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Laboratory-Based Full-Scale Calibration Chamber for Grout Injection Studies

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ABSTRACT: Permeation grouting is a widely used soil improvement technique in civil and geotechnical engineering, aiming at enhancing soil strength, stiffness, and cohesion by injecting consolidating mixtures into pore spaces or discontinuities. Its applications include foundation stabilization, tunnelling ground improvement, and mitigation of landslide or subsidence risks. Effective implementation requires a detailed understanding of both grout injection mechanics and the resulting modifications to soil properties. Traditionally, grouting performance is assessed through in situ tests. While these provide practical insights, they are costly, offer limited control over boundary conditions, and provide restricted information on the spatial propagation of grout. To overcome these limitations, this research introduces a laboratory-based calibration chamber (CC) methodology, to replicate grouting operations under controlled yet representative conditions. The CC framework here presented enables reduced experimental costs, precise control of key parameters, and systematic investigation of variables such as grout composition, injection pressure, and soil structure. The paper describes the design of the CC and reports preliminary injection trials. Grout propagation was continuously monitored using embedded sensors, allowing real-time tracking of the injection process. Following treatment, soil specimens underwent hydro-mechanical testing to assess the spatial extent and efficiency of grouting. Results reveal the formation of cemented bulbs within the soil, showing improved mechanical performance that diminishes with radial distance from the injection point. This laboratory approach demonstrates the potential for detailed, cost-effective investigation of permeation grouting processes, offering insights that can inform field-scale applications and optimize soil improvement strategies.

1 INTRODUCTION

Permeation grouting is a widely adopted ground-improvement technique used to enhance soil strength, stiffness, or reduce permeability in granular materials and fractured rock (Arroyo *et al.*; Chang et al., 2016;).

It involves injecting low-viscosity grouts into the porous soil matrix to enhance its properties while minimizing soil displacement (Warner, 2004). Despite its broad application in engineering practice, the quantitative understanding of the physical mechanisms governing grout propagation, filtration, and the resulting hydro-mechanical modifications of the treated soil remains incomplete (Boschi *et al.*, 2020).

Design procedures for grouting operations often rely on in situ testing, which provides valuable operational insight but suffers from limitations such as high execution costs, limited control over boundary conditions, and the inability to directly observe the spatial evolution of the treated zone (Flora & Lirer, 2011). At laboratory scale, the column injection test(ASTM D4320) remains the only standardized method for evaluating the grout injectabiliy. However, its one-dimensional configuration fails to represent realistic confinement conditions and does not account for the operational complexities of field equipment such as tubes-à-manchettes (TAMs).

To overcome these constraints, several studies have attempted to reproduce grouting processes at laboratory scale using large-volume experimental setups (Perret et al., 2000; Bouchelaghem, 2002). However, these configurations do not allow the simultaneous representation of key elements required for realistic injection scenarios: the use of TAMs equipped with sleeve valves, the presence of a bentonite liner, and the accurate control of confining pressures. The absence of these factors limits the capacity of such models to replicate the inherently three-dimensional nature of in situ injections. In this context, controlled physical modelling becomes a crucial tool for systematically investigating grout–soil interactions. The development of a dedicated calibration chamber capable of supporting full-scale three-dimensional injections provides a means to bridge the gap between traditional laboratory tests and field applications. This offers a reliable platform to study permeation grouting mechanisms under repeatable and representative conditions.

2 EXPERIMENTAL FRAMEWORK

The study focuses on evaluating the influences of injection parameters on grout propagation and the morphology of the treated zone. how injection parameters—such as pressure, flow rate, and grout rheology—affect the spatial distribution and morphology of the injected zones. It also seeks to quantify the hydro-mechanical improvements induced by the injection process, including reductions in soil permeability and increases in stiffness and strength. Furthermore, the research investigates the role of the bentonite liner and confining boundary conditions in controlling preferential flow paths and ensuring reproducibility of grout propagation. Overall, the proposed framework is intended to procid a systematic methodology for reproducing field grouting operations in the laboratory, allowing direct comparison between different grout mixtures, injection sequences, and soil types (Flora & Lirer, 2011).

