

Design and Strength Development of a Low-Mobility Grout for Repair of Embankment Dams

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Abstract

If the core of an embankment dam is damaged by internal erosion, it can be remediated by injection grouting. The grout material should not be allowed to harden, but rather become a natural part of the core after injection, exhibiting similar geotechnical characteristics as the core. However, the grout material must be pumpable during the injection. A new type of non-hardening grout material made for embankment dams has therefore been developed and tested. The grout material is made from natural, rounded sand and gravel aggregates, limestone filler, water, superplasticizer, air release agent, and bentonite powder. Since no hardening materials are included in the grout material, such as cement, the hardening of the grout material after injection relies on the effect of the superplasticizer to wear off. Test results show that this type of grout material is possible to pump and inject, eventually becoming part of the original core. Due to its tendency to absorb air, the grout material should not be homogenized longer than 15 minutes. After 34 days of storage, the undrained shear strength of the grout material was ~13 kPa, and its bulk density and water content had similar values expected in a core.

Keywords

Embankment Dams, Glacial Till, Grouting, Internal Erosion

1. Introduction

In Sweden, most hydropower dams are zoned embankment dams with a core of

low-permeability moraine surrounded by filter zones. With time, internal erosion may develop and fines from the moraine are washed out by seepage. Internal erosion in a dam may cause (a) increased seepage, (b) turbidity, and (c) sinkholes (Fell et al., 2005). To prevent the progression of internal erosion, cavities from eroded material can be filled by remedial injection grouting. There are several grouting techniques that have been used in embankment dams, such as compaction, permeation, fracture, and jet grouting (Lagerlund, 2009). The main purpose of remedial injection grouting in a core soil is to lower the hydraulic conductivity (Foster et al., 2000). Grouting in embankment dams must be done carefully to minimize excessive pore water pressures, but at the same time minimizing the void ratio, i.e., compaction grouting (Yang & Zou, 2009), or maximizing the filling of voids, i.e., permeation grouting (Fell et al., 2005). Ideally, the grouting procedure should be performed without interfering with the normal dam operation, such as lowering the reservoir level. According to Warner (2004), the important factors to control while grouting are grout pressures and the amount of injected grout material. In Sweden, most remedial grout works are executed with the compaction grouting technique, using a low-mobility grout (LMG) material, traditionally made from sand, cement, and bentonite. Occasionally, compaction grouting is complemented by permeation grouting, as seen in studies such as Ekström et al. (2016), Johansson and Edeskär (2012), Lagerlund (2007), Ekström and Pusch (2001), and Sjöström (1999).

In compaction grouting, the hydraulic conductivity of the core soil decreases because the void ratio is reduced (Brown & Warner, 1973; El-Kelesh et al., 2012; Shrivastava & Ken, 2018; Yea et al., 2013). The LMG material used for compaction grouting should neither permeate nor fracture the surrounding soil. LMGs are defined by their high viscosity and yield strength. According to the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, 2017), LMGs behave as plastic materials with high internal friction due to their high solids content. In practice, LMGs typically exhibit slump values of 0 - 50 mm in standard slump tests, and yield strengths ranging from 100 to 300 Pa (ASCE/G-I 53-19, 2019). During injection, it expands and densifies the surrounding soil. In addition, Warner (2004) reports that LMG material was used to fill voids caused by internal erosion. In permeation grouting, the grout material has a low viscosity and low yield strength, enabling the grout material to permeate the porous structure of the damaged soil (Granata et al., 2012; Kociánová et al., 2015; Littlejohn, 2003; Park et al., 2018). Once in place, it cures and seals the soil due to the adhesion of the original soil particles, consequently lowering the hydraulic conductivity.

After injection grouting, zones with geotechnical characteristics, such as shear strength and hydraulic conductivity that are different from that of the surrounding core, should be avoided (Lim et al., 2004). For example, cracks may develop after hydration at the interface between cementitious grout material and core soil due to shrinkage of the grout material (Lagerlund, 2009). Remedial injection grouting of a damaged core therefore requires a grout material to have no hard-

ening material, e.g., cement, and to have a particle size distribution and water content similar to those of the intact core soil. However, although an LMG material with this particle size distribution and water content is ideal after injection, it will initially be too lumpy and difficult to inject. Hence, a temporary lowering of the viscosity and yield strength of the LMG material during the injection is beneficial. The injection process will then be facilitated, the grout material will travel further away from the injection pipe, and the same LMG material may also be used for permeation grouting. A superplasticizer (SP) can therefore be used to temporarily lower the viscosity and yield strength of the LMG material. An SP is an additive that lowers both viscosity and yield strength without increasing the water content in fresh concrete (Lu et al., 2019). Lagerlund et al. (2023) show that the addition of an SP also lowers the viscosity and yield strength of a non-hardening LMG material for embankment dams. However, the development of shear strength, air content, water content, and bulk density of the LMG material from the start of the homogenization until 34 days of curing were not investigated.

The objective of this study is to investigate the effects of the addition of an SP on the short- and long-term mechanical properties of an LMG material in the repair of embankment dams. The following questions will be addressed: (a) What materials should be used in an LMG material when SP is used? (b) How does the homogenization process affect the mechanical properties of the grout material (short term)? (c) How do the mechanical properties of the grout material change with time from start of homogenization (long term)?

2. Material and Methods

2.1. Material

The LMG material in this study was made with aggregates (sand and gravel), tap water, and a limestone filler material. Furthermore, additives such as bentonite powder (DantoCon Pure C), SP (MasterGlenium ACE45), and an air release agent (MasterCast 202) were used.

