w/w) with respect to the dry weight.

Calculate the bentonite content, to an accuracy of 0.1 % (w/w) from:

$$A = \frac{1 - \left[\frac{z_b}{ZB} \right]}{\left[\frac{z_b}{ZB} \right] - 1} \times 100\%$$

where:

- A is the content of dry bentonite with respect to dry granular material, in % (w/w)
- b is the dry weight of the bentonite, in g;
- B is the consumption of MB solution by the bentonite, in ml;
- z is the dry weight of the granular material, in g;
- Z is the consumption of MB solution by the granular material, in ml;
- z_b is the dry weight of the sand-bentonite, in g; the consumption of MB solution by the BES, in ml.

Remarks

Where upon the start of the test the bentonite content is known approximately, this may be taken into account when adding MB solution. This is to prevent the 'turning point' being exceeded with a low bentonite content, or titration being carried out for an unnecessarily long time with a high bentonite content. The blank determinations of the bentonite and the support media must be repeated when taking a new MB solution into use. Also the processing of new bentonite or a new batch of support can result in repetition of the blank determinations.

Appendix 4: Determining the mixing quality of a BES

Purpose and application

The mixing quality of a BES mixture is decisive for the homogeneity and the properties of the BES barrier. The purpose of the test is to quantify the mixing quality.

Principle

From a batch of BES 12 a-select samples must be taken, of which the bentonite content is determined with the methylene blue method as per Appendix 4. The spread (standard deviation) of the bentonite content is a measure of the homogeneity or mixing quality of the mixture.

Requisites

Equipment: small scoop, plastic bags.

Preparation

Mixed in plant/divorced mixing: Scoop from one batch with a small scoop 12 randomly selected samples of around 50 g BES. These samples must not be homogenised.

Mixed in place: Take from part of a rotovated course with an area $A \text{ m}^2$ and randomly spread over the whole depth of the layer, take 12 randomly selected samples of around 50 g using a spade. Choose the area A such that in relation to the layer thickness a volume of 1 m^3 mixture is sampled. Do not homogenise the samples and keep them in plastic bags.

Execution

Determine the bentonite content of each of 12 samples of sand-bentonite using the methylene blue method as per Appendix 4. Calculate the mean and standard deviation of the bentonite content.

Calculation

Calculate the mean bentonite content, accurately to 0.1 % (w/w) from:

$$B_{gen} = \frac{\sum_{i=1}^{12} B_i}{n}$$

where:

B_{gem} is the mean bentonite content, in % (ww);

B_i is the bentonite content of the sample i , in % (w/w);

n is the number of samples (= 12).

Calculate the standard deviation of the bentonite content, accurately to 0.01% (w/w) from:

$$s = \sqrt{\frac{\sum_{i=1}^n (B_i - B_{gen})^2}{n - 1}}$$

where:

s is the standard deviation, in % (w/w);

B_{gen} is the mean bentonite content, in % (w/w);

B_i is the bentonite content of the sample i, in % (ww);

n is the number of samples (= 12).