3 CALIBRATION CHAMBER (CC)

This research aims to investigate the mechanisms of permeation grouting through controlled laboratory conditions, emphasizing the three-dimensional propagation of grout and its effects on the hydro-mechanical behaviour of granular soils. To achieve this goal, a large calibration chamber (CC) was developed to reproduce full-scale grouting operations under laboratory-controlled conditions. Thanks to its design it allows to accommodate actual field equipment such as TAM), double packers, and turbomixers. Boundary conditions representative of in situ stress states are imposed through controlled confinement, while a bentonite coating is incorporated to replicate the sealing and support conditions of the hole that can be found on site. This setup allows continuous monitoring of injection pressure, flow rate, and injected volume thereby providing high-resolution data for process analysis. Post-injection investigations enable the characterization of grout distribution and the geometry of the cemented bulbs within the soil matrix.

The chamber is designed to replicate both geometric and mechanical aspects of in situ injections. Its cylindrical shape was selected to minimize edge effects and ensure uniform stress distribution around the soil specimen. This geometry also facilitates the orthogonal arrangement of injection valves, consistent with common field practice, and reduces potential leakage along joints or interfaces. At the centre of the device, a bentonite liner is installed using a 100 mm diameter tube. The tube is sized to accommodate the TAM while preserving a 35 mm thickness of bentonite coating around it, providing structural support to the borehole. The presence of this liner is important for two reasons. First, it provides structural support to the borehole, preventing collapse induced by horizontal ground stresses. Second, it inhibits the backflow of the injected mixture along the manchettes, thereby avoiding the formation of preferential flow paths. This effect is achieved through the confining pressure exerted by the liner itself, and it is a function of its density and the depth at which it is installed.

Scaling considerations guided the choice of soil volume and injection layout, ensuring that the results are representative of realistic grout propagation patterns while remaining compatible with laboratory monitoring and instrumentation. The chamber dimensions were selected to allow the injected mixture to develop without significant interference at the boundaries, while reproducing the typical centre-to-centre distance of the injection pipes used in field applications (approximately 700 mm).

The position of the injection valves was defined in accordance with the standard tube-à-manchettes (TAM) layouts used in practice and was further selected to position the injection point at mid-height of the soil sample, thus favouring a more symmetrical propagation of the grout in all directions. Although it is not possible to achieve complete similarity with in situ conditions on a laboratory scale, this approach allows realistic reproduction of the dominant flow mechanisms, preferential pathways and geometries of the treated zones, enabling systematic comparison under controlled conditions.

3.1 Design of the laboratory equipment

Th apparatus (Figure 1) is divided into three main parts: a lower parts as the base (a); the central part whit the cylindrical formwork where the soil sample is located (b); and the upper part, as the lid (c).

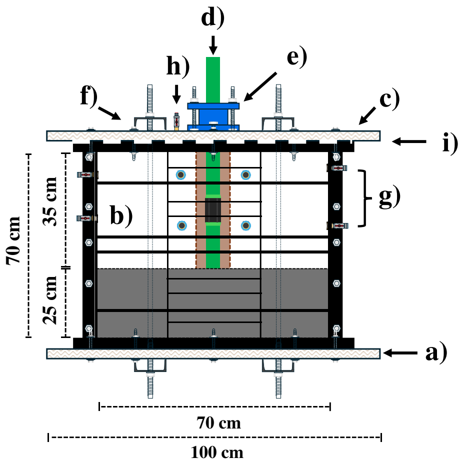

Figure 1: Vertical cross section of the CC: a) base panel; b) central body; c) top panel; d) TAM; e) anti-extraction flange; f) U-profile; g) drainage system; h) air inlet for lithostatic load; i) top membrane to impose lithostatic load

The lower part of the CC consists of a base made of a 1 m × 1 m wooden panel, 30 mm thick, treated to limit swelling due to water or grout absorption. Structural confinement is ensured by two U-shaped steel bars (10 cm wide, 1 m long) positioned beneath the base and oriented perpendicular to the formwork closure. These are connected, via threaded rods, to two corresponding U-shaped steel bars placed above the lid, thereby enhancing structural tightness and limiting deformation.

The base panel is drilled with 14 holes: 10 holes (⌀ 8 mm) for M8 screws (100 mm long) used to fasten the panel to the cylindrical formwork, and 4 holes (⌀ 10 mm) accommodating M14 threaded rods approximately 1 m long, which connect the bottom panel to the top panel.