- **Aggregates and water**—The aggregate particles must be rounded to facilitate pumping (Adiguzel & Bascetin, 2019). The amount of fines (<0.063 mm) used in the LMG material was chosen to be 20% by weight. This amount was expected to give a sufficiently low hydraulic conductivity in the LMG material (Vattenfall, 1988). The water content was chosen to be 10% - 12%, which is similar to a typical core soil. Otherwise, a considerably high water content will lower the bulk density of the LMG material and consequently raise its hydraulic conductivity (McCartney et al., 2007). Furthermore, with a water content that is too high, the LMG material will settle when excessive pore water drains after injection, leaving ungrouted voids. A considerably low water content, on the other hand, will make the LMG material lumpy and difficult to pump and inject. The D_{max} of the aggregates used will generally affect the penetrability of the grout material.

- **Limestone filler**—is fine-grained crushed CaCO_3 filler material where most particles are <0.125 mm. It is used in concrete to reduce the amount of cement while maintaining workability (Byggjtjänst, 2017). When the limestone filler is mixed with water it functions as a paste material, which is the lubricant, facilitating the pumping and injection of the LMG material (Benjeddou et al., 2017). The limestone will not cause any hardening after injection and will enable the use of an SP.
- **Bentonite**—is a clay consisting mainly of the swelling clay mineral Smectite and is used to slow down the drainage of water in the LMG material (Ekström & Pusch, 2001). Bentonite can be added to an LMG material as dry powder or pre-swelled in water. An LMG material made with dry bentonite powder will swell over time after injection. This will ideally improve the sealing effect and prevent settlements of the injected LMG material.
- **Superplasticizer**—is used to lower the viscosity and yield strength in fresh concrete. When an SP is added to an LMG material, it is adsorbed onto the particle surface, interfering with the interparticle attractive forces caused by the addition of water. This has the effect that the particles will not bond with each other. For an LMG material for embankment dams, where low water contents are used, a polycarboxylic SP can be used, which causes steric repulsion between the particles (Lu et al., 2019; Flatt & Schober, 2012). Due to steric repulsion, air can be absorbed into the LMG material during its homogenization. The selection of a polycarboxylic ether (PCE) superplasticizer was deliberate, as this class of SPs is particularly effective in low-water-content, high-fines mixtures. In contrast, traditional lignosulfonate-based SPs rely on electrostatic repulsion and are less effective in dense, clay-rich systems. Moreover, lignosulfonates are known to cause prolonged setting times, which is undesirable in non-cementitious grout materials where strength gain depends on particle interaction rather than hydration. The use of a PCE-based SP thus ensured sufficient fluidity during injection while allowing the grout to regain stiffness over time as the SP effect diminished.
- **Air release agent**—The air content of an LMG material should be kept low for two reasons: 1) air contents $> 5\%$ will make pumping or injection difficult (Byggjtjänst, 1997) and 2) the porosity of LMG material will increase, making it more prone to undergo settlements after injection. Therefore, an air release agent may be used to facilitate the evacuation of air after homogenization. An air release agent removes air bubbles from the LMG material by facilitating the transport of air bubbles to the surface where they dissipate.

2.2. Methods

The composition (recipe) of the LMG material was determined via an iterative pre-testing process where several smaller batches were made. The goal was to develop two LMG materials with different D_{max} (2 and 4 mm), since D_{max} is an important factor in determining the penetrability of a grout material into a coarser

soil material. The following ratios between the coarse soil to be injected (d) with the grout material (D) have been proposed; $d_{min}/D_{max} \geq 10$ (Awal, 1984), $d_{15}/D_{max} \geq 14$ (Byggtjänst, 1997), $d_{min}/D_{max} \geq 8 - 10$ (Lindvall, 2012), $d_{min}/D_{max} > 4$ (Lagerlund et al., 2023). D_{max} of 2 and 4 mm were chosen for practical reasons for the future testing presented in Lagerlund et al. (2023), since a larger D_{max} (≥ 8 mm) would require an impractically large coarse soil material to be grouted in laboratory tests. The following factors were determined before the pre-testing:

- **The aggregates** used for the $D_{max} = 2$ mm LMG material were two different 0/2 mm sands labelled sand A ($C_u = 3.6$) and sand B ($C_u = 1.5$). Aggregates used for the $D_{max} = 4$ mm LMG material was a 0/2 mm sand (sand B) and a 0/4 mm gravel ($C_u = 6.4$). The particle size distribution for the three original materials, i.e., sand A, sand B, and gravel, is shown in Figure 1. The amount of aggregates and limestone filler in each LMG material is shown in Table 1. All aggregates used had natural and rounded particles. The aggregates had a grain density of 2650 kg/m^3 . The limestone filler was a crushed product, 0/0.5 mm with a grain density of 2710 kg/m^3 . Grain densities were estimated by a pycnometer (SS-EN 1097-6:2022, 2005).

