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Briefing: Common laboratory procedures to prepare and cure stabilised soil specimens: a short review

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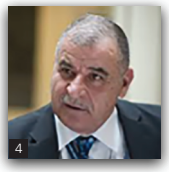

Soil stabilisation is used extensively to improve the physical and mechanical properties of soils to achieve the desired strength and durability properties. During the design process, laboratory investigation is conducted firstly to obtain an enhancement in soil strength and stiffness, in addition to the type and amount of binder required. The methods of preparing and curing specimens of soil–binder mixtures directly influence the properties of the stabilised soils. The most common laboratory protocols used for preparing and curing the specimens of stabilised soil are presented in this short review. The review focuses on several aspects such as homogenisation of the natural soil, mixing type and duration, mould type, moulding techniques and curing time and condition. This review can assist various construction projects that deal with soil improvement to choose an appropriate method for preparing and curing a soil–binder mixture to simulate the field conditions as much as possible and obtain uniform soil–binder mixtures.

Introduction

For soil stabilisation applications, the specimens of a soil–binder mixture are prepared in a laboratory according to a standard procedure, which in principle should simulate the field conditions. These procedures vary between different countries; in addition, there are variations between different testing companies (Åhnberg and Holm, 2009; BRE, 2002; BSI, 2005; Carlsten and Ekström, 1997; Kitazume, 2012). In Sweden, the specimens of soil–binder mixtures are prepared according to the common procedure described by the Swedish Geotechnical Society (SGS) (Carlsten and Ekström, 1997) and the Building Research Establishment (BRE, 2002). In Japan, the specimens are prepared according to the Japanese Geotechnical Society standard (Kitazume and Terashi, 2013). These variations are related to differences in soil type, type and procedure of soil stabilisation in the field and differences in traditional laboratory testing in general (Åhnberg and Holm, 2009).

Generally, the specimen of a stabilised soil is prepared in a laboratory according to a standard protocol, which normally consists of several steps. Firstly, natural soil is homogenised, and then a cementitious binder is added in dry or in slurry form, and the mixture is blended by hand or an electric blender for a certain time. Then, the soil–binder mixtures are gradually filled as layers in a mould or tube according to the specified technique. Usually, five different moulding techniques can be used or combined to prepare a specimen, as summarised in the following (Kitazume *et al*., 2015).

- Tapping. For each layer, the mould is tapped (hit) against a table or the floor for a specified number of times until the specimen height is subsequently filled.
- Rodding. For each layer, the mixture is slowly tamped down for a specified number of times using a rod to compact/smooth out each layer.
- Dynamic compaction. Each layer is compacted by using a Proctor hammer for specified drop height, weight and number of blows to achieve standard compaction energy (600 kJ/m^3) or according to the specified compaction energy.
- Static compaction. Each layer is compressed by using a specified static load for a certain time.
- No compaction. The soil–binder mixture is filled in the mould by either pouring or placing.

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Table 1. Most common procedures for homogenisation of natural soil prior to treatment, specimen preparation methods and curing conditions (continued on next page)

