Politecnico di Torino

Master of Science in Petroleum and Mining Engineering

Master's thesis

Experimental study on Sustainable reuse of the muck to produce two-component grout Backfilling

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Abstract

Tunnel Boring Machines are widely used for the construction of tunnel infrastructures. As a result, a considerable volume of muck is frequently generated during the excavation process. This muck can be considered as a resource for other constructions and can be reused again.

One of the aspects that can be considered in order to reuse the muck for the aim of sustainability is backfill grouting, especially in two-component grout, which is a widespread technique with a lot of versatility and fast reaction in order to avoid settlement. Two-component grout consists of a component A, a mortar, and a component B, an accelerator, which can be used in shielded TBM.

Thus, a laboratory test campaign was performed to understand the effect of the presence of aggregate in a two-component grout. In this campaign, ten different mix designs were prepared with various amounts of aggregate. For each sample, different tests such as flowability, unit weight, bleeding on component, A and gel time on the gelled grout, which is a mixture of components A and B, Surface Compressive Strength (SCS) and Uniaxial Compressive Strength (UCS) on the hardened grout were measured, and results are presented at the end.

Keywords: Backfilling, Two-components grout, Sustainability, Muck reuse

Introduction

Tunnel boring machines (TBM) can be considered the most common technology used in tunnel project construction in recent years. Due to the increasing of different tunnel projects on the one hand and the shortage of the raw materials needed in these constructions, on the other hand, a massive problem could arise both in terms of providing the material and/or dumping huge amounts of waste in the future. Since environmental factors and circular economy are significant concerns, reusing the mucks turn out to be useful. The muck obtained from the tunnel excavation can be used as a source of raw materials needed in the construction of tunnels, such as backfilling materials, railway embankments, or in highway construction. This thesis aims to study how aggregates obtained from TBM excavation can be reused as a backfilling material, specifically in producing two-component grout, which is used in backfilling when shielded TBM are used to perform the excavation.

Two-component grout is obtained as a mixing of component A, which consists of bentonite, cement, retarding/fluidifying agent, while in this thesis, an additional element is introduced (aggregates obtained from excavation of shielded TBM) to achieve the goal of sustainable reuse of the muck. On the other hand, component B is an accelerating agent (usually Sodium Silicate). These two components are mixed, and a gelled grout is obtained in a range of few seconds (5-15 s).

To understand the behavior of the new two-component grout and obtain the optimal condition, several tests were conducted to assess the characteristics of component A, gelled grout, and hardened grout.

The tests performed on component A consisted of the Viscosity test, Unit Weight test, and bleeding test, and they were carried out on the mixture of components A and B involving gel time, which was conducted on the gelled grout, Surface Compressive Strength (SCS) on hardened grout in a short time (1 hour and 3 hours) and Uniaxial Compressive Strength (UCS) on the hardened samples after one day, seven days, and 28 days. The methods to prepare component A, gel time, SCS, and UCS are suggested in (Todaro et al., 2019, 2020).

In Chapter 1, the general layout of full-face mechanized tunneling, together with the types of TBMs used for hard rock, and the importance of the backfilling are discussed. Chapter 2 examines different types of backfilling materials injection methods, and the difference between mono-component and two-component grout. In chapter 3, the idea of sustainable reuse of the muck is discussed, and the properties of the muck used in the test are explained. Chapter 4 consists of the laboratory tests, results, and charts related to the tests. Finally, chapter 5 is devoted to the discussion of the results obtained.

1. Full face mechanized excavation

In full-face mechanized excavation, the procedure of excavation, stabilization, and mucking is done in a continuous way which is carried out by using Tunnel Boring Machines (TBMs). Using TBMs, the shape of the tunnel obtained is circular. Considering the type of ground, Tunnel Boring Machines are classified as rock TBM and soil TBM (Bilotta et al., 2022).

1.1 Rock TBMs

According to rock mass setting, there are different types of TBM that can be used for excavation of a Tunnel. Hard rock TBMs can be categorized as open TBMs (grippers) and shielded TBMs. In addition, shielded TBMs are classified as single shield TBM and Double shield TBM.

1.1.1 Open TBMs

Open TBMs (grippers) are the kind of TBMs used in competent rock masses, which allow the excavation operation without providing any support to the face or cavity and when there is no need for a final lining (Singh & Goel, 2011). The gripper system in open TBMs is used to support the machine to the surrounding ground and allow the needed thrust to be applied to the cutter head(EFNARC, 2005).

In open TBMs, the machine itself performs the cutting and mucking. As the cutters and the cutter head rotate, the disk cutters on the cutter head apply pressure to the face of the rock in order to break it. As a result, chips of rock are detached. The cutter diameter is ranged from 14 to 20 inches (350 to 500 mm). The excavated material is then transferred to the rear of the machine for disposal through a conveyor belt. The roof shield provides temporary support for the rock as well as the safety of the workers. The main beam provides access to the machine, so workers can install the supports and perform the maintenance. The stability of the machine is achieved by fitting its gripper shoes against the walls, and advancement is accomplished by thrust cylinders.

1.1.1.1 The advancement cycle in open TBMs

First Grippers are fitted against the rock, the foot of the machine is raised, and cylindrical jacks apply motion to the cutter head. As the cylindrical jacks push the cutter head against the rock, by applying a given pressure, the cutter disks break the rock while the cutter head is rotating. After a stroke is reached, the rotation of the cutter head stops, the rear foot of the machine is extended to provide stability to the machine and finally the grippers are de-gripped from the rock; in this way, one boring cycle is completed. Figure 1 shows different parts of open TBM.

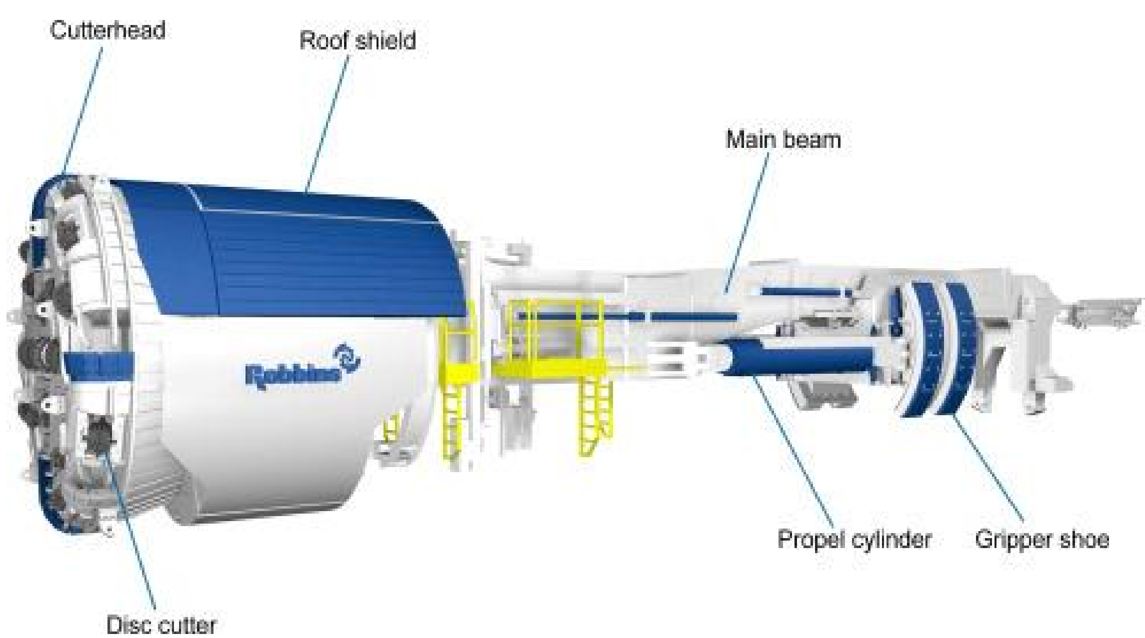


Figure 1. Representation of the open TBM (main beam) with indication of the main components (Robbins company)

1.1.2 Shielded TBMs

Shielded TBMs are used to excavate poor to medium rock masses. In addition, due to the low stand-up time, shield provide a temporary support of the cavity and the segment lining is installed under the protection of the shield. Furthermore, the shield also has a role of the protection of the main body of the TBM and provides the safety of the workers during the excavation process.

1.1.2.1 Single shield TBM

Single shield TBMs are used to perform the excavation in poor rock quality with considerable discontinuities. This kind of TBM is equipped with cylindrical protective shield immediately behind the cutter head. This type of TBM is working in a cyclic manner that include excavation for a length equal to the stroke of the thrust jacks, which is followed by assembling of the concrete segments lining and retraction of the jacks and then the new excavation stroke can start. Figure 2 shows a cross-section view of the single shield TBM.

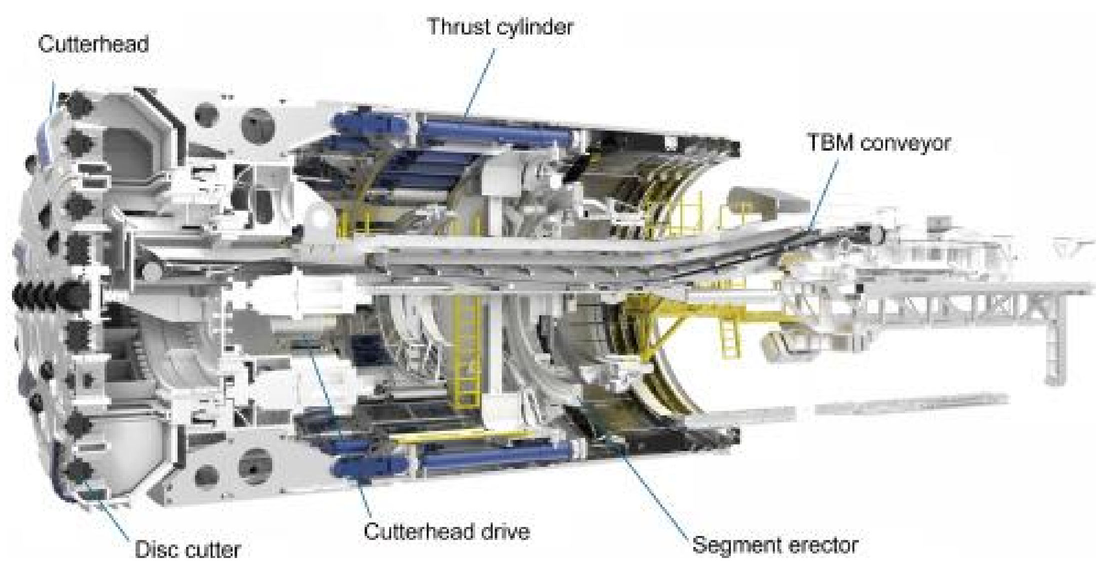


Figure 2 Cross section of the single shield TBM with indication of the important parts (Robbins company)

1.1.2.2 Double shield TBM

It is commonly considered that double shield TBMs are the fastest type of tunnel boring machine for hard rock tunnels under favorable conditions. They can be used in a poor to moderate rock mass. Double shield TBM is a variant of single shield TBM, consisting of two main components: the front shield and the grippers. These two parts are connected with a telescopic joint. So that advancement and installation of segment lining are allowed to happen in a continuous way. With the help of the grippers, the segments are installed under the tail shield while the cutter head is applying the thrust. Then, the telescopic shield extends to cover the advancing of the machine, connecting the tail shield to the front shield. After installation of the segments, thrust jacks are pushed against the segments lining to advance the rear of the machine and replace the grippers. A cross-sectional view of the double shield TBM and its important parts are showed in the Figure 3.