A cylindrical body is adopted as the core element of the apparatus for two main reasons. First, in field applications, permeation grouting is a three-dimensional process and is typically performed using injection systems equipped with four valves arranged orthogonally (at 90° intervals) along the circumference, with a vertical spacing of approximately 33 cm. Consequently, a cylindrical geometry is adopted, as it best reflects the spatial arrangement and operational principles of full-scale injection systems and ensures greater fidelity in reproducing field conditions. Secondly, the cylindrical geometry minimizes the risk of fluid and/or pressure leakage. Alternative geometries, such as cubic configurations, inherently involve multiple discontinuities (i.e., edges and vertices), which are more difficult to seal and are more susceptible to boundary-related artefacts. The cylindrical body therefore constitutes the most reliable solution, both in terms of geometric coherence and in achieving the level of hydraulic tightness required for controlled laboratory modelling. The cylindrical chamber employed in the experimental set up is made up of Acrylonitrile Butadiene Styrene (ABS) and designed to function as a formwork. It has a total height of 605 mm, an internal diameter of 700 mm—selected to replicate the typical centre-to-centre spacing of injection pipes in field applications (approximately 700)—and a wall thickness of 82 mm.

The required soil height is 350 mm, and it is achieved positioning a 250 mm extension. The latter one is produced by casting a mixture of polyurethane resin and expanded clay within the formwork. After it has hardened, it is overlayed with a mixture of water and quick-hardening cement to provide surface levelling.

The upper part of the CC mirrors the lower one and consists of an identical treated wooden panel.

Two U-shaped steel bars are positioned above the lid, oriented perpendicular to the formwork closure point. These bars are connected, via threaded rods, to the two corresponding U-shaped steel bars of the base. The panel is drilled with a total of 14 holes divided as follows: 10 holes (⌀ 8 mm) allowing the passage of M8 screws (100 mm long) to attach the panel to the cylindrical formwork; and 4 holes (⌀ 10 mm) for M14 threaded rods approximately 1 m long, used to connect the top and base panels.

A hole of 80 mm in diameter is provided at the centre of the panel to accommodate the tube-à-manchette (TAM). Four additional through-holes (Ø 10.2 mm) are arranged around this opening to allow the installation of mechanical anchoring components.

3.1.1 Drainage system

The drainage system is made up of eight holes: four located at 90° with respect to the junction between the two semi-formworks, and four aligned along this junction. This last point is identified as a critical area for potential grout and pressure leakage. The holes are distributed over two different vertical levels and arranged in a mirrored configuration, thereby ensuring geometric symmetry and a balanced hydraulic response.

The drainage holes provide a direct hydraulic connection between the soil and the external environment. To promote a uniform flow towards the outlets, a geonet–geotextile drainage layer is installed between the soil and the chamber wall. The discharged fluids are conveyed either to collection containers or to pressurized tanks. The latter option enables confinement of the pore fluid and allows the simulation of in-situ hydrostatic pressure conditions.

The soil tanks are configured as follows. The main body consists of a polycarbonate cylinder with a diameter of 20 cm, while two wooden panels measuring 50 × 50 cm form the base and the top of the tank. These elements are assembled and restrained by a rigid frame composed of four M8 threaded rods, which provide structural stiffness and ensure resistance to the internal pressures developed during operation. The top panel is equipped with three holes: one connecting the tank directly to the CC drainage system, one dedicated to water filling, and one used for air pressurization. The latter is connected to a compressed-air line and, through a pressure regulator and pressure gauge, allows precise control of the hydrostatic pressure applied to the pore fluid within the soil sample.

3.1.2 Hydraulic and mechanical sealing strategy

The calibration chamber is equipped with a comprehensive hydraulic and mechanical sealing system designed to ensure confinement, prevent fluid leakage, and allow the controlled reproduction of in-situ stress conditions during injection.

At the base of the chamber, hydraulic tightness between the wooden panel and the cylindrical formwork is ensured through a multi-layer sealing system. A perforated rubber sheet (90 cm × 90 cm × 0.5 cm) is placed directly on the base panel, with its openings aligned with those of the panel. An annular rubber gasket, 0.2 cm thick, is interposed between the lower rim of the cylindrical formwork and the rubber sheet to guarantee sealing at the soil–confinement interface. The gasket is cut to match the annular cross-section of the cylinder wall, with a width equal to or slightly greater than the wall thickness (10–12 cm), ensuring continuous contact along the entire perimeter and preventing leakage of water or grout during injection.