Preparation standards and reference	Natural soil homogenisation method	Mixer type	Mixing duration	Specimen mould	Number of layers in the mould	Moulding techniques	Curing conditions
Tokyo Institute of Technology, Japan (Kitazume *et al.*, 2015)	Soil is homogenised by mixing with its initial water content	Domestic dough mixer with a 5000–30 000 cm^3 mixing bowl	10 min with occasional hand-mixing	Cylindrical plastic moulds with 50 mm diameter and 100 mm height	Three to six layers	■ Tapping[a] ■ Rodding[b] ■ Dynamic compaction[c] ■ Static compaction[d]	Sample ends are properly sealed with specified sealants and stored at 20 ± 3°C for specified time at 95% relative humidity
Sapienza University of Rome, Italy (Grisolia *et al.*, 2012, 2013; Marzano *et al.*, 2012)	The soil is homogenised by remixing alone. Water is added at this stage to adjust the soil water content	Hobart mixer	10 min with occasional hand-mixing	Cylindrical plastic moulds with 50 mm diameter and 100 mm height. The largest particle contained within the specimen shall be smaller than one-fifth of the specimen diameter	Three layers	■ Tapping[a] ■ Rodding[b] ■ Dynamic compaction[e] ■ Static compaction[d] ■ No compaction[f]	Each mould is covered with a sealant and stored in a special curing room at 95% relative humidity to prevent water evaporation from the specimen
University of Coimbra, Portugal (Correia *et al.*, 2013)	The soil is homogenised by remixing at a mixing speed of 136 revolutions per min (rpm). To readjust the soil water content, water is added to the soil as a slurry of water–binder mixture	Hobart mixer (model N50)	3 min with a mixing speed of 136 rpm	Polypropylene random copolymer pipes, with 50·8 mm internal diameter and 330 mm height. The height of the sample is 140 mm, and the remaining height of the mould serves as a guide for the dead load, corresponding to a vertical pressure of 24 kPa. The mould has two holes near the top to allow the sample to submerse	Six layers (thickness/diameter ratio equal to 0·5)	■ Static compaction[g]	A non-woven geotextile porous disc is placed at the bottom and top of the mould. Samples are stored at 20 ± 2°C for a specified time. A vertical pressure of 24 kPa is applied during curing
SGS, Sweden (Åhnberg and Andersson, 2011; Carlsten and Ekström, 1997)	The soil is first homogenised thoroughly by mixing the soil alone	Dough mixer or kitchen mixer with sufficient capacity and rpm	5 min	The moulds used are plastic tubes commonly used for piston sampling in Sweden, with a diameter of 50 mm and a height of 170 mm	Four to five layers (about 30 mm thickness per layer)	■ Tapping[h] ■ Rodding[i] ■ Static compaction[j]	Sample ends are properly sealed with specified sealants and stored at 7°C in a climate-controlled room
JGS 0821 (JGS, 2005), Kitazume and Terashi (2013)	The soil is homogenised by stirring it using a mixer. The soil water content is adjusted by adding water	Domestic dough mixer with a 5000–30 000 cm^3 mixing bowl	10 min with occasional hand-mixing	Specimen moulds with 50 mm diameter and 100 mm height. The maximum grain size of the sieved sample should be less than one-fifth of the inner diameter of the mould	Three layers	■ No compaction[k]	Sample ends are properly sealed with specified sealants and stored at 20 ± 3°C for a specified time at 95% relative humidity

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Table 1. Continued

Preparation standards and reference	Natural soil homogenisation method	Mixer type	Mixing duration	Specimen mould	Number of layers in the mould	Moulding techniques	Curing conditions
BRE (2002)	The soil is mixed until it becomes visually homogenous	Dough mixer or kitchen mixer with sufficient capacity and rpm	5 min (depending on the soil type)	Plastic tubes or plastic-coated cardboard, 50 mm diameter and 100 mm height coated with oil or wax on the inner side	Four layers	■ Static compaction[l]	No standard specified for humidity. Samples are stored at a constant temperature of 18–22°C in properly sealed conditions
Jacobson *et al*. (2003)	The conglomerate of soil is mixed thoroughly for 3–4 min	KitchenAid dough mixer with a dough hook. Outer spindle rotating at 155 rpm and the inner spindle at 68 rpm	3–5 min	50 mm diameter and 100 mm height	Four layers	■ Tapping ■ Static compaction[m]	Cured at 100% relative humidity (moist environment) and 20 ± 3°C for 7, 14, 28 and 56 d
Janz and Johansson (2002), Edstam (2000)	The soil is homogenised by mixing it alone for 2–6 min. This is normally done the day before the stabiliser is added	Kitchen mixer or concrete mixer	4–10 min	The moulds used are plastic tubes commonly used for piston sampling in Sweden, with a diameter of 50 mm and a height of 170 mm	Layer thickness between 2 and 4 cm after compaction	■ Tapping[n] ■ Static compaction[o]	The specimens containing only lime are stored at room temperature (+22°C) for the first 10 d and the remaining time at +7°C. Other specimens are stored at a temperature of +7°C all the time
ASTM D 3551-17 (ASTM, 2017), ASTM D 5102-09 (ASTM, 2009), ASTM (1992)	Soil is air-dried for 24 h and mixed with a dry binder for 1 min or until the mixture is homogenised visually	Mechanical mixer capable of producing uniform and homogeneous mixtures	5 min	Moulds with a minimum inside diameter 50 mm and length-to-diameter ratios between 2·0 and 2·5. The largest particle contained within the specimen shall be smaller than one-tenth of the specimen diameter	At least three layers	■ Tapping and kneading ■ Dynamic compaction[p]	Compacted specimens are cured in an airtight, moisture-proof container at a temperature of 23 + 2°C
Federal Highway Administration Design Manual (Bruce *et al*., 2013)	The soil is mixed for approximately 3 min at the lowest setting of the mixer (approximate rotation of the mixing tool of 100–175 cycles/min). Water is added to adjust the soil water content	Kitchen mixer with a sufficient capacity	10 min	50 by 100 mm plastic moulds with lids	Three layers	■ Tapping ■ Rodding	Sealed specimens are cured under controlled conditions at 95–100% relative humidity and at a room temperature of 20–25°C