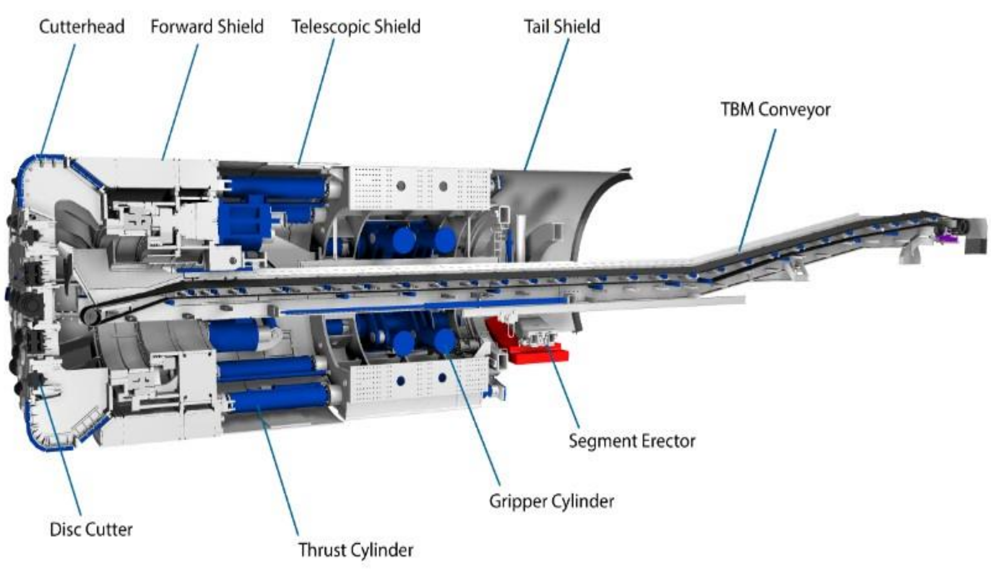


Figure 3 C cross-section of double shield TBM with indication of the important parts (Robbins company)

The main characteristics of the Robbins TBM that used for performing the excavation at the Maddalena exploratory tunnel (related to the Mont Cenis base excavation tunnel located in Susa valley [Piemonte, Italy] is mentioned in Table 1(Rispoli et al., 2016).

Table 1 Main characteristic of the main beam TBM used for excavation at the Maddalena exploratory tunnel (Rispoli et al.2016)

Main Beam' Gripper TBM characteristics	
TBM Diameter	6.3 m
Machine Thrust	13700 kN
Cutter head Thrust	12800 kN
Cutter Head speed	0-11 rpm
Cutter head Torque	2083 kNm
Cutter head Power	2203 kW
Thrust Cylinder Stroke	1830 mm
Number of Main Thrust Cylinders	4
Gripper Total force	36400 kN
Number of Disc cutters	43
Cutter disc size	432 mm
Average disc cutter spacing	77 mm

1.2 Rock Breaking process

In TBMs, the rock breaking process is done by the cutter disc mounted on the cutter head. When the cutter discs are pushed against the rock, high pressure is exerted at the contact area, and, due to the rotation of the cutter head, a cracking zone is created. As a result, stress grows and there is a propagation of the cracks around the rock mass. The detachment of the rock chips is obtained thanks to the rotation of the discs along their axis and rotation of the cutter head along its axis (Bilgin et al., 2013). in hard rock TBMs, the cutter discs are commonly ring shaped and are selected according to geological and geomechanical properties of intact rock. Figure 4 depict TBM cutter disc with indication of the main parts.

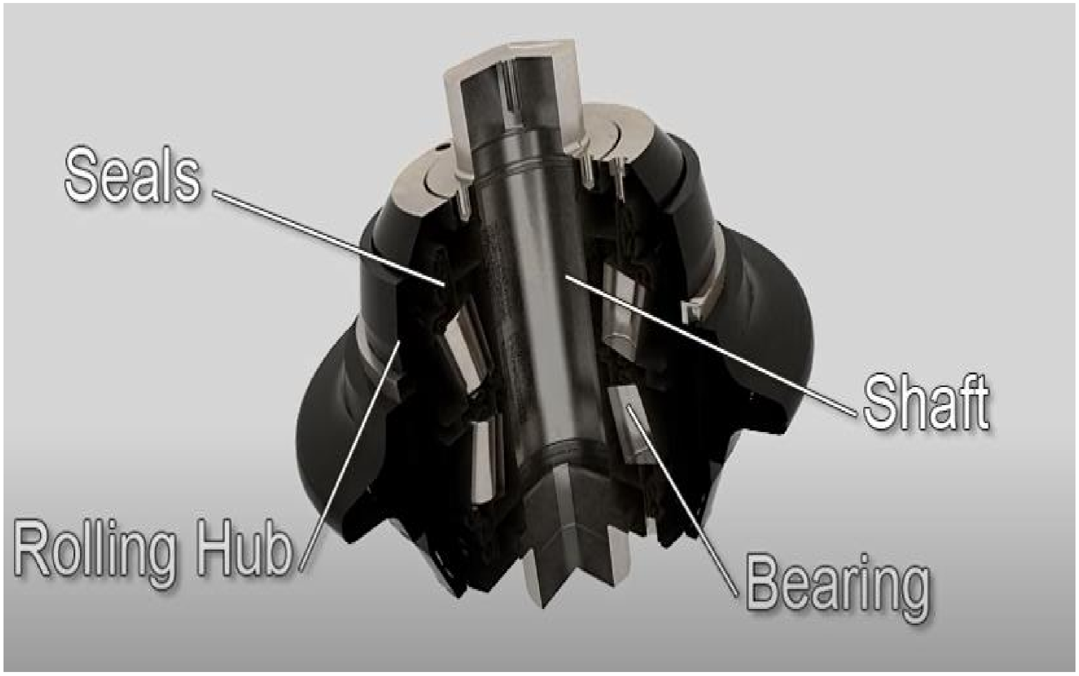


Figure 4 Photo of a TBM cutter disc with indication of the main parts (Robbins company)

However, three forces can be recognized during this process(Figure 5)(Cho et al., 2010):

- Normal force: the force applied vertically by the cutter head to the cutter discs. This force can be varied during the process of advancement.
- Rolling force: this force can be applied thanks to the cutter head torque.
- Side force: this force is applied on the edge of the cutter disc.

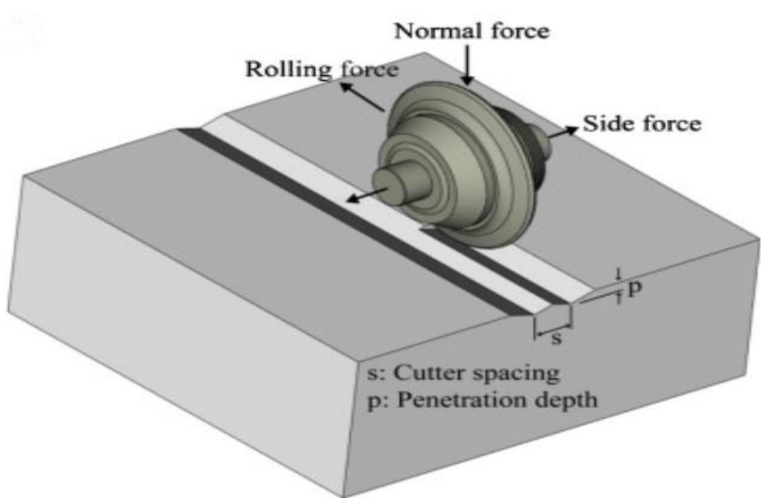


Figure 5 Forces acting on the cutter disc during cutting process (Cho et al.2010).

Chips form when the cracks generated by cutting paths coincide with those produced by adjacent cuts. Consequently, the spacing between tools, the penetration, and the properties of the rock to be excavated have a significant impact on the cutting process.

Over-crushing occurs when the spacing among the discs is too small, resulting in an increase in specific energy, which is not economical. Conversely, when the spacing is too big among the discs, the tools cannot penetrate the rock mass effectively, resulting in no chips being created in a complete round of the head. In order to achieve an efficient cutting process, it is important to maintain an optimum spacing between cutter discs.

To obtain the optimal Specific energy, the ratio between spacing and penetration depth must range between 10 and 20. This range can be changed according to the type of the rock during the excavation (Ozdemir, L., 1992). Figure 6 shows the relation between specific energy vs cutter spacing/depth of cut ratio.

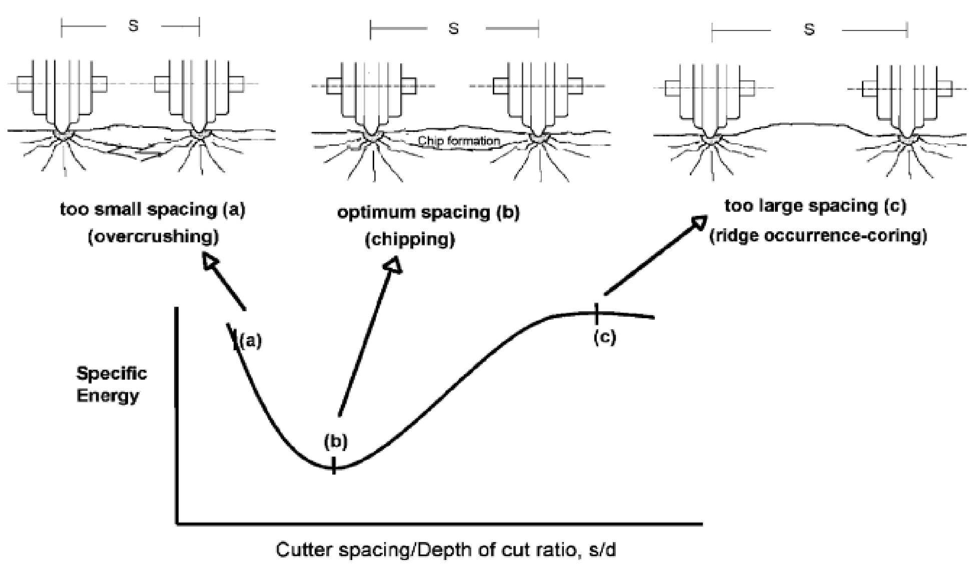


Figure 6 Relationship between spacing/ penetration on specific energy and chip size ((Tuncdemir et al., 2008))

1.3 Explanation of the Annular Gap formation

During the advancement of the tunnel with a full-face mechanized machine, a circular void is created, and prefabricated segments are installed for tunnel lining. An unavoidable circular gap, which is limited from the inside to the segments lining and from the outer part to the ground, is created. This gap is the result of the over-excavation due to the presence of the cutter rings which provide the advancement of the machine, the shield conicity, the thickness of the shield, and the tail brushes. This width is ranged from 13 to 18 cm. these factors are depicted in (Figure 7) (Thewes et.al., 2009).