At the top of the chamber, lithostatic stress conditions are simulated through a pressurized confinement system. A rubber sheet with a thickness of 5 mm is clamped between the upper panel and the cylindrical formwork. This sheet is connected to a compressed-air line through a dedicated opening (⌀ 16 mm) in the lid Figure 2). By regulating the applied air pressure, the rubber membrane inflates and transmits a uniform vertical load to the soil specimen, reproducing the lithostatic pressure corresponding to the target depth. Additional sealing is provided around the tube-à-manchette (TAM) to prevent pressure dissipation and upward grout migration along the central opening. A rubber nozzle is bonded to the upper rubber sheet, extended into the 80 mm central opening, and mechanically secured by the combined use of a flat flange and an anti-extraction flange anchored through four surrounding through-holes. This configuration counteracts the axial forces generated during injection and ensures hydraulic tightness at the TAM–lid interface.

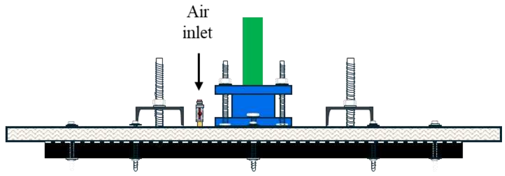

Figure 2: schematic representation of lid

Overall, the combined use of perimeter gaskets, pressurized rubber confinement, and mechanically restrained sealing elements ensures full hydraulic tightness of the system and reproducibility of the experimental boundary conditions. This integrated sealing strategy enables controlled observation of grout propagation and soil–fluid interactions under representative confinement and stress states.

3.2 Testing of on-site equipment in the lab

The proposed system design introduces the innovative capability of employing field injection equipment directly under laboratory conditions.

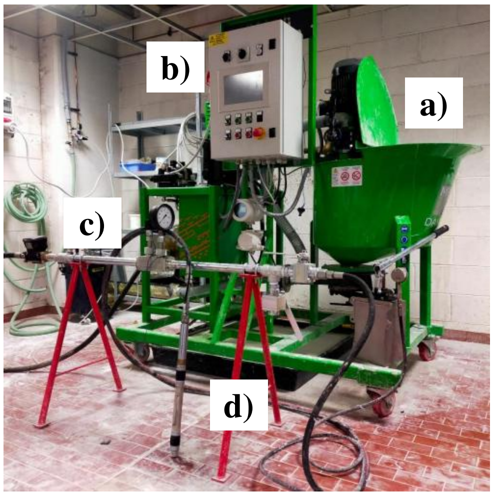

Figure 3: injection set-up: a) turbomixer; b) injector; c) injection stand; d) double packer

This approach makes it possible to reproduce field injection conditions with a high degree of accuracy, while ensuring full control over all parameters and variables influencing the injection process. The injection setup (Figure 3) used in conjunction with the CC described above consists of an injector coupled with a turbomixer (a-b), an injection stand (c), a double hydraulic packer (d), and a tube-à-manchette (TAM).

Grout preparation was performed using the MDPT150-DEOL3 system, which includes both a turbomixer and an injector. This system is equipped with a digital control interface that allows the definition of injection parameters for each individual valve of the tube-à-manchette. Furthermore, it enables real-time monitoring of the injected volume, injection pressure, and flow rate throughout the grouting process. During injection, the grout flow through the borehole is monitored by means of an injection stand fitted with a manometer and a flowmeter. The manometer is used to track pressure variations, while the flowmeter allows continuous monitoring of the injected flow rate.

Valve tubes made of Durvinil ($Ø_{internal}$ = 40 mm, $Ø_{external}$ = 48 mm), equipped with external valves and sealing rings, are employed. Along the tube, non-return valves are installed at 33 cm intervals; these valves permit the passage of the cementitious mixture exclusively toward the ground, preventing any backflow of the fluid inside the pipe. The system is fitted with DUR-O-RING hand valves, which provide several operational advantages. Specifically, they allow selective injections by enabling the operator to activate individual valves and to record pressure and injected volume over time, for example by means of a data logger. In addition, they permit repeated injection cycles, as the valves ensure complete closure after each injection, preserving their functionality for subsequent operations. The system also offers flexibility with respect to the type of grout mixture used, including standard cement, microfine cement, and silicate-based formulations.