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Table 1. Continued

Preparation standards and reference	Natural soil homogenisation method	Mixer type	Mixing duration	Specimen mould	Number of layers in the mould	Moulding techniques	Curing conditions
European standard EN 16907-4 (CEN, 2018)	The soil in the field is corrected to the particle size distribution before adding the binder by blending the soil alone to break up large blocks or boulders	Mechanical mixer capable of producing uniform and homogeneous mixtures	The mixing time is not specified, but the produced mixture should be homogenised	Different mould dimensions are used according to the compaction method used for preparing the sample and the maximum particle size permitted in the sample. The length-to-diameter ratio of the specimen is 2	Layers	■ Proctor equipment or vibrating table compaction[q] ■ Vibrating hammer[r] ■ Vibrocompression[s] ■ Static compression[t]	In a temperate region, sample ends are properly sealed with specified sealants and stored in the air at 20 ± 2°C for a specified time at relative humidity >90%. The sample is cured also in water. Other conditions can be adopted in a warmer or colder climate
French standard NF EN 13286-53 (Afnor, 2005) and the technical guide by Laboratoire Central des Ponts et Chausses (LCPC, 2004)	The sample is disintegrated or homogenised for several minutes	Kitchen mixer with enough capacity	The mixing time is not specified, but the produced mixture should be homogenised	Cylindrical steel mould with different dimensions (35 × 70, 50 × 100 and 100 × 200 mm). The length-to-diameter ratio of the specimen is 2. The mould has flanged pistons (plugs) from both ends. It is used to produce a specimen with a density gradient such as the density in the central part being less than that at the ends	One layer	■ Static compaction or compressing the specimen from both sides by a compression-testing machine with a sufficient force. The additional flanged piston parts are removed during the compression process	The sample is sealed and cured at control room temperature (20–25°C)
ASTM (1992)	The soil is air-dried for 24 h at room temperature and mixed with a dry binder for 1 min or until the mixture is homogenised visually. The soil is passed through sieve number 16	Hand-mixing or using a mechanical mixer	The mixing time is not specified, but the produced mixture should be homogenised	Cylindrical steel mould with dimensions of 71 × 299 mm. The mould has flanged pistons from both ends to compress the specimens and produces a specimen with dimensions of 17 × 142 mm. The length-to-diameter ratio of the specimen is 2	One layer	■ Static compaction ■ Dynamic compaction[p]	Compacted specimens are cured in a moist room

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Table 1. Continued

Preparation standards and reference	Natural soil homogenisation method	Mixer type	Mixing duration	Specimen mould	Number of layers in the mould	Moulding techniques	Curing conditions
BSI (1990a, 1990b)	The untreated soil is mixed alone either by using a mechanical mixer or by hand	Kitchen mixer with a sufficient capacity	10 min	Tapered mould with two steel plugs with the following dimensions: 50 × 100 mm for fine-grained soil and 100 × 200 mm for medium-grained soil	One layer for a 50 × 100 mm specimen and six layers for a 100 × 200 mm specimen	■ Constant compaction effort ■ For 50 × 100 mm specimen[u] ■ For 100 × 200 mm specimen[v]	Specimens are coated with wax and cured at constant temperature of 20 ± 2°C