To avoid the settlement of the surface and counterbalance the ground convergence and guarantee the homogenous distribution of the load along the segments, this void which is a part of tunnel excavation should be filled continuously (ITAtech, 2014). This operation is called backfilling and the grouting must have properties that are the same or better as the surrounding ground in the final state, and installation of the segmental Lining are necessary to transmit forces from the tunnel to the surrounding ground.

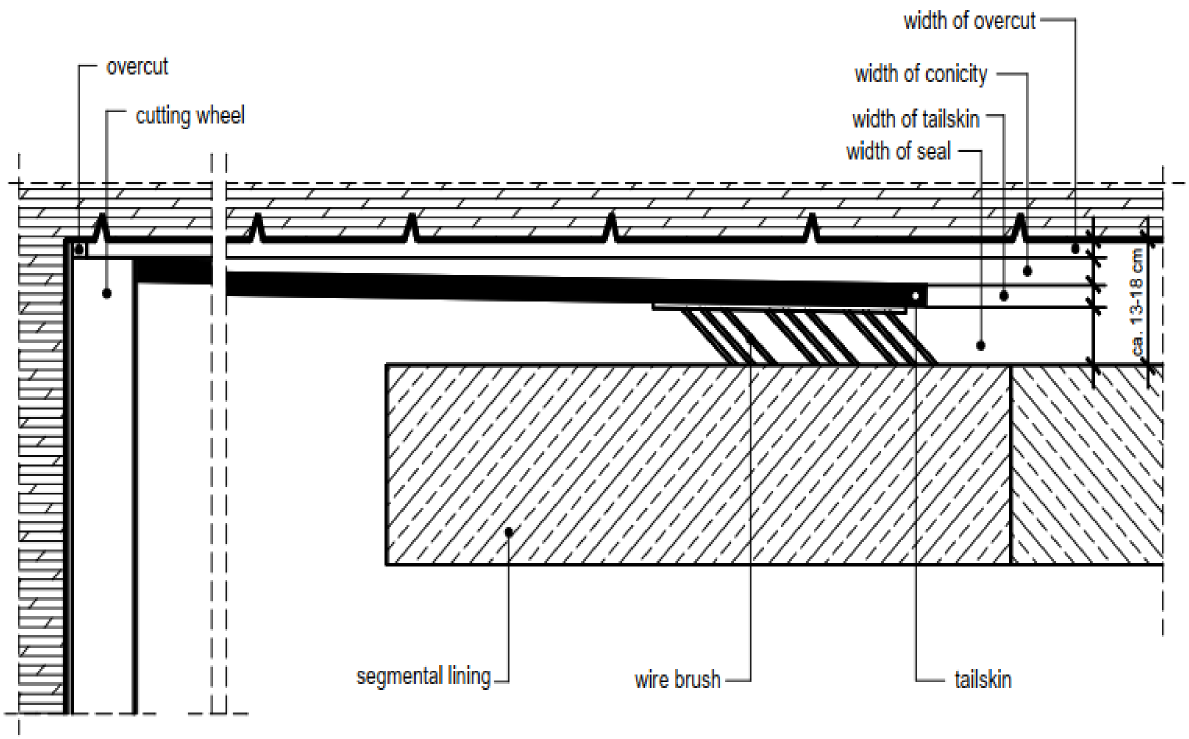


Figure 7 Factors that influence the width of the annular gap (Thewes et al.2009)

2 Backfilling

The annular gap cannot be avoided and, being the filling of the gap extremely crucial, this gap must be filled instantaneously and accurately, with the aim of:

- Preventing the water inflow in cooperation with gaskets by creating a continuous layer.
- Preventing puncture loads by guarantee a homogenous and symmetrical loading along the segment lining.
- Ensuring immediate and homogenous contact between the ground and the Lining and avoiding the settlement of the surface, by counterbalancing the ground convergence.
- Guaranteeing the homogenous distribution of the load along the segments, locking the segments lining in their position and avoiding their movement due to segments weight

and also due to the thrust force or bear the load due to the weight of TBM back-up (Peila et al., 2011).The injection system of backfilling is shown in Figure 8.

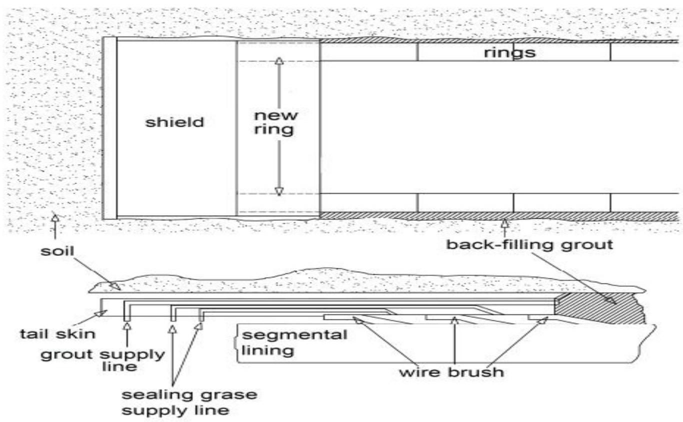


Figure 8 Simplified scheme of backfilling system: longitudinal section of a shield machine(up) and the injection system(down) (Todaro et al.2020)

Wire brush are installed in the inner side of tail skin (final part of the shield) with the aim to impede the enter of backfilling injection inside the working chamber of the machine. Grease fills the gap between wire brushes sets and it is fundamental to guarantee the efficiency and waterproof of the whole system. On the other hand, on the outside of the ring, there is excluder, like a fish scale seal which is mounted, and this excluder is designed to prevent grout from moving forward over the tail shield. This prevents the cementation of the tail shield to the surrounding rock (Figure 9)(ITAtech, 2014).

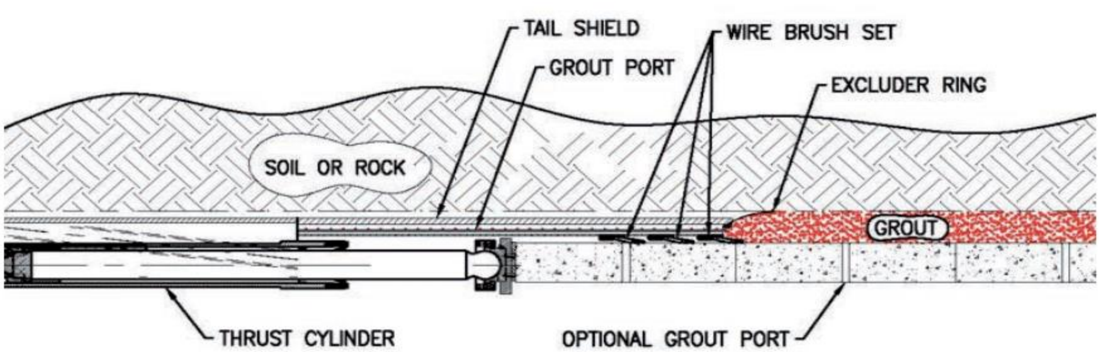


Figure 9 The basic principle of backfill grouting, wire brush sets and excluder in backfilling (ITAtech,2014)

In order to achieve the above-mentioned goals, it is necessary that the anulus gap is completely and continuously filled. The filling material must promptly fill the gap to avoid the presence of the void in anulus and as a result avoid the ground settlement. In addition, the annular gap should be filled regularly and completely, also with respect to mechanical behavior and physical characteristics, so that the Lining could be perfectly linked to the surrounding ground. Furthermore, the injection material must provide a quick support to segmental Lining without cause clogging, chocking the injection pipes and nozzles and should be resistant against ground water (Peila et al., 2011).

As a logistical requirement, the material that is used for backfilling should be designed so that it can provide transformability, pumpability and workability for a long period, up to 72 hours. To avoid chocking of injection material during the regular stops of the machine and to be able to resume the operation at any time. As a result, it is essential that through the transforming of the backfilling material from the batching plant to the point of injection, phenomena such as bleeding and segregation must not occur (Peila et al., 2011 ; EFNARC, 2005).

2.1 Backfilling injection method

Two different methods are established to fill the annular gap with grout material: on the one hand through the ports that are located in the tail shield, on the other hand through the ports in segment lining. Keep in mind that tail skin injection is the only approach that allows for full and continuous filling of the gap, maximizing the benefits of the backfilling procedure.

2.1.1 backfill injection through the shield's ports

Backfilling through the shield's ports, also known as tail tube grouting, occurs at the end of the tail shield and start of the segment lining and thanks to the tubes that are fitted to the grouting holes in order to fill the annular gap. This method permits continuously filling the annular gap, providing immediate stabilization of the segmental Lining and avoids occurring of the settlement and ground displacement. However, there is the risk of tail tube clogging. To avoid this phenomena, cementitious mix such as mono-component grout without aggregates (sand and gravel) and two-component grout are employed (Figure 10) (Thewes et al., 2009; ITAtech, 2014)

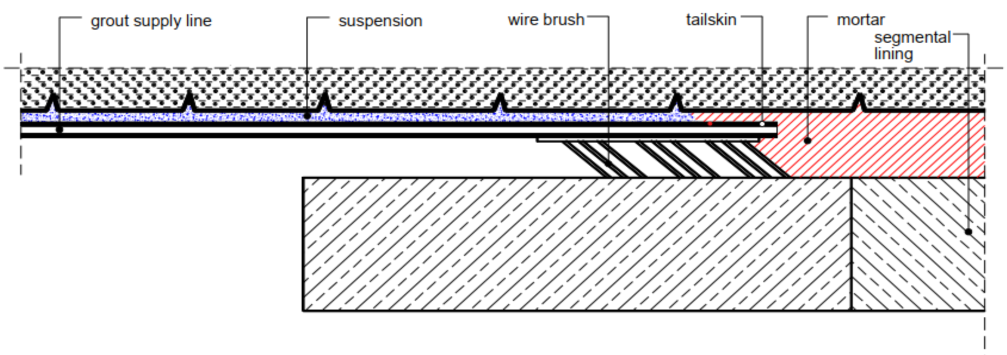


Figure 10 Grouting through the holes in tail skin (Thewes et al.2009)

2.1.2 backfill injection through segment lining ports

At a given distance from the machine's tail, backfill injection through ports in the segment lining takes place, which means that the gap may not be filled immediately after it forms and may remain unfilled for a longer period. As a result, there is much higher risk of settlement and ground displacement. The Backfilling material is injected through a predesigned hole in the segments which are easily created after their installation. The injection can be performed when the shield completely passes the Lining. A mechanism, such as non-return valves or plugs, should be included in the grout holes to keep the grouting material in the annular gap. This technique eliminates the possibility of clogging because of the large dimensions of the holes, allowing the injection of cementitious mixes that also include aggregates and pea gravel (Figure 11).