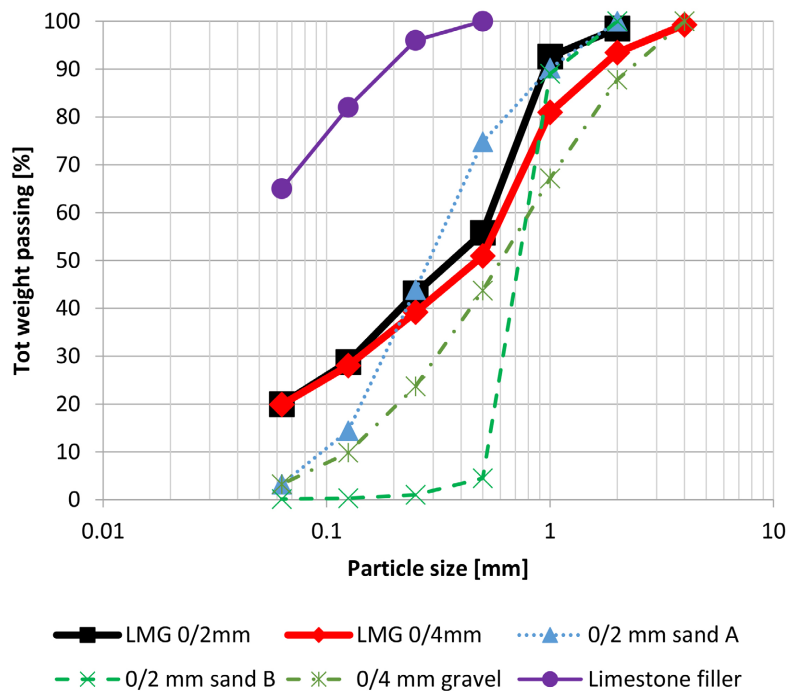


Figure 1. Particle size distributions of sand A, sand B, gravel, and limestone filler used in the two different LMG materials.

- **Amount of fines** = 20% of weight (sufficiently low hydraulic conductivity).
- **Water content** had a starting value of 12%.

With the particle size distribution curves and water contents decided beforehand, the necessary amounts of SP, air release agent and bentonite were investi-

gated. The amount of SP had a starting value of 3% by weight of the amount of water used. The aim was to find the amount needed to lower the yield strength of the LMG material to an equivalence of 100 mm as measured with a mini-slump flow test (Tan et al., 2017). A conical steel ring with a height of 40 mm and a bottom and top diameter of 85 and 75 mm, respectively, was filled with grout material. The ring was removed upwards, allowing the grout material to settle. Because of the settlements, the diameter of the grout material increased, as shown in Figure 2.



Figure 2. Mini-slump flow test. Bottom diameter of the grout material is ~100 mm (Lagerlund et al., 2023).

When the right amount of SP was found, the amount of air release agent was investigated (using a starting value of 0.5% by weight of the amount of water used), and finally, the amount of bentonite powder (starting value 3% by weight of the amount of water used). All pre-test batches, in which the amounts of air release agent and bentonite were investigated, were either approved or improved by measuring the following factors:

- **Bulk density [kg/m^3] > 2150 kg/m^3** (SS-EN ISO 17892-2:2014, 2014). The bulk density is correlated to the particle size distribution, water content, and air content. If the bulk density of the batch fell below 2150 kg/m^3 , the air content was too high (>5%).
- **Bleeding [%] < 1.0% after 24 hours** (SS-EN 480-4:2005, 2005). Bleeding occurs when all aggregates, including the paste material, undergo sedimentation, leaving the upper layers of grout material filled with only water (Warner, 2004). When this water seeps, an ungrouted zone might form after injection.
- **Settlements [%] < 1.0% after 24 hours** (measured during the bleeding test).

High settlements of the LMG material can cause ungrouted voids of the core soil after injection.

The limiting values for bleed and settlements were derived from previous experiences by the authors when developing other grout materials, e.g., Lagerlund and Holmberg (2021). Each batch of LMG material was prepared and homogenized, in the following way:

1. The water content of each aggregate was measured. A dry weight of 2000 g of the aggregates and limestone filler were used for each batch.
2. If the bentonite powder was used in the batch, it was weighed and added dry to the aggregates and limestone filler.
3. Tap water at 8°C was weighed and added to the moist aggregates so the desired water content was obtained.
4. If the SP or SP and air release agent was used in the test, it was weighed and mixed with the tap water.
5. Aggregates and bentonite powder (if any) were homogenized dry for 5 minutes in a Hobart mixer with a flat stainless-steel beater at 139 RPM, as shown in Figure 3.
6. The water with additives was slowly added, and the LMG material was homogenized for another 10 minutes.
7. The LMG material was tested accordingly by bleeding, settlement, bulk density, and mini-slump flow test. If results fell below or over the decided limits, the LMG material had to be improved.



Figure 3. Hobart mixer used to prepare the grout material.

The final two LMG material recipes that met the stated requirements of yield strength, bleeding, setting and bulk density are shown in Table 1. together with particle size distributions shown in Figure 1.

Table 1. Recipes (proportioning) of the two LMG materials. Note that the amount of aggregates are treated separately from the amount of water and additives.

Material	LMG 0/2 mm	LMG 0/4 mm
	[% by weight]	[% by weight]
0/2 mm sand A	34	
0/2 mm sand B	37	21
0/4 mm gravel		51
0/0.5 mm limestone filler (CaCO ₃)	29	28
Water ¹ (tap water)	13.1	12.0
Superplasticizer ²	4.6	5.0
Air release agent ²	0.19	0.21
Bentonite ²	2.6	3.06
Content of fines (<0.063 mm)	20.0	19.9

¹Percent by weight of all aggregates. ²Percent by weight of water.