Finally, injections through the valves are carried out using a double hydraulic packer, which allows the isolation of each individual valve to be treated. The packer operates through an oil-based hydraulic system: pressure is applied to the hydraulic circuit using a manual pump, causing the rubber seals to expand radially. In this manner, the packer isolates the volume surrounding each valve, ensuring that the grout mixture is injected into the soil in a controlled and localized manner, valve by valve, while enabling precise regulation of the injected volume at each outlet.

4 MATERIALS AND TEST PROCEDURES

4.1 Soil and grout characterization

It is necessary to study all the elements that characterize the injection itself. The aim is to evaluate the groutability of a specific soil.

4.1.1 Soil characterization

Injections can be performed on: (a) standard soils sourced from quarries; (b) soils reconstructed by mixing standard soils; and (c) real soils collected from the field. Soil injectability is assessed by comparing the particle size distribution (PSD) with established groutability criteria for cement- and silicate-based mixtures. Injectability curves for the wo main types of mixtures have been identified by Pettinaroli et al. (2019). The soil can be considered injectable with a specific grout if its PSD lies on the right side of the injectability curve of the mixture to be used (Figure 3). The experimental programme involves injections in type (c) soil under dry conditions (Figure 3).

4.1.2 Mixture characterization

There are two main types of mixtures currently in use (Burwell et al., 1958): cement-based and silicate-based mixes. In the present study, only cement-based mixtures were employed. Two consecutive injections were carried out on the same soil using cement mixtures with different component proportions (Table 1). The formulations were designed to provide distinct rheological properties: the first injection utilized a mixture with higher density and viscosity, intended to penetrate the larger pore spaces of the soil matrix, whereas the second injection employed a mixture with lower viscosity to enhance penetrability and allow the filling of the remaining, potentially smaller, voids not occupied during the first injection.

Mixtures are characterized in terms of viscosity, density, and stability over time. This is performed through laboratory tests to evaluate the suitability of the mixtures for permeation grouting at low injection pressures.

Table 1: mixtures used for injections: cement mix proportions relative to cement (W: water; C: cement; B: bentonite; Add: additive)

CEMENT MIXTURES				
	W/C	B/C	Add/C	Soil
Cem_mix1	1.5	0.06	0.01	c)
Cem_mix2	2.5	0.07	0.01	c)
Sheath.	2	0.1	-	-

Tests conducted to characterize the mixtures' properties include:

- Fluid viscosity: measured using a Marsh funnel, where viscosity is expressed as efflux time, and a hand-crank rheometer, with viscosity evaluated from the fluid response to rotational speeds of 300 and 600 rpm.
- Fluid density: determined as mass per unit volume using a graduated cylinder and verified with a Baroid mud balance.
- Fluid stability: evaluated through bleeding and filter-press tests.

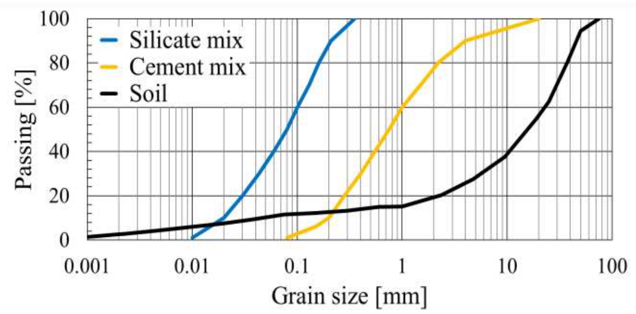

Figure 4: soil PSD compared with the groutability curves for: cement (yellow) and silicate mix (blue).

The rheological characterization of the mixtures was followed by mechanical testing, in which uniaxial compressive strength and stiffness were measured as reference values to assess the effects of injection.

The mixtures were prepared by blending water, additive, and bentonite into a slurry, allowing it to rest for 10 minutes, and then adding cement and mixing for a further 10 minutes. Both have been prepared twice with different batch volumes and mixing equipment. Preliminary tests on 5 L batches were performed using a drill and whisk, whereas validation for the 3D system was carried out on 30 L batches using on-site mixers, following the same sequence and timing.

4.2 Injection procedures

The TAM is installed at the centre of the cylindrical system, and a casing pipe (Ø 100 mm) is placed around it to enable the subsequent casting of the bentonite sheath. The chamber was filled by placing the granular soil in successive layers approximately 5 cm thick, each of which was compacted to achieve a target porosity of 30%. A total mass of 242 kg was placed in the chamber whithin a known volume of 132 lt. During the placement of each layer, the soil surface was sprayed with nebulized water to prevent excessively dry conditions, which could otherwise lead to claquage phenomena during injection.