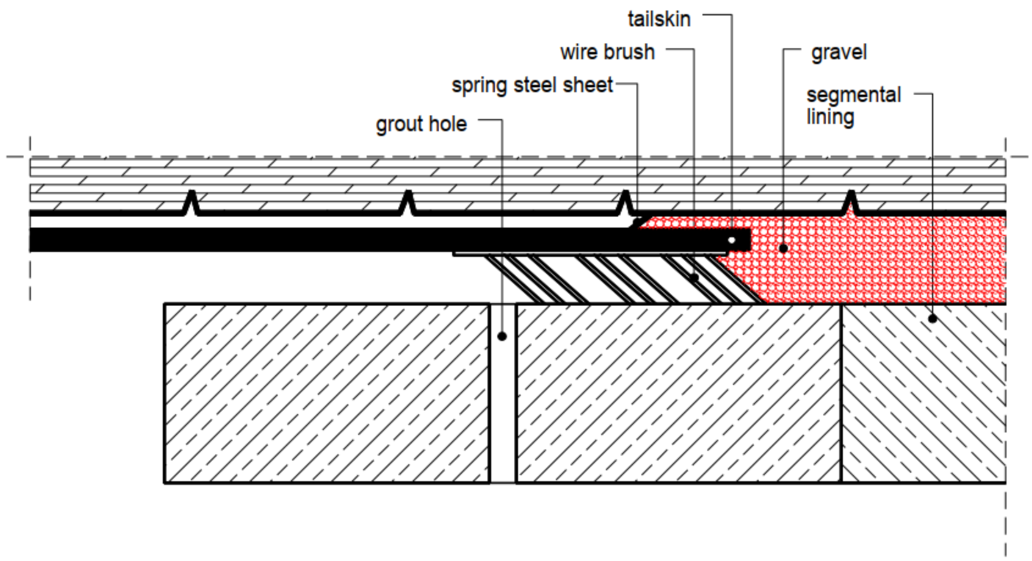


Figure 11 Grouting through the holes in segment lining (Thewes et al.2009)

2.2 Backfill Material

Different materials can be used in backfilling operations to achieve the requirements mentioned. Two classifications according to possible materials are reported (EFNARC, 2005). The first classification is based on the specific ability of the grout to perform the hydration process. This classification is based on the amount of cement in the material, considering the cement as the most used binder element. It consists of the following:

- Active grout: the injected material contains a binder that performs a Complete hydration process and grout contain over 200 kg/m^3 cement.
- Inert grout: there is no cement inside the injected material (pea-gravel).

- Semi-inert grout: the injected material is the same as the inert grout plus a small amount of material able to generate a certain degree of hydration. The cement fraction is between 50 to 100 kg/m^3.

The second classification is simpler and based on the number of components used to obtain the final grout. This classification consists of the following:

- Mono-component grout
- Two-component grout

Table 2 explains the main filed of application and pumping system required for various types of the backfilling grouting(Thewes et al., 2009; Peila, et al., 2011, modified).

Table 2 Field of application of different backfilling technologies (redrawn from Peila et al.2007)

Backfill Material		**Application range**		**Backfilling system**		**Required equipment**			
		Hard rock	**Soil**	**A**	**B**	**a**	**b**	**c**	**d**
Mono Component	**Active system**	×	×	×	×	×			
	Semi-active system	×	×		×	×			
Inert system			×		×	×			
Pea-gravel		×		×					×
Two-component grout		(×)	×	×	×		(×)	×	

×: applicable, (×): limited applicability

A-backfilling through the ports of segment lining

B-Backfilling through the ports of tail skin

a: piston pump, b: peristaltic pump, c: progressive cavity pump, d: pressurized air

2.2.1 Inert mix

In order to reduce the chance of the injection system being clogged, this type of mix is characterized by the absence of any binders, such as cement. They are composed of fly ash that is carried in the water, filler, and sand. The sand needs to be sorted and chosen properly. Due to the significant danger of clogging if the injection happened from the ports of the tail skin, the heterogeneities of the mix are reduced first, and then the mix is injected from the hole in the segment lining (Peila et al., 2011).

2.2.1.1 Pea-gravel

Pea-gravel as a backfilling is used to immediately stabilize a rock mass during the excavation with single or double shielded TBMs. It has a diameter between 8 and 12 mm and is obtained by washing and screening alluvial pebbles and crushed rocks. To inject the pea-gravel, pressurized air is used, and powerful compressors are required to guarantee the spreading of the material and the filling of the annular gap. To avoid any damage to wire brushes, the pea-gravel is injected from ports in the segment lining at an appropriate distance from the machine's tail to prevent any contact with seal brushes. During the application of the pea-gravel, the void is not filled, but it is filled with a certain angle of repose, which is the angle that permits to compute the distance from the head where it could be possible to perform the injection of pea-gravel and living unfilled void at the top (Figure 12). Afterward, the unfilled void, which can last for a longer time, is usually filled with the second injection of mono-component grout through the ports in the segment lining. Pea-gravel works effectively as drainage in the presence of flow toward the tunnel (Thewes et al., 2009; Peila et al., 2011; ITAtech, 2014).

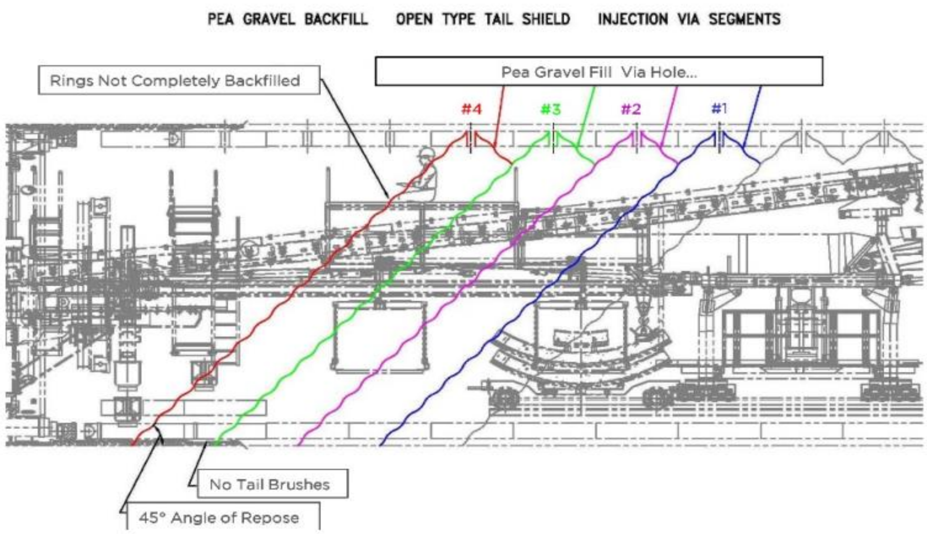


Figure 12 Angle of repose criterion which in this example is 45 degrees (ITAtech, 2014).

2.2.2 Mono-component grout

Mono-component grout is a cementitious mix that is made up of water, bentonite, cement, aggregate (sand and gravel), and retarding/fluidifying agents to improve its properties like water/binder ratio, initial and final setting time, mechanical strength, and pumpability. The mix should be fluid at least for some hours, to avoid clogging of the pipes during transportation, injection, and stops of the machine during the normal working phase.

The mix is typically batched outside the tunnel, driven to the machine in grout cars, and then injected through ports in the tail skin, to fill the void completely and effectively. By continuously filling the generated void, the segment lining is well embedded, and settlements are decreased. It is also feasible to inject through ports in the segment lining, particularly, if materials like sand and gravel are used to lessen the chance of clogging the tail-skin pipes. On the other hand, the segment lining injection does not deliver the same advantages as a tail shield injection. Mixtures of this type are characterized by a slow set time due to cement hydration, which delays the support of the Lining while the mix attains high mechanical strength, around 15-20 MPa after 28 days, which is not necessary for backfilling. Moreover, mono-component grout is not applicable when there is a high ground water flow due to the dilution of the grout before it could reach its hardening phase (EFNARC, 2005; Thewes et al., 2009; Peila et al., 2011; ITAtech, 2014).

Piston pumps are typically used to inject the mono-component grout, and the delivered amount of the grout can be regulated by the pace of the piston. Piston pumps can be single or double piston pumps. Double piston pumps are usually installed in TBMs due to their compact design (Figure 13)(Thewes et al., 2009).

Figure 13 Double piston pump for injection of mono-component grout (Thewes et al.2009)

2.2.3 Two-component grout

A two-component grout was used for the first time in Japan in 1982 for the construction of the Osaka subway, achieving a good result to control the settlement. Thus, two-component grout is widely used around the world (Hashimoto et al., 2006).

In a two-component grout, component A is composed of water, bentonite, cement, eventually with adding fly ash, and retarding agents, while component B consists of an accelerator (usually silicate solution) that is run separately from the batching plant and mixed with high turbulence just before injecting. This mixture is hardened in a very short time (5-15 seconds) and develops mechanical strength, providing a rapid and homogenous stabilization of the annular gap (Hashimoto et al., 2006).

After mixing component A and B, the mixture assumes a plastic state in a few seconds and keeps this condition up to 30 minutes before getting hard. Figure 14 and Figure 15 show the behavior of two- component grout over the time after injection and injection equipment respectively. It should be considered that gel time, harden time and set time can be changed by acting on the mix design and additives.