[a] For each layer, the mould is tapped 50 times against the floor
[b] Performed using an 8 mm dia. steel rod and tapping down (30 times) the mixture with the rod for each layer
[c] Each layer is compressed by the weight of a rod (1·6 kg) and compacted by a falling weight (0·6 kg) using a special apparatus. The fall height is set to 10 cm, and the number of blows is five
[d] Each layer is statically compressed with a vertical pressure of 25 kPa for 10 s using a heavy rod
[e] Each layer is compacted by a falling weight (1·5 kg) using a special apparatus. The fall height is set to 10 cm and the number of blows to five
[f] Simply consists of filling the mould by either pouring or placing in the case of mixtures with a higher consistency
[g] For each layer, the mixture is tapped by hand and statically compressed with a vertical pressure of 100 kPa for 10 s. Finally, the surface is lightly scarified and another layer is introduced
[h] Tapping of the mould is performed 30 times for each of the approximately 30 mm thick layers of the soil–binder mixture put into the mould. The filling is performed in four layers
[i] A rod is used to compact/smooth out evenly each 20–30 mm thick layer of the soil–binder mixture by hand
[j] Each layer with about 30 mm thickness is statically compressed with a vertical pressure of 100 kPa for 5 s to squeeze out air pockets from each layer
[k] For each layer, the mould is lightly tapped against the floor, hitting the mould with a mallet, and subjecting the mould to vibration
[l] Each layer with about 30 mm thickness is statically compressed with a vertical pressure of 100 kPa three times for 2 s to squeeze out air pockets from each layer
[m] Each layer with about 25 mm thickness is statically compressed with a vertical pressure of 100 kPa for 5–10 s
[n] A 1 kg heavy load is placed on each layer, and the mould is tapped three times against the floor
[o] Each layer with about 30 mm thickness is statically compressed with a vertical pressure of 100–200 kPa for 5–10 s
[p] Each layer is compacted to achieve standard compacting effort of 600 kN m/m^3 according to ASTM D 698-12 (ASTM, 2012). Suitable for preparing a specimen at the desirable unit weight
[q] The dimensions of the mould are a diameter of 100 ± 1 mm and a height of 120 ± 1 mm or a diameter of 150 ± 1 mm and a height of 120 ± 1 mm, and the maximum particle sizes allowed are 16 and 31·5 mm, respectively
[r] The dimensions of the mould are a diameter of 100 ± 1 mm and a height of 100 ± 1 mm or a diameter of 150 ± 1 mm and a height of 150 ± 1 mm, and the maximum particle sizes allowed are 22 and 31·5 mm, respectively
[s] The dimensions of the mould are a diameter of 100 ± 1 mm and a height of 100 or 200 mm or a diameter of 160 mm and a height of 160 or 320 mm, and the maximum particle sizes allowed are 22 and 31·5 mm, respectively
[t] The dimensions of the mould are a diameter of 50 mm and a height of 50 or 100 mm or a diameter of 100 mm and a height 100 or 200 mm, and the maximum particle sizes allowed are 11·2 and 20 mm, respectively
[u] Placing the soil–binder mixture inside the mould gently and uniformly as one layer with the tamping rod and then compacting the mixture inside the mould with 15 blows of the rammer dropped from a height of 300 mm
[v] Placing the soil–binder mixture inside the mould as six layers and compacting each layer with 25 blows of a rammer dropped from a height of 300 mm

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Preparing and homogenising the natural soil before adding the cementitious binders represent the most common concern for obtaining a uniform soil–binder mixture. Disaggregating natural soil prior to treatment has many effects such as homogenising the soil, reducing the variation in water content and obtaining smaller-sized particles by separating the agglomerated particles. This process could assist in obtaining a uniform distribution of the cementitious binders around soil particles. Table 1 summarises the most common procedures for homogenising natural soil prior to treatment, specimen preparation methods and curing conditions. The most common step in these procedures is that natural soil has to be disaggregated and homogenised by remixing it alone before adding the stabiliser. Most of the standards do not specify the time required for the disintegration and homogenisation process because it can be influenced by several factors, such as the type and gradation, consistency limits, water content and organic content of the soil (Åhnberg and Holm, 2009; Bhadriraju *et al*., 2007; BRE, 2002; Bruce *et al*., 2013; Carlsten and Ekström, 1997).

For the effect of mixing time after adding the cementitious binder on the obtained uniform soil–binder mixture, several investigations have shown that the mixing time significantly influences the properties of stabilised soils. Several factors control the uniformity of soil–binder mixtures, such as mixing time, type of mixer used and the characteristics of the original soil, in addition to the type, amount and form of the added binder (in dry or in a slurry form). Kitazume (2005) pointed out the influence of mixing time and form of binder used on the unconfined compressive strength of the stabilised soil. These results were based on the laboratory mixing tests by Nakamura *et al*. (1982). The laboratory tests were conducted according to the Japanese standards for preparing the laboratory specimens (JGS, 2005) but using different mixing times. Portland cement was added to the soil in either a dry form or a slurry form with a water-to-cement ratio of 100%. The results showed that the unconfined compressive strength of the stabilised soil significantly decreased, as the mixing time was decreased to shorter than 10 min, particularly for the case of when low binder amounts were used. The results also showed that adding the binder in a dry form required a longer mixing time compared with adding the binder in slurry form. The recommended mixing time to mix the soil and binder is set as 10 min according to Japanese and British standards (BSI, 1990a, 1990b; JGS, 2005). In contrast, in Sweden, the recommended mixing time is set as 5 min and the produced mixture should be visually homogenised (Åhnberg and Andersson, 2011; Carlsten and Ekström, 1997).