After completing soil placement, the annular space between the TAM and the soil is filled with the bentonite sheath (Table 1). During this operation, the casing pipe is progressively withdrawn, and the sheath is subsequently allowed to cure for 2–3 days.

Grouting is performed at a controlled flow rate, and all relevant parameters, including pressure, flow rate, and injected volume, are monitored and recorded for the entire duration of the injection (Figure 4). Looking at the recorded data, it is possible to understand how different mixtures with different rheological properties behave during an injection. The first injection (Figure 5a) utilized a mixture with higher density and viscosity, intended to penetrate the larger pore spaces of the soil matrix. The second injection (Figure 5b), instead, employed a mixture with lower viscosity to improve penetrability and fill the remaining, potentially smaller, voids not occupied during the first injection. This is shown by the pressure trend, which is less constant and reaches higher peaks (up to 15 bar) just in the first injection than in the second.

Furthermore, analysis of the flow rate evolution indicates that the second injection allowed for better control of the injection rate, which remained more stable over time. Conversely, during the first injection, the higher density of the mixture made it more difficult to maintain a constant flow rate, likely due to the need for the grout to permeate pore spaces with highly heterogeneous shapes and sizes associated with the natural soil structure, rather than the more uniform voids left by a previous injection stage.

4.3 Treated sample extraction and laboratory testing

After 28 days of curing time, specimens were extracted from the injected soil. The sampling technique is predominantly controlled by the grain size of the host ground. Specimens can be extracted in 3 different ways: manual trimming, core drilling, and circular saw cutting. When the host soil is characterised by large grains, circular saw cutting to extract cubic samples resulted to be the best solution to attain representative samples for mechanical testing. Samples were collected at three distinct vertical levels (upper, middle, and lower) to assess the vertical distribution of the injected mixture along the height of the treated volume. Furthermore, to account for radial variability in the injection process, the extracted specimens were classified according to their radial distance from the injection point, as illustrated in Figure 5. This methodology enabled the evaluation of the spatial propagation of the injected mixture within the soil mass, providing insight into the advancement and penetration extent of the grout as a function of distance from the injection source.

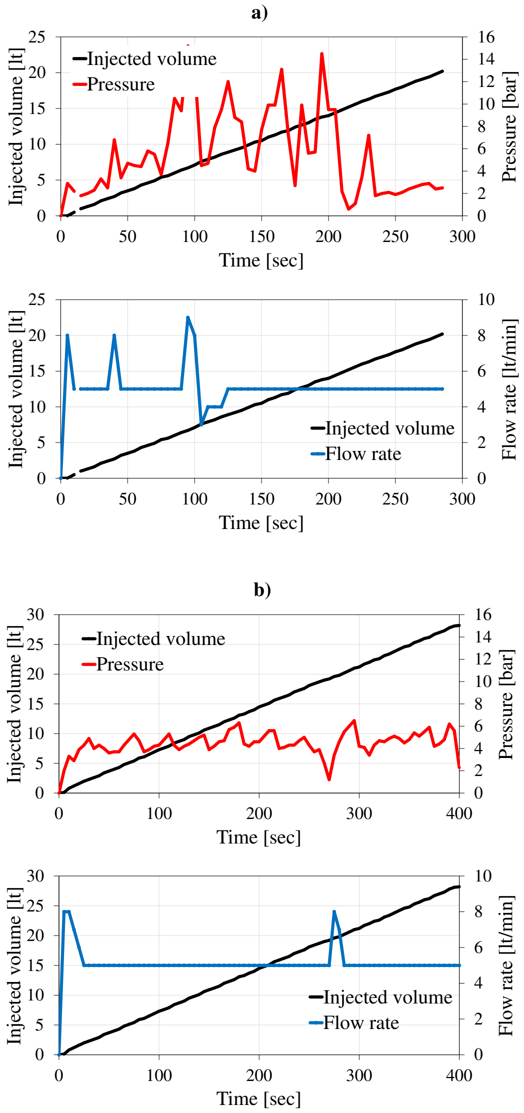

Figure 5: injection parameters monitoring during the first (a) and second (b) injection: injected volume (black), pressure (red) and flow rate, all expressed over time