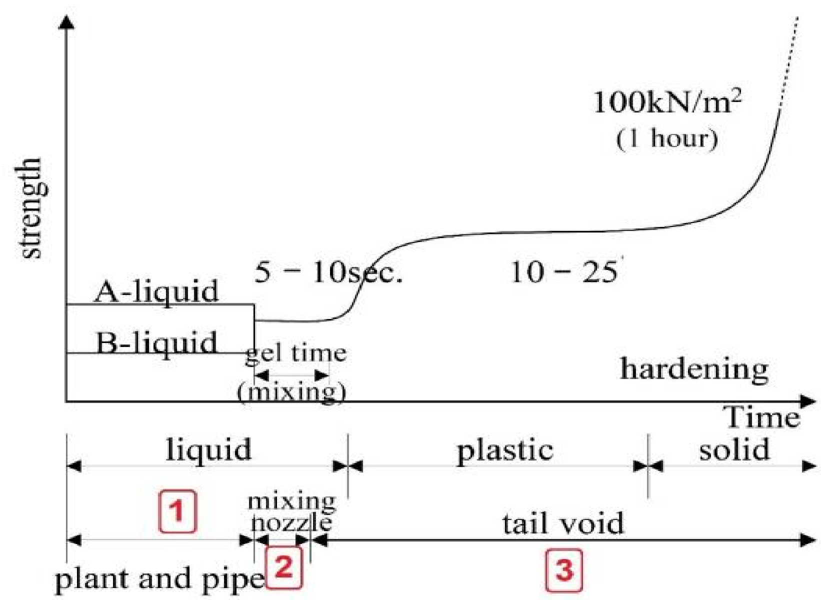


Figure 14 Two-component grout behavior over the time after injection (Hashimoto et al.2006)

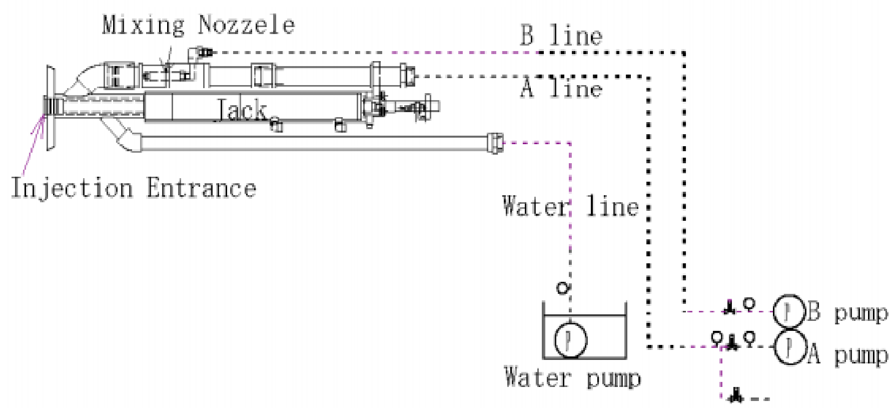


Figure 15 Injection equipment for simultaneous grouting (Hashimoto et al.2006).

2.2.3.1 Creation of an Incompressible annular bubble

Given that two-component grout contains a significant volume of water (about 800 l/m^3) and has a thixotropic consistency because of the addition of an accelerator agent before injection, it is an uncompressible fluid. As a result, the annular bubble that is created is continuously filled with the uncompressible fluid mixture while the shield advances.

Thus, every movement of the surrounding ground that tends to enter the bubble or every movement of the concrete lining that tends to reduce the bubble volume immediately causes the creation of a new reaction-pressure which is uniform along the volume and above all the surfaces of the volume, preventing any kind of deformation. Therefore, this gel should confine homogenously and completely in the location where the ring is installed. To achieve the above-mentioned behavior, the following condition must be respected:

- The injected material should remain incompressible.

- The fluid cannot escape from the bubble (neither permeation through the surrounding ground and outer surface of the tail shield, nor leakage through the gaskets).
- The segment ring should be installed correctly, avoiding any deformation (without having oval-shape deformation) due to its own weight.
- The injected grout should not be diluted by groundwater.
- The convergence of the surrounding ground toward the bubble should be avoided, since it increases the pressure needed for the advancement of the machine. This should be balanced by controlling the equilibrium between injection pressure and pressure inside the excavation chamber.

2.2.3.2 Durability and test on two components

When a superfluid two-component mix is used, the short-term mechanical strength is more important than the long-term mechanical strength, since its objective is to reduce the pressures and loads, to lock the segment ring in its location, and to avoid the settlement due to the advancement of the TBM. The concrete lining has a general role in bearing the hydrostatic and geostatic loads and pressures. Due to that, two-component grout should not be affected by degradation, to provide the above-mentioned properties.

The durability of the gel fills the annular bubble under normal conditions of humidity, where no water loss occurs by evaporation or filtration, and keeps the filler without deformation. To describe the favorable condition of this situation, the permeability of the ground should be less than 10^{-8} m/s, to assure no loss of the water through the ground.

Due to the importance of creating the gelled grout within seconds, measuring the mechanical strength of the grout usually after 0.5, 8, and 24 hours is necessary. It is possible to measure the strength with a pocket penetrometer. However, extracting core samples through the Lining (while the grout reaches its maximum strength to allow sampling) is the most reliable way to measure the strength and check the filling of the annular gap.

2.2.3.3 Elements of two components

Commonly, cement of Portland type I with high mechanical strength, usually between 42.5-52.5 R is used.

- **Water** is provided by a local aquifer, while its physical and chemical properties must be controlled due to the effect that it has on the degradation of two-component.
- **Bentonite** provides physical stability to component A, by reducing the bleeding and permeability of component A. Furthermore, reducing the bleeding can lead to obtain a thixotropic consistency when the flow stops. However, bentonite can reduce the mechanical strength of a component if it is used in excessive amounts.
- **Retarding agents** provide chemical stability/long workability up to 72 hours after batching for the component A. it has a purpose to delay the setting time of the component A. it is useful during the normal stops of the machine or unforeseen working delays with the possibility to stockpile and use it later.
- **Component B**, which is often a silicate solution and acts as an accelerator, causes component A to gel in a matter of seconds (between 5 to 15 seconds). The gel needs to

be uniform, have a thixotropic consistency, and start developing mechanical strength immediately (Peila et al., 2011).

2.2.3.4 Batching the grout plant

Depending on the scope of the operation, each type of equipment will have a different type, size. However, in general, the mixing facility and storage tanks should have enough capacity to grout at least a full ring without halting (EFNARC, 2005).

Component A is frequently batched using a low-shear paddle mixer or a high-shear colloidal mixer; the latter is generally acknowledged as the most effective way to mix cement-based grouts, due to less bleeding and greater strength. Colloidal mixers have been used in civil construction and are widely recognized as the most efficient method of mixing cement-based grouts. The discar in the colloidal mill rotates at over 2100 rpm. At this point, strong turbulence and significant shearing action are produced, which can break down clusters of dry cement particles. The intense vortex action inside the tank rapidly assimilates the mixed ingredients (water, cement, bentonite, retarding agent). As a result, the grout exhibits colloidal properties such as minimal settling or bleeding (Reschke et al., 2011).

Water must be added either through flow meters or weighing batches. In either scenario, the accuracy of addition must be ± 1.0% of the mix design's stipulated quantity. The water circulates inside the mixer and is left to clean it thoroughly. The retarding agent is then measured and weighed using a flow meter and a diaphragm pump. The accuracy of addition shall be ±5% of the specified, designed weight. Bentonite and cement screw conveyors are controlled by frequency drives to feed in the required amounts of material at rapid and slow feed rates (accuracy ± 2% of their intended weights)(Figure 16) (EFNARC, 2005; Reschke et al., 2011).

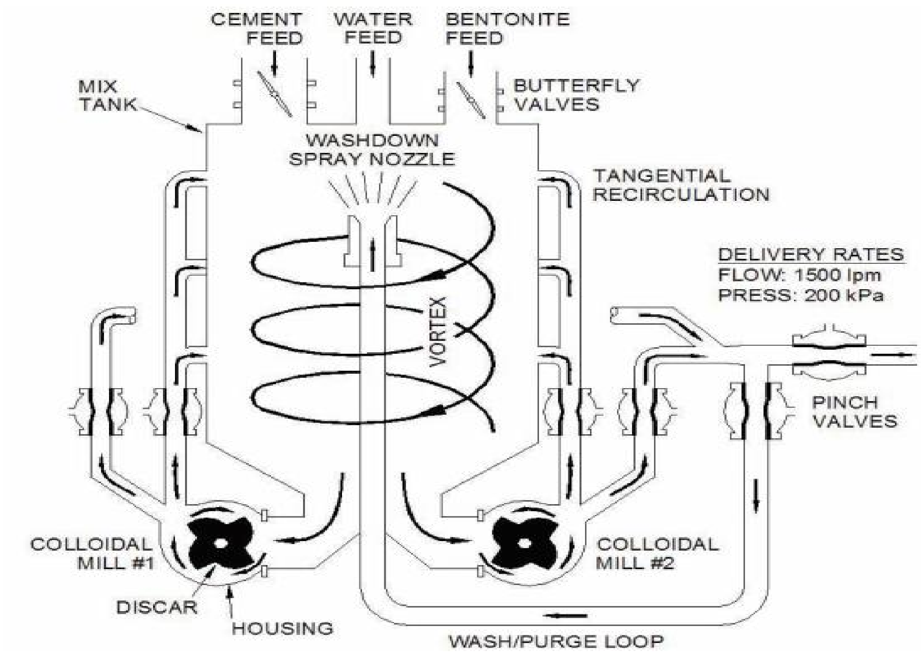


Figure 16 High shear Colloidal mixer that used in brisbane airport link project,Australia (Reschke et al.2011)

Mixing the component must be as short as possible with the complete mixing of the ingredients. First, the bentonite is added and mixed for the desired amount of time (30 seconds). Then, the cement and retarding agent are added, respectively. Mixing is continuous for a certain amount of time, and after that, the batching grout is transferred to the agitation tank. Then, batched components are transferred by a pump to the holding tank through a pipe on the TBM. On the other hand, a similar pump transfers component B to another holding tank via a pumping system on a TBM. Pumping pressure must be continuously monitored on both pipes, especially on component A, to avoid choking the material due to the segregation of the cement (EFNARC, 2005; Reschke et al., 2011).

2.2.3.5 Pumping equipment

To transport the liquid of the two components, two types of pumps are employed: peristaltic pump and progressive cavity pump. The main element of a peristaltic pump is a flexible tube installed inside the circular pump casing. The pump moves the material inside the tube by creating a vacuum, simultaneously pushing forward the material by rotating the rollers on the flexible tube. A progressive cavity pump contains a horizontal spiral within a tube to transport the material due to the friction at the spiral blade (Figure 17 ,Figure 18) (Thewes et al., 2009).