Main Testing

The first part of the main testing was done by comparing the mechanical properties of two batches of the same grout material after being homogenized for 15 minutes and thereafter stored for 110 minutes (*ceased homogenization*) or continuously homogenized for 125 minutes (*continuous homogenization*). The tests were executed in either way:

Ceased homogenization—After the 15 minutes of homogenization, the full batch of LMG material was divided into nine samples and placed in paper cups (no water suction through the sides of the cups). They were tested for undrained shear strength, water content (SS-EN ISO 17892-1:2014, 2014), and bulk density. The undrained strength of the LMG material was measured in each of the 9 cups, one after the other, at 10-minute intervals, using the fall cone test that will be described later. The total time from the start of homogenization to the test of the last cup was 125 minutes. After the last measurement, water content and bulk density were measured in the last cup.

Continuous homogenization—After the first 15 minutes of homogenization, the mixer was stopped so that the LMG material in the mixing bowl could be tested for undrained shear strength, water content, and bulk density. The LMG material was kept in the mixing bowl and was continuously homogenized for the remainder of the test. Every ten minutes, the homogenization was stopped to determine the undrained shear strength. The total time of the test was 125 minutes. After the last measurement, water content and bulk density were measured.

To determine whether the effect of the SP wore off with time, the undrained shear strength in the LMG materials was measured using the fall cone test (SS-EN ISO 17892-6:2017, 2017). In the fall cone test, a cone with a certain weight and angle was left suspended by a supporting assembly over the sample so that its tip was touching the surface of the LMG material. The cone was released and the

penetration depth was measured. The undrained shear strength T_{fu} was then calculated according to (1).

$$\tau_{fu} = K \frac{Qg}{h^2} \quad (1)$$

where:

K = Shape factor of cone angle;

Q = Weight of cone [g];

g = Gravitational constant [9.81 m/s²];

h = Penetration depth [mm].

When measuring early shear strength increase in cementitious materials, the Vicat needle test is used (ASTM C807-20, 2020). A weighted needle is allowed to penetrate the material and the depth of penetration is correlated to the shear strength of the material. However, since the LMG material is expected to have a lower shear strength and a slower strength development compared to a cementitious material, the use of the fall cone test to evaluate the undrained shear strength in the LMG material is proposed instead. The use of the fall cone test in similar materials have been studied by several authors. Kumar and Wood (1999) found a sharp change in the results when clay content fell below 40%. The content of gravel influenced the test when the granular volume exceeded ~45%. Cabalar and Mustafa (2015) used the fall cone test on clay-sand mixtures with D_{max} up to 4.75 mm. They concluded that the undrained shear strength decreased as the content of sand increased, but gradation of the sand had no effect on the undrained shear strength results if the sand had rounded particles. Kang et al. (2020) found the fall cone test to be a robust tool for evaluating undrained shear strength development. Conclusively, the fall cone test in this study is used as an index test and not as a test to determine the undrained shear strength in absolute terms. The validity of the fall cone test, i.e., if results are to be interpreted as absolute or as an index test, is uncertain but will be evaluated by analysing the standard deviations of the penetration depths.

The second part of the main testing was done by producing test specimens of both types of LMG materials for storage. After certain time intervals (see Table 2), the undrained shear strength, water content, and bulk density was measured. The undrained shear strength was evaluated using the unconfined compressive strength (UCS) test (SS-EN ISO 17892-7:2018, 2018). During the UCS test, the strain rate was chosen to be 1.5 mm/min and the undrained shear strength was calculated according to (2). The fall cone test was also performed to verify its suitability as either an absolute test or an index test.

$$\tau_{fu} = \frac{F}{2A} \quad (2)$$

where:

F = Force [N];

A = Area [m²].

Three samples were used for each UCS test at storage times shown in **Table 2**.

Table 2. Days of storage and tests performed on both types of LMG material.

Storage time [d]	Fall cone	UCS	Water content	Bulk density
2	X		X	X
4	X		X	X
7	X	X	X	X
15	X	X	X	X
34	X	X	X	X

The LMG materials were homogenized as in the pre-testing and recipes are shown in **Table 1**. For the fall cone test, two batches (2500 g dry aggregates per batch) were made successively for each type of LMG material. Bulk density was measured directly after homogenization. Each of the two types of LMG material were put in five fibre glass tubes, 50 mm in diameter and 170 mm in height, and with a rubber cap seal on top and a filter stone at the bottom. The LMG material was not compacted inside the fibre glass tubes but could settle due to its own weight while in storage. The tubes were then placed in a bucket where the bottom was covered with a two cm thick layer of coarse gravel to allow drainage of pore water (**Figure 4**). For the UCS test, samples were homogenized and prepared the same way as for the fall cone test. However, three batches (4000 g dry aggregates per batch) were made successively for each type of LMG material, i.e., 12 samples per LMG material. Three samples were used for each UCS test. All samples were stored in a fridge at a constant temperature of 8°C before testing.

Before each test of the stored samples, the settlement of the LMG material in the fiber glass tube was measured.



Figure 4. Preparation of samples of LMG material for storage.

3. Results and Discussion

3.1. Pre-Testing

The inclusion of SP to lower the yield strength and viscosity of the LMG materials was very efficient. Without the SP, the LMG material behaved like a moist, lumpy fine-grained sand, but with the SP, it turned into a paste-like material that is possible to pump. The water content in the 0/2 mm LMG material had to be slightly increased compared to the 0/4 mm LMG material since the former became very sticky and got stuck on the sides of the mixing bowl, i.e., the viscosity was too high. This behaviour could not be controlled by the additives alone, therefore, more water had to be added.