Several investigators have shown that different curing procedures such as curing time and curing temperature significantly influence the strength and stiffness properties of stabilised soils. For the effect of curing time, Kitazume (2005) pointed out the influence of curing time and soil types on the unconfined compressive strength of lime-stabilised soil based on the results from Terashi *et al*. (1977). The results showed that the strength properties of lime treatment are dependent on the soil type (lime is more effective in clay) and the unconfined compressive strength increases almost linearly with the logarithm of the curing time. For lime treatment, 50–75% of the final shear strength is obtained after 1–3 months of curing, respectively, while 90% of stabilised soil shear strength is expected to be obtained after 1 year of curing (Broms, 2004: p. 263). For cement treatment, the improvement in soil strength and stiffness increases as the cement content and curing time increases, and the major improvement in soil strength occurs during the first 28 d of curing (Hassan, 2009; Ho *et al*., 2017; Kang *et al*., 2017; Lorenzo and Bergado, 2006; Sariosseiri and Muhunthan, 2009; Subramaniam *et al*., 2016). For the effect of curing temperature, Kitazume (2005) mentioned that a higher strength can be obtained under a higher curing temperature during short-term curing, and almost the same impact can be obtained at a longer curing time for different soil–binder treatments.

For soil stabilisation applications, choosing an appropriate laboratory method for preparing and curing the specimens of soil–binder mixtures is considered highly important to simulate the field conditions as much as possible. For instance, in shallow soil stabilisation applications such as road projects where the stabilised soil in the field is usually compacted as layers using a compactor to obtain certain compacting efforts, the dynamic compaction method is the most appropriate laboratory procedure to prepare the soil–binder mixture to simulate the desired compaction efforts. In contrast, for deep soil stabilisation, the compaction efforts are less important compared with those for road projects; therefore, the tapping or static compaction technique can be used. Moreover, choosing the appropriate method also depends on soil type, initial water content and the type and amounts of binder used.

For deep soil stabilisation, a group of researchers studied the influence of different laboratory moulding techniques on the wet density and the unconfined compressive strength of stabilised soil (Kitazume *et al*., 2015). The study was a part of an international collaboration between four organisations, the Tokyo Institute of Technology, the Sapienza University of Rome, the University of Coimbra and the Swedish Geotechnical Institute. Details of their studies are presented in the first four methods mentioned in Table 1. Regardless of the soil type and the type and amount of binder used, they observed that the modelling technique considerably influenced the wet density and the unconfined compressive strength of stabilised soil. The liquidity index and the undrained shear strength of the soil–binder mixture after treatment were used as indices to evaluate the results. They found that the tapping and rodding techniques were highly applicable when the undrained shear strength was less than 10 kPa or the liquidity index was larger than 1. The rodding technique was highly applicable when the undrained shear strength ranged from 10 to 20 kPa or the liquidity index ranged between 0·5 and 1·0. Moulding with rodding and dynamic compaction were highly applicable when the undrained shear strength was larger than 20 kPa or the liquidity index was smaller than 0·5.

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Conclusions

This short review presents the most common laboratory procedures used to prepare and cure the specimens of soil–binder mixtures. The aspects of the various laboratory procedures presented include homogenisation of the natural soil, blending time, mould types and moulding techniques and curing conditions (time and temperature). Different moulding techniques and curing conditions considerably influence the properties of the soil–binder mixture. For soil stabilisation applications, choosing the appropriate method for preparing and curing the specimens of soil–binder mixtures is considered highly important to simulate the field conditions as much as possible, which subsequently reflect the strength and stiffness of stabilised soil in the field site. Dynamic compaction and rodding methods are more applicable for shallow soil stabilisation such as road projects or when the soil shear strength is greater than 20 kPa. Static compaction and tapping methods are more applicable for deep soil stabilisation or when the soil shear strength is lower than 10 kPa.

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