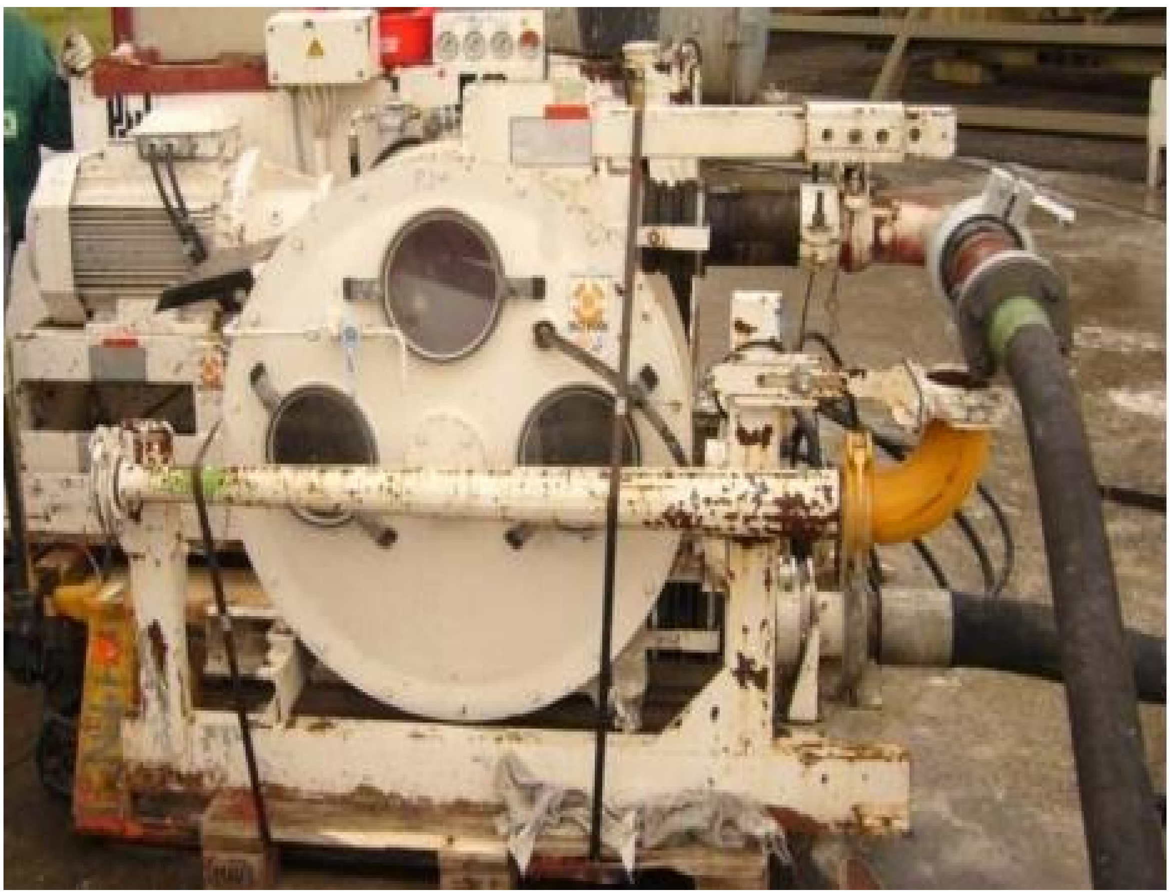


Figure 17 Peristaltic pump for injection of two-component (Thewes et al.2009)

Figure 18   Progressive cavity pump for two-component grout (Thewes et al.2009)

2.2.3.6 Injection method of two-component

Component A is transported from the batching plant through a pipe system and injected under pressure throughout the annular gap via pipes fixed inside a tail shield. Then, at a certain distance from the injection port, component B, which is also usually transported via a piping system, is introduced and mixed along this length due to the turbulence phenomena before being discharged out of the injection port.

However, the two-component grout system needs a level of sophistication, which means both component A and component B must be sufficient to fill the annular gap. After injection of the grout, the TBM moves forward and leaves the void that is instantly filled with grout. In order to reduce the chance of the choking of the grout in the system, a proper mix design, selection of suitable equipment, and cleaning and maintenance regime must be determined. Furthermore, to remove a possible gelled grout in a piping system and avoid choking, high-pressure water is introduced to the system(Figure 19)(Hashimoto et al., 2006; Peila et al., 2011; Reschke et al., 2011; (ITAtech, 2014).

Considering the injection ports, each grout port must have an independent pump to control the injection volume, pressure and, to prevent clogging, they are usually evenly distributed on the tail shield perimeter (also spare ports), and their number depends on the type of grout, the forward speed, the machine cutter-head diameter, the type of ground to excavate, and the dimension of the grouting ports (Figure 20).

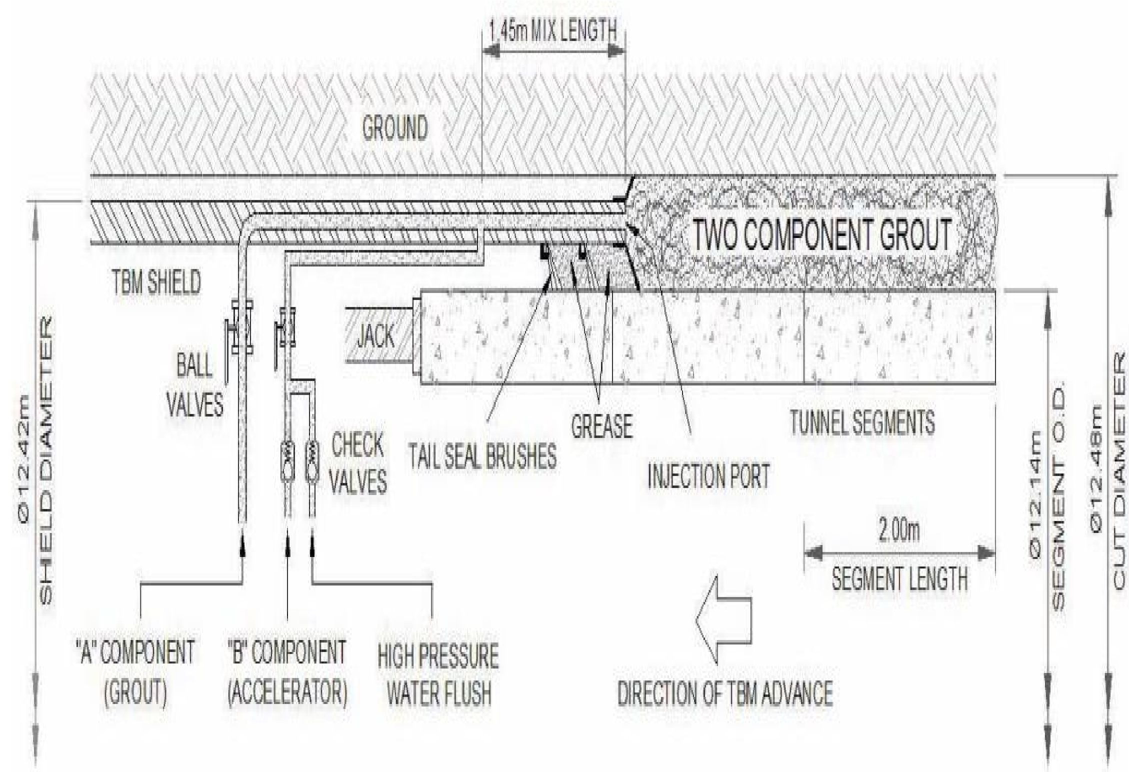


Figure 19 Two-component annular grout through the tail skin. a Herrenknecht machine that used in Brisbane airport link, Australia (Reschke et.al 2011)

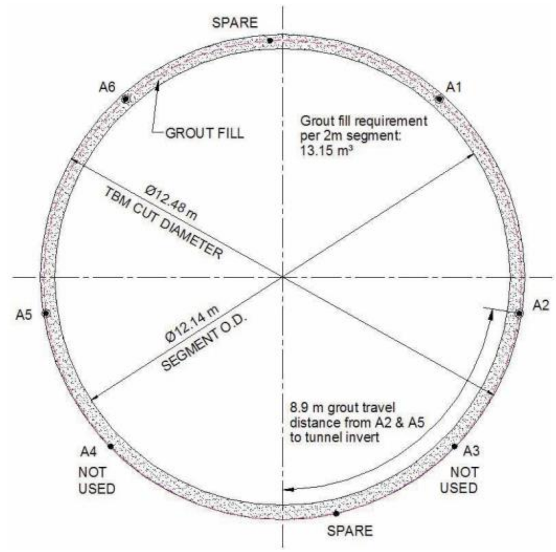


Figure 20 Details of grouting through the ports embedded in tail shield. Herrenknecht machine that used in Brisbane airport link, Australia (Reschke et al.2009)

2.3 Comparison between Mono-component and Two-component grout

Table 3 shows the comparison between mono-component and two-component grouts.

Table 3 Comparison between Mono-component and Two-component grout (ITAtech 2014)

Grout Types Advantages Chart		
Consideration	**Mono-Component**	**Two-Component**
Strength	×	
Cost	×	
Transportation		×
Ground water		×
Early Set-time		×
Early Support		×
Fluidity		×
Batching		×
Maintenance		×

2.3.1 Strength

Due to the presence of aggregates, mono-component grout can be designed with high mechanical strength because of the mixture properties, allowing it to harden and be more homogenous. The desired strength can be achieved by modifying the component for the mix. On the other hand, a two-component mixture does not show strength like mono-component grout due to a lack of aggregate. However, the final strength is not a prominent characteristic, since it is usually required that the grout provide sufficient strength to bear the load from the surrounding ground, TBM, and to support the segment lining.

2.3.2 Cost

Mono-component grout has a lower initial cost than two-component grout, even though, when the volume of grout mix and the amount of mix thrown out are taken into consideration, it might cost more than two-component grout. Furthermore, grouting through the segment lining does not increase the bore diameter, while grouting through the tail skin increases the bore diameter, thus increasing the amount of grout that is needed. On the other hand, it should be considered that injection through the segment increases the risk of settlement because grouting cannot be started until the grout hole in the segment has cleared the tail shield, leaving the void exposed.

2.3.3 Transportation

The method of transportation of the mixture has a great role in construction and timing consideration. Two-component grout is commonly pumped from the batch plant, while mono-component is usually brought into the tunnel via grout cars.

2.3.4 Groundwater effect

In the tunnels excavated below the water table, the water can interact with the grout in various ways. However, the dilution of the grout can happen only with the mono-component grout; two-component grout has in fact a low permeability, due to the bentonite which has the effect of waterproofing. To increase the impermeability of the mono component, it is possible to add anti-washout agents as an extra step.

2.3.5 Early support of Lining

Compared to setting time, due to the hydration of the cement in a mono-component, it has a longer setting time than two-component grout. Thus, settlement and ground convergence are reduced. In addition, two-component grout can guarantee the lock of the segment lining in its place, preventing displacement and movement between joins of the segment lining. Furthermore, supporting the forces applied from the ground, from the machine's thrust, and from moving the trailing gear (back-up) over the newly set rings is essential. This configuration can assist in lowering maintenance expenses and repair work during the tunnel drive.