On a final note, it was found during the development of the LMG material that its yield strength changed depending on the type of tap water used during the homogenization. Tap water with a higher degree of hardness increased the effect of the SP. When tap water with a hardness of 12.5 and 19° dH were used, the diameters of the LMG materials measured after the mini slump flow test were 36% and 42% larger, respectively, compared to when deionized water was used (0/4 mm recipe used). These brief findings suggest that the efficiency of the SP is correlated to the pore water chemistry, particularly hardness. The increased mini-slump diameters observed with harder tap water suggest that calcium and magnesium ions may enhance the dispersion efficiency of polycarboxylate-based SPs. In field applications, where water chemistry can vary significantly, this effect could lead to inconsistent grout rheology if not accounted for. Therefore, it is recommended that site-specific water sources be tested during mix design, and that potable water conforming to ASTM C1602 standards be used to ensure predictable SP performance (ASTM C1602/C1602M-22, 2022).

3.2. Main Testing—First Part

Bulk density, water content, and air content from start of homogenization of both LMG materials and after 125 minutes are shown in **Table 3**.

Table 3. Results from bulk density (ρ_{tot}), water content (w), and air content (n_a) in the two LMG materials after 15 minutes (first test) and 125 minutes (last test) of “ceased homogenization” and “continuous homogenization”. Air content was calculated.

LMG material	Time [min]	0/2 mm			0/4 mm		
		ρ_{tot} [kg/m ³]	w [%]	n_a [%]	ρ_{tot} [kg/m ³]	w [%]	n_a [%]
Ceased homogenization	15	2130	13.2	4.1	2170	12.4	3.2
	125	2140	13.2	3.7	2170	11.9	3.7
Continuous homogenization	15	2150	13.4	3.0	2190	12.2	2.5
	125	1920	10.2	16.5	2180	9.1	6.4

Both types of LMG materials had a significant increase of air and loss of water

when continuously homogenized for 125 minutes. In the 0/2 mm LMG material, the increase in air content was particularly high. After 125 minutes of continuous homogenization, both types of LMG material became “lumpy” and dry. The results clearly indicate the tendency of LMG materials to absorb air when homogenized for a longer period, most likely caused by the steric repulsion of the SP used, as was also observed by Lu et al. (2019).

Results from the development of undrained shear strength in both LMG materials are shown in Figure 5.

Table 4. Difference in undrained shear strength (index test) measured with fall cone in the two LMG materials after 15 minutes (first test) and 125 minutes (last test) of “ceased homogenization” and “continuous homogenization”.

LMG material	Time [min]	0/2 mm		0/4 mm	
		τ_{fi} [kPa] ¹	Increase [%]	τ_{fi} [kPa] ¹	Increase [%]
Ceased homogenization	15	0.18		0.18	
	125	0.35	~100	0.50	~180
Continuous homogenization	15	0.18		0.18	
	125	6.9	~3700	11.3	~6200

¹Index values.

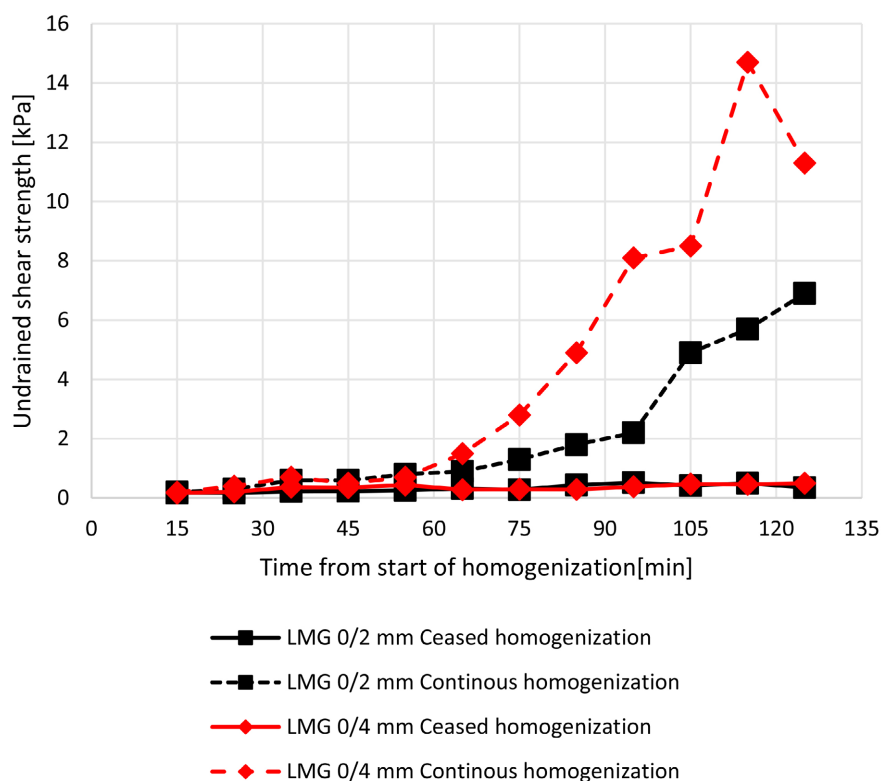


Figure 5. Development of undrained shear strength (index test) measured with fall cone test in the two LMG materials during the “ceased homogenization” and “continuous homogenization” tests.

The results indicate that LMG materials homogenized for a longer time will have an increased undrained shear strength. This is most likely caused by the fact that when air is absorbed into the LMG material, moisture is lost and consequently the effect of the SP is diminished. A stiff, low density LMG material will be unsuitable for pumping and injection. The results implies that the time for homogenization of a LMG material should be kept short and not to be continuously homogenized as the case with conventional LMG materials containing cementitious materials. After 25 minutes of homogenization, the undrained shear strength according to the index test had doubled compared to when the homogenization was stopped after 15 minutes. Moreover, the results indicate that if the injection process with this type of LMG material is stopped or hindered, there is no risk of the LMG material to harden inside the pipes or pumps, at least not during the first 125 minutes from the start of homogenization. The change of the undrained shear strength for both types of LMG materials increased during the test with magnitudes shown in **Table 4**.