A total of 21 specimens were extracted. All of them were tested under uniaxial compression tests to measure the resistance developed by the soil following the injection itself. For each sample a stress-strain curves are obtained and so the stiffness E, expressed as the slope of the tangent to 50 % of the peak strength (E_{t50}), can be derived. This allows to obtain the average UCS (Figure 7) and stiffness (Figure 8) of the entire treated soil. This value is then compared with the stiffness of loose soil (E_0) obtained through an oedometric test in displacement control. All tests carried out yielded an average stiffness of 76.3 MPa. Comparison of this value with the stiffness values obtained on natural soil indicates that the injection had the effect of increasing the stiffness of the treated soil by a value between 2 and 4.3 times the E_0 value.

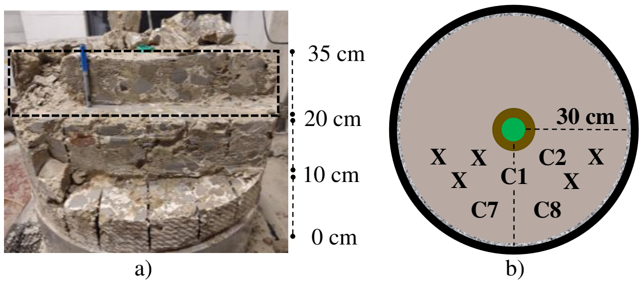

Figure 6: Sample extraction scheme for uniaxial compression tests, showing the vertical sampling levels (a) and the radial distribution of specimens with respect to the injection point (b).

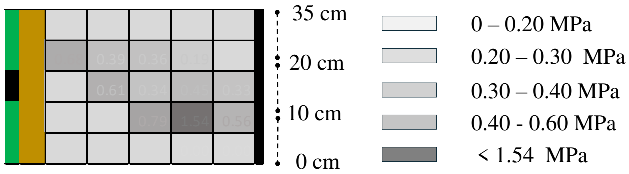

Figure 7: UCS values distribution related to height and radial distance from the injection point

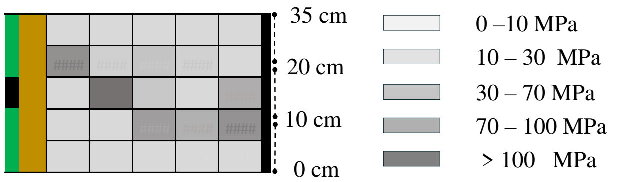

Figure 8: Et50 values distribution related to height and radial distance from the injection point

5 CONCLUSIONS

This study presents the development of a calibration chamber (CC) designed to study permeation injection processes under controlled but filed type conditions. The proposed experimental framework enables the direct use of field equipment, including tube-a-manchette (TAM) systems, dual hydraulic packers, and on-site mixing and injection units. Moreover, the system enabled continuous monitoring of key injection parameters, such as pressure, flow rate, and injected volume, providing high-resolution information on mortar propagation mechanisms. The cylindrical geometry of the system, combined with the use of bentonite sheath and the implementation of hydraulic and mechanical sealing strategy, aims to reproduce realistic confinement and boundary conditions.

The results of the injection tests highlighted the significant influence of mixture rheology on injection behaviour and spatial distribution. The first injection, performed with a denser, more viscous cement mix, showed higher pressure peaks and greater variability in flow rate, reflecting the interaction with the naturally heterogeneous porous structure of the soil. In contrast, the second injection, carried out with a less viscous mixture, showed better control of the injection rate and more stable pressure conditions, allowing the mixture to penetrate and fill the smaller residual voids left by the initial treatment phase. Post-injection specimen extraction and uniaxial compression tests confirmed the formation of cemented zones within the soil mass, with mechanical performance decreasing with increasing radial distance from the injection point. The measured stiffness values (E) indicate a substantial improvement in soil stiffness, ranging from approximately two to more than four times that of the untreated soil, demonstrating the effectiveness of the permeation grouting process.

Overall, the study and results presented show that the designed CC is an efficient and versatile tool for the systematic investigation of permeation grouting mechanisms. Its ability to replicate field-scale injection processes in a controlled laboratory environment opens new opportunities for optimizing grout formulations, injection sequences, and operational parameters. Future work will focus on extending the experimental program to different soil types, grout compositions, and stress conditions, as well as on integrating advanced monitoring techniques to further enhance the understanding of grout–soil interactions.

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