2.3.6 Fluidity/Pumpability

Grout injection and transportation around the segments depend heavily on the fluidity and pumpability of the grout. Because it is pasty, mono-component grout is more difficult to pump and transport. On the other hand, the two-component is highly fluid, pumpable, and thus it’s simpler to transport.

2.3.7 Batching

The batching procedure can have an impact on the logistical and physical characteristics of the grout. Automated grout plants can easily mix both types of grouts with small equipment.

2.3.8 Maintenance

In a two-component grout, components remain fluid and pumpable until they are mixed at the nozzle, whereas Mono-component can remain fluid for a shorter period, and there is a possibility of clogging and choking them in the injection pipe, which an require to change the lines in the machine.

3 Issue of sustainable reuse of the muck

In recent years, muck reuse has become an increasingly prominent issue. Some projects for route extension around Europe to establish a better connection for the transportation of people and goods within European countries are under construction. Due to the presence of the mountain range, Italy has always been one of the countries with a high concentration of tunnels through it. Due to the high number of tunnels, railways, and underground metropolitan tunnels under-construction, a high amount of muck is going to be produced. At the same time, there will be a great demand for the aggregates for the required Lining. Thus, aggregates produced during the construction of different infrastructures can be reused as raw materials for other construction projects instead of being disposed as a waste.

Recently, the muck has been reused in several different tunnel infrastructure projects. The muck from the excavation can be used again for various projects, including as a source for some raw materials for industrial purposes, asphalt mixing, or backfilling material.

One of the most outstanding examples of reusing the muck for onsite production of construction aggregate are the Lötschberg (34.6 km long) and Gotthard (57 km long) tunnels that are part of the Alptransit project.

The construction of these two tunnels produces a great amount of excavated material: 13.3 Mm^3 in total from the Gotthard base tunnel. There were three primary goals for Alptransit: reuse most of the excavated material, economically manage the material, and minimize the environmental impact (Olbrecht & Studer, 1998). As a result, good-quality muck was used to produce aggregates for the concrete. In contrast, the excavated material with a lower quality was used as a filling material, environmental restoration, and railways embankments(Sakatadi, 2022). Around 46% of the muck recycled in this tunnel was used as concrete and embankment aggregates. The other 54% of the remaining materials were used for environmental restoration projects and landfills (Bellopede, 2011).

In several past tunnel projects related to muck reuse, it has been observed that a small amount of muck, compared to the total amount of muck produced, can be reused as an aggregate in structural construction instead of other types of construction or waste (Voit & Zimmermann, 2015). For example, a primary evaluation done on the Brenner base tunnel for sustainable reuse of the muck predicted that approximately 15% of the muck was suitable for use as a land filling material, and about 6% of that was ideal for concrete aggregates. The remaining material was primarily evaluated as a waste, depending on different factors (environment, economic) involved in the project. Though, depending on the characterization of the muck, with its further processing, an optimal enhancement can be obtained for several construction applications. In addition,(Riviera et al., 2014) investigated reusing the tunnel muck excavated from different excavation sites and using different methods as aggregates for road construction. Furthermore, they emphasized the need to increase muck recycling in various applications.

The muck obtained from TBM can be classified based on different parameters to understand all possible reuse applications. Also, a methodology can be proposed based on different scenarios that may happen during the tunnel's planning (Oggeri, 2010).

For optimal recycling of muck, rock characterization should be investigated first and then followed by effective processing with an efficient facility. The final objective in every tunneling project is to recycle as much muck as possible, and this depends on a variety of factors (geological, environmental, economic, etc.), which are influenced by the rock quality, the processing facilities near the construction site for processing the muck, and the availability of free space around the site.

A good hard rock muck generally needs a minimum amount of treatment, such as washing, drying, and modifications can be made to meet the reuse requirements. In most cases, regardless of the intended reuse of the muck, these modifications refer to physical properties such as grain size, shape, mineralogy, and bulk density, while the mechanical properties mainly refer to the ability of the material to withstand any degradation that can compromise its strength (Gertsch et al., 2000).

The size and grading must be categorized, and fine grains are characterized; according to the standards UNI EN 932-2 and UNI EN 933-1:2012 PART 1 for preparation of the laboratory samples and determination of particle size distribution, respectively.

3.1 Characterization of the muck from Tunnel Boring Machine

The muck studied in this thesis came from the Maddalena exploratory tunnel, related to the Mont Cenis base excavation tunnel located in Susa valley [Piemonte, Italy] (Figure 21). Geological investigation and literature review revealed that the rock mass is a massive metamorphic rock with good quality.

Figure 21 Geographical location of Maddalena exploratory tunnel, Chiomonte, ITALY (google maps)

3.1.1 Mineralogical and petrographic Characterization

Based on the level of precision needed for petrographic analysis, a microscope can be used to determine the mineralogical composition and rock type. Furthermore, the level of precision also depends on the geological data, for instance, the geological information about the presented rock sample(Figure 22)(Sakatadi, 2022).

As a preliminary approach, the mineral types can be determined using the geological data and the visual examination of the rock sample. The stereoscopic microscope and other proper equipment can be used to do so. The mineral can be identified based on the morphology (cleavage, color, etc.) and other optical characteristics of the crystals. Then, the sample is named according to the percentage of minerals constituent and their texture.

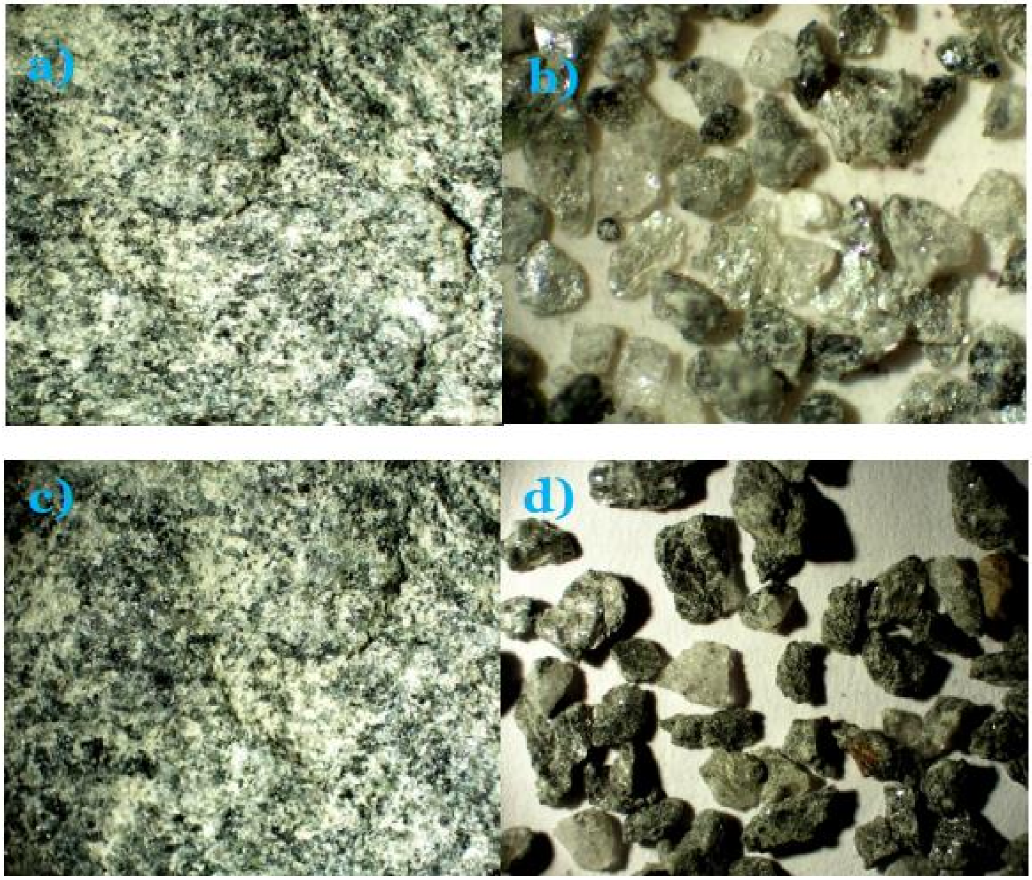


Figure 22 Microscopic view: a) grain particle size of 12 mm; b) grain particle size of 8 mm; c) grain particle size of 1 mm; d) grain particle size of 0.5 mm

As a result of various observations, through microscope, focusing on the texture, color, cleavage, etc., the rock type was found to be mica schist having quartz, chloride, and muscovite as dominating minerals. Petrographic information and geological data must be collected to evaluate the minerals before the XRD analysis effectively.

3.1.2 XRD analysis

To perform the quantitative analysis, the X-ray diffractometer with an advanced detector from Rigaku SmartLab SE, which is a multipurpose powder diffraction analytical machine that can determine the crystalline phase identification (phase ID) and quantification, percentage of crystallinity, strain, size of crystallite, lattice parameter refinement, Rietveld refinement, and molecular structure was used(Figure 23).

The sample used for the test was obtained from the sieving method. The fraction of the samples retained on the sieve of 125-250 microns,125-63 microns, and Lower than 63 microns were selected. The samples were then ground into a finer powder to prepare for testing. They were then put into a slide holder plate and appropriately compressed.

Figure 23 XRD Rigaku smart lab SE, DIATI (Politecnico di Torino) [Sakatadi,2022]

3.1.2.1 Result

According to the results of the mineralogical composition obtained from 3 different samples with the XRD test, all of them are composed of silicate minerals (muscovite, quartz, silicate) while the amount of muscovite and quartz are at least 75%. Considering the rock type, the result obtained from XRD was matched with the preliminary petrographic evaluation, and the sample was identified as mica-schist. The spectral results and mineral proportion of each sample are presented in (Figure 24,Figure 25,Figure 26,Figure 27,Figure 28,and Figure 29) (Sakatadi, 2022).