For both types of LMG material with ceased homogenization, the changes in undrained shear strength were minimal compared to LMG material with continuous homogenization. The slight increase of undrained shear strength of the LMG material, where the homogenization was stopped, was attributed to the swelling of the used bentonite powder, slightly increasing its shear strength.

In **Table 5**, the fall cone tests are presented in terms of penetration and standard deviation within each test series. The following cones were used in each test series. Each test has been repeated three times.

- 0/2 mm, ceased homogenization: 10 g and 60° at 15 - 125 min.
- 0/2 mm, continuous homogenization: 10 g and 60° at 15 - 65 min; 60 g and 60° at 75 - 105 min; and 100 g and 30° at 115 - 125 min.
- 0/4 mm, ceased homogenization: 10 g and 60° at 15 - 45 min; 60 g and 60° at 55 - 85 min; and 100 g and 30° at 95 - 125 min.
- 0/4 mm, continuous homogenization: 10 g and 60° at 15 - 125 min.

Table 5. Mean penetration and standard deviation from all fall cone tests (LMG 0/2 mm is denoted as 0/2 and LMG 0/4 mm as 0/4).

	Time [min]	15	25	35	45	55	65	75	85	95	105	115	125
0/2 ¹	Penetration ³ [mm]	12.0	12.0	10.3	10.2	9.7	8.7	9.3	7.5	6.8	7.7	7.0	8.3
	Std. Dev. [mm]	0.8	0.8	1.2	0.6	0.9	0.6	1.2	0.4	0.8	0.9	1.1	0.9
0/2 ²	Penetration ³ [mm]	13.7	9.0	7.0	6.8	5.5	5.3	10.3	9.0	6.7	5.5	13.3	12.0
	Std. Dev. [mm]	1.2	1.6	0.8	0.5	0.4	1.2	0.9	0.4	0.5	0.4	1.2	0.8
0/4 ¹	Penetration ³ [mm]	12.0	10.8	8.0	8.3	7.5	9.3	9.0	9.3	8.0	7.2	7.3	7.0
	Std. Dev. [mm]	1.5	0.8	0.8	0.5	0.7	0.5	0.4	1.2	0.8	0.6	0.6	1.6
0/4 ²	Penetration ³ [mm]	12.3	8.7	7.8	5.3	12.0	9.8	7.3	5.5	11.0	10.7	8.2	9.3
	Std. Dev. [mm]	1.2	0.9	0.2	0.5	0.8	0.6	0.5	0.4	1.4	2.4	0.8	0.9

¹Ceased homogenization, ²Continuous homogenization, ³Mean value of three drops.

According to the standard for fall cone test (SS-EN ISO 17892-6:2017, 2017), no penetration value should deviate more than 0.5 mm from the value of a second drop. This occurred very rarely so the decision was made to make three drops for each test for increased accuracy since remolding samples could not be done. Considering the standard deviations, the results presented in **Table 5** therefore indicate that the undrained shear strength should indeed be regarded as an index test and not as absolute values.

3.3. Main Testing—Second Part

It was noted that during the sample preparation, air pockets formed in the LMG material inside the fiber glass tubes. The longer the LMG material was stored, the more it stuck to the filter stone at the bottom of each tube when it was removed for testing. Preparing the stored LMG material for UCS testing furthermore proved to be difficult due to the low shear strength of the samples. When a soil cutter was used to prepare the samples, it often disturbed the sample closest to the cutting zone and a small portion of the LMG material often got stuck to the cutter.

Settlements of the LMG material occurred in all tubes during storage and were measured prior to the USC testing, as shown in **Table 6**.

Table 6. Mean value of settlements in samples used for USC testing. Three tubes were used and measured for each testing day. Original height of sample = 170 mm.

	Storage time [d]	7	15	34
LMG 0/2 mm	Settlements [%]	4.1	4.1	2.4
LMG 0/4 mm	Settlements [%]	4.1	3.1	2.2

Settlements of the LMG material were also measured prior to the fall cone testing of stored samples (**Table 7**). However, since only one tube of LMG material was made for each test day, no standard deviation could be calculated.

Table 7. Settlements in samples used for fall cone test. Only one tube was used and measured for each testing day. Original height of sample = 170 mm.

	Storage time [d]	2	4	7	15	34
LMG 0/2 mm	Settlements [%]	5.3	4.7	4.1	4.1	5.9
LMG 0/4 mm	Settlements [%]	2.9	3.5	2.4	4.1	2.4

In absolute terms, the settlements varied from 3 to 12 mm (1.5% - 7.1%) and were generally higher for the 0/2 mm LMG material than the 0/4 mm. The settlements did not seem to increase with storage time, but rather occurring as early as 2 days into the storage. Settlements were not observed during pre-testing where the maximum allowed settlement was set to < 1.0% over a period of 24 hours of storage. However, during storage, pore water in the LMG material was allowed to drain through the filter stone at the bottom of each tube, which was not the case in the

pre-testing.

Bulk density, water content, and air content from 0 to 34 days of storage were measured when the fall cone test was performed (Figure 6).

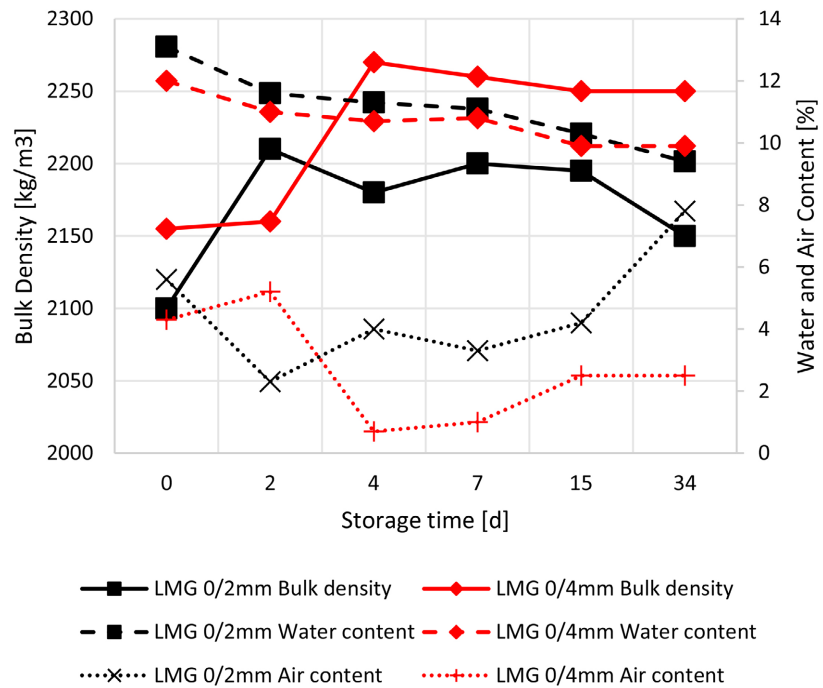


Figure 6. Bulk density, water content, and air content in stored LMG material samples.

It can be seen in Figure 6 that storing the samples under drained conditions worked as intended since their water content decreased continuously. The increase or decrease in the tested factors from 0 to 34 days of storage can be seen in Table 8.

Table 8. Change in bulk density (ρ_{tot}), water content (w), and air content (n_a) after 34 days of storage under drained conditions.

	ρ_{tot} [%]	w [%]	n_a [%]
LMG 0/2 mm	2.4	-28	39
LMG 0/4 mm	4.4	-18	-42

The bulk density increased in both LMG materials while the water content decreased. Air content however increased in the 0/2 mm LMG material but decreased in the 0/4 mm LMG material. Between 15 and 34 days of storage, there was a sharp incline in air content in the 0/2 mm LMG material but not in the 0/4 mm LMG material. The reason behind this difference can't be explained from the measurements.

Undrained shear strength development, measured using both fall cone and UCS tests in both LMG materials from 2 to 34 days of storage, is shown in Figure 7 and

the standard deviations from the measurements in **Table 9** and **Table 10**. For the fall cone test, the 100 g and 30° cone was always used.

Table 9. Standard deviations for all UCS tests. Three tests per test days.

	Storage time [d]	7	15	34
LMG 0/2 mm	Std. Dev. [kPa]	2.1	2.1	2.2
LMG 0/4 mm	Std. Dev. [kPa]	0.1	0.7	1.2

Table 10. Mean penetration and standard deviation from all fall cone tests on stored LMG material.

	Storage time [d]	2	4	7	15	34
LMG 0/2 mm	Penetration ¹ [mm]	15.2	12.0	11.5	11.7	9.0
	Std. Dev. [kPa]	0.8	2.2	1.2	0.5	2.2
LMG 0/4 mm	Penetration ¹ [mm]	16.3	12.2	15.3	12.8	10.8
	Std. Dev. [kPa]	1.7	2.2	2.5	0.8	0.8

¹Mean value of three drops.

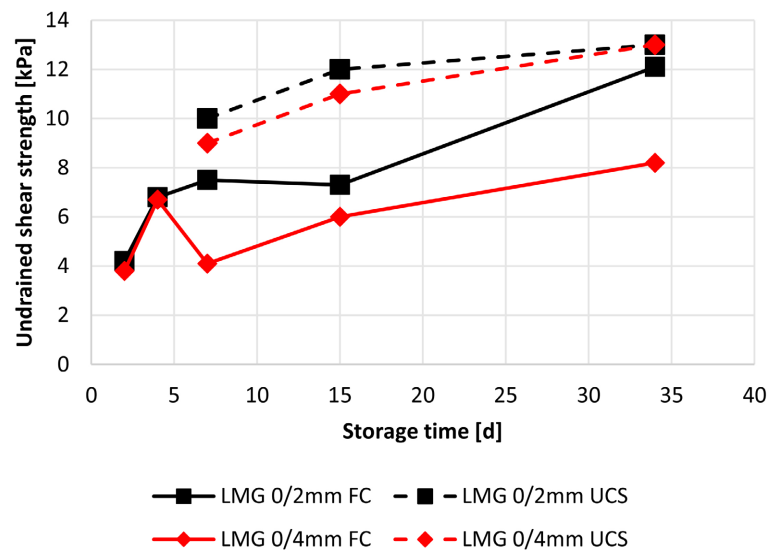


Figure 7. Development of undrained shear strength of stored samples measured using fall cone test (index test) and UCS test.