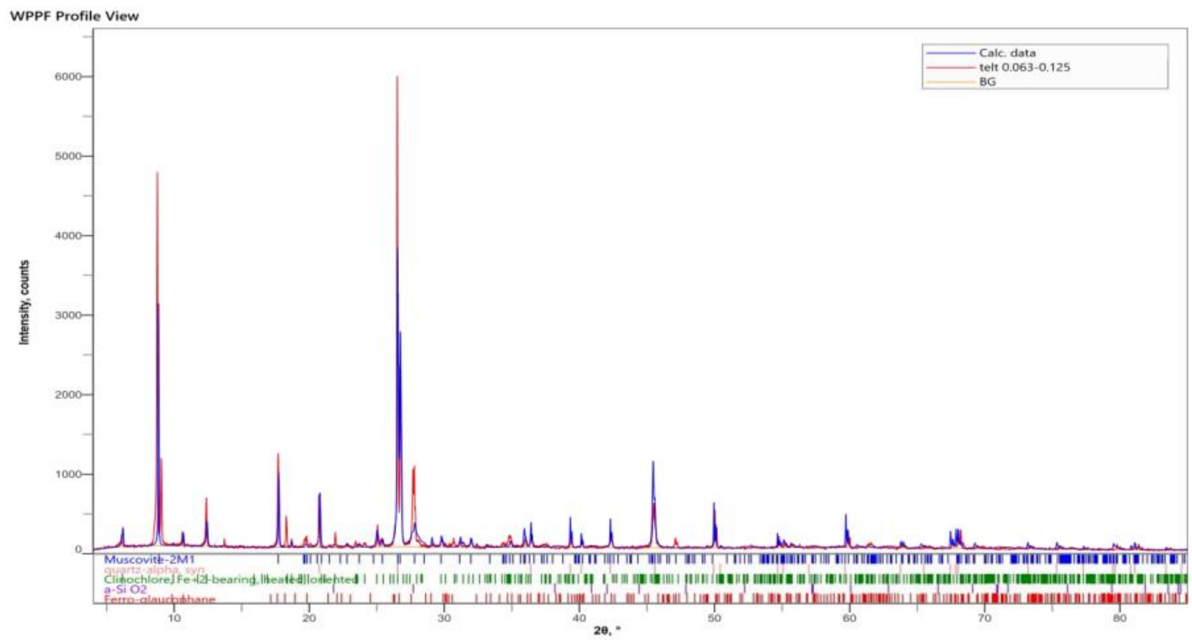


Figure 24 Sample 1 spectral result test

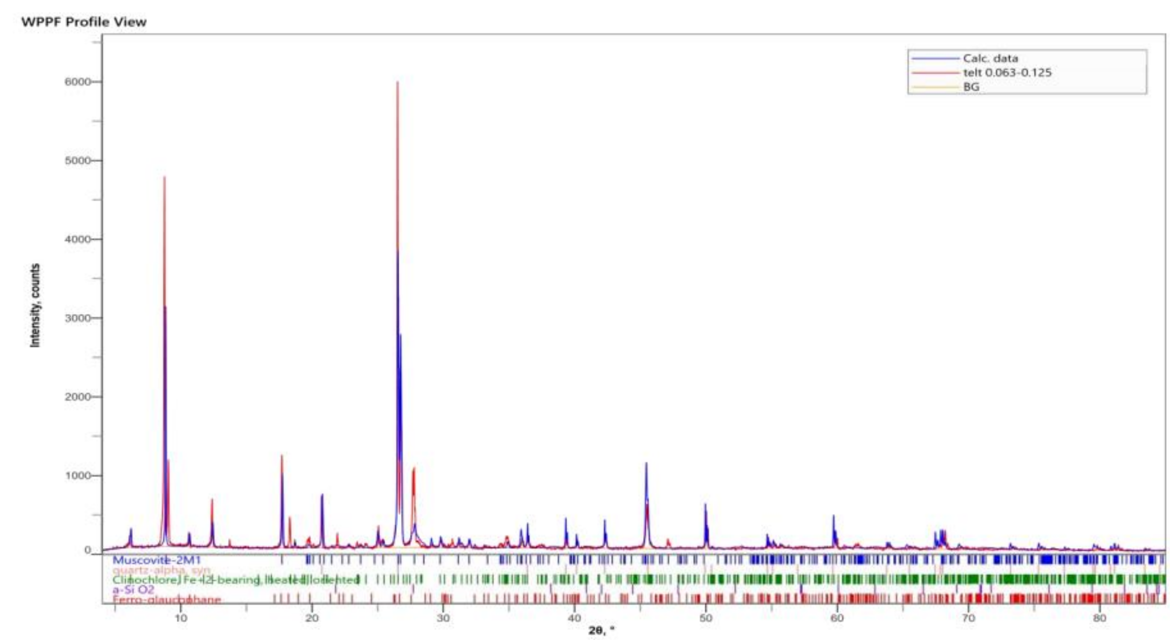


Figure 25 Sample 2 spectral test result

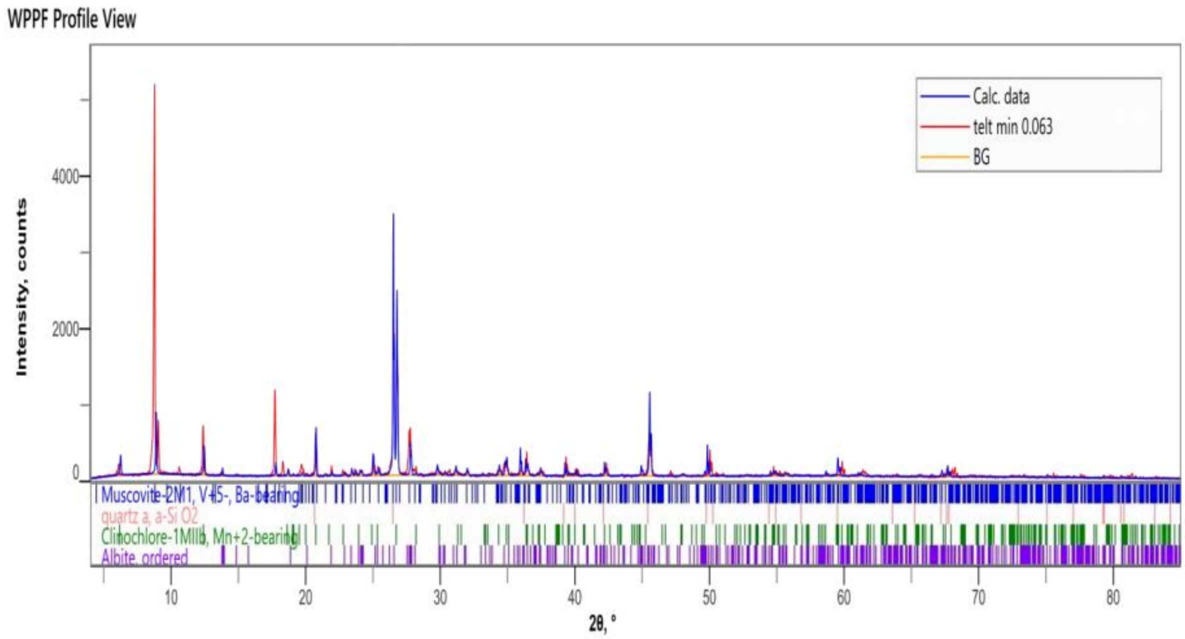


Figure 26 Sample 3 spectral test result

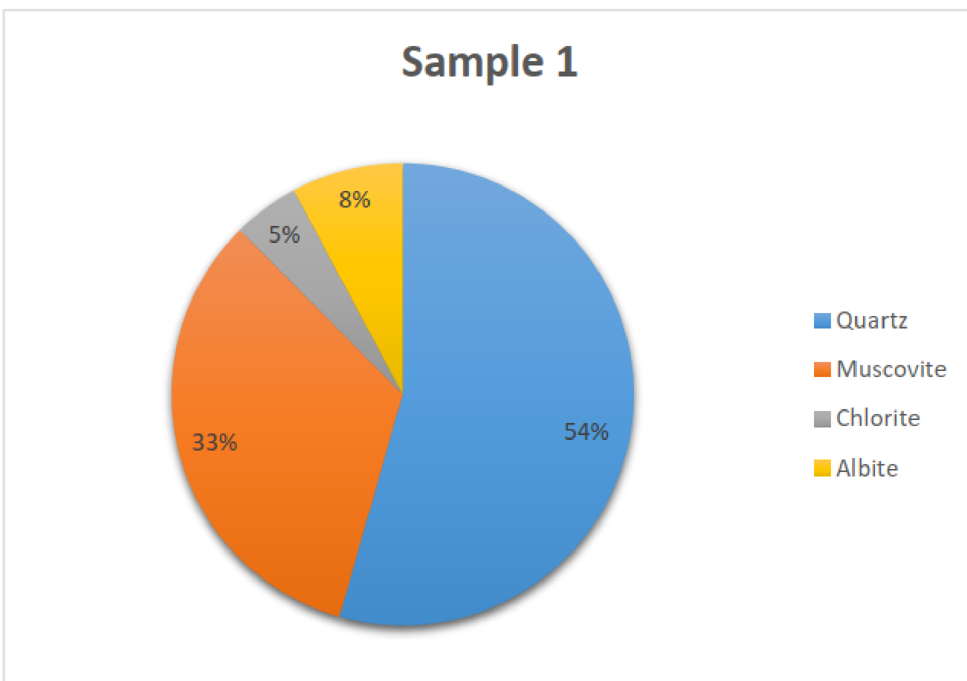


Figure 27 Percentage of Mineralogical composition for sample 1

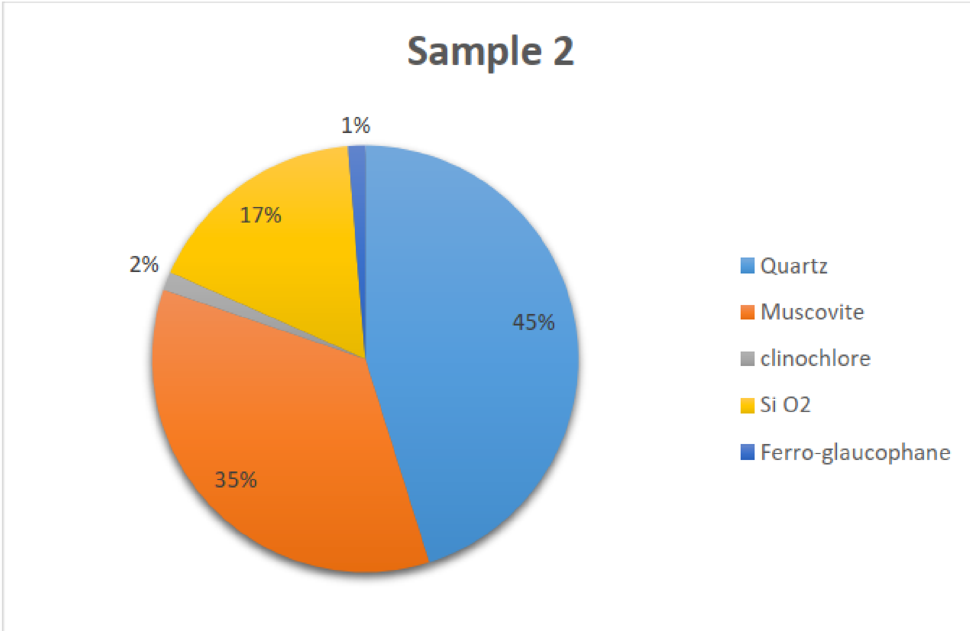


Figure 28 Percentage of Mineralogical composition for sample 2