The development of undrained shear strength was similar in the two LMG materials and after 34 days of storage, the mean value of undrained shear strength (UCS test) in both LMG materials was 13 kPa. The standard deviations for the UCS tests were low, especially for the 0/4 mm LMG material. The standard deviations for the fall cone tests were always higher than the maximum allowed 0.5 mm according to the standard (SS-EN ISO 17892-6:2017, 2017). Finally, the standard deviations were higher compared to the measured standard deviations during fall cone tests on the fresh LMG material (see **Table 5**). In comparison, the undrained

shear strength results from the fall cone test were observed to be consistently lower than that of the UCS test but had a similar development (see [Figure 7](#)). The fall cone test functions as an index test, and its results should not be taken as absolute values. Reference values for naturally occurring moraines (core soil material) are between 30 and 220 kPa, according to [Gribulis et al. \(2019\)](#). From this point of view, the undrained shear strength results of the LMG materials are low. However, neither compaction nor grout pressures were applied when the samples were made. Single spare samples were tested after 56 days (0/2 mm) and 70 days (0/4 mm) of storage, with undrained shear strength at 19 kPa and 23 kPa, respectively. Although the grout material's 34-day undrained shear strength (~13 kPa) is significantly lower than that of moraine (typically 30 - 220 kPa; [Gribulis et al., 2019](#)), this does not necessarily compromise the long-term performance of the repaired zone. The injected grout material is expected to undergo gradual densification and drainage under confining stress from the surrounding core and overburden, which may increase its strength beyond the 23 kPa observed in unconfined laboratory storage. However, the lower initial strength implies that the repaired zone may deform more readily under load, potentially leading to localized settlement. Importantly, the use of a non-hardening grout material avoids the creation of overly stiff inclusions that could crack or debond from the surrounding core ([Lim et al., 2004](#)), thereby reducing the risk of preferential seepage paths.

4. Final Notes

The methodology for storing samples was chosen because it would allow the LMG material to be slowly drained. In an embankment dam, the injected LMG material will most likely be slowly drained or percolated by seepage. If the samples had been sealed in both ends during storage, this situation would not have been representative for an injected LMG material. If drainage had been hindered, the effect of the SP would probably have remained unchanged, resulting in no to little increase of the shear strength after storage. An interesting storage methodology would be to have the LMG material percolated by seepage while subjected to a load. This could possibly simulate a more life-like situation of a LMG material after injection inside an embankment dam. The percolating water should, with time, exchange the initial SP and water mixture in the LMG material to water only. The loading would simulate an external load from the surrounding core and densify the LMG material. This life-like storage methodology would probably cause an increase of the shear strength after storage.

While this study focused on strength development and settlement behavior, it did not include direct measurements of hydraulic conductivity of the cured grout material. However, based on the grout material composition, particularly its 20% fine content and bulk densities exceeding 2150 kg/m³—it is expected to exhibit low hydraulic conductivity comparable to that of intact moraine core soils. Previous studies have shown that glacial tills with similar fines content and density typically achieve hydraulic conductivity values in the range of 10⁻⁷ to 10⁻⁸ m/s ([Fell et al.,](#)

2005). Thus, the grout material is anticipated to meet the permeability requirements for dam core repair, although future work should include direct hydraulic conductivity testing to confirm this assumption.

The settlements of the LMG-samples during storage were too high, i.e., 2.2% - 5.9% compared to the limit used in the pre-testing of 1%. If a LMG material undergoes settlements after injection, the grout procedure will be less successful (Warner, 2004). This deviation from the <1% settlement criterion established during pre-testing (Lagerlund & Holmberg, 2021) is significant and underscores the need for further optimization of the grout formulation. To reduce post-injection settlement, increasing the bentonite content or overall fines fraction is recommended. Bentonite's swelling capacity can help retain water and reduce bleeding, thereby minimizing volume loss during curing. However, reducing water content alone is not advisable, as it may lead to excessive viscosity and hinder pumpability at water contents < 12%. Future formulations should aim to balance workability with stability by adjusting the bentonite dosage and potentially incorporating finer limestone filler fractions.

5. Conclusion

- Natural aggregates, i.e., sands and gravel, limestone filler, water, superplasticizer, air release agent, and bentonite powder have been successfully used to create a new type of non-hardening grout material for remedial injection grouting in embankment dams. It behaves like a fluid when pumped and injected but slowly gains shear strength over time, transforming it into a material with similar characteristics to a moraine.
- The addition of SP in the LMG material improved its workability. Without the SP, the material behaved like a moist sand, making it unsuitable for pumping and injection.
- During homogenization, the LMG material containing SP has a strong tendency to absorb air. Air content increased by a factor of 5.5 (0/2 mm) and 2.6 (0/4 mm) after about 2 hours of continuous homogenization. When homogenized for only 15 min, the air content in both LMG materials decreased by a factor of 0.9 after approximately 2 hours of resting and only a minor increase in undrained shear strength was noted. Homogenization should therefore not take longer than 15 min.
- Measuring the undrained shear strength of the material was used to determine if the effect of the SP wore off with time. Fall cone test was found to work very well as an index test.
- When the LMG materials were stored in fiber glass tubes, they were allowed to be drained. This caused settlements between 2.2% and 5.9% to occur and an increase of the bulk density, especially for the 0/4 mm LMG material. No mechanical loading was applied before or during storage apart from the LMG materials own weight. Most of the settlements occurred within 2 days of storage.

- Undrained shear strength (UCS) after 34 days of storing was 13 kPa for both LMG materials. Triple testing was applied, and the standard deviations were low (0.1 - 2.2 kPa). Single spare samples were tested after 56 and 70 days of storage. Undrained shear strength was then 19 kPa and 23 kPa respectively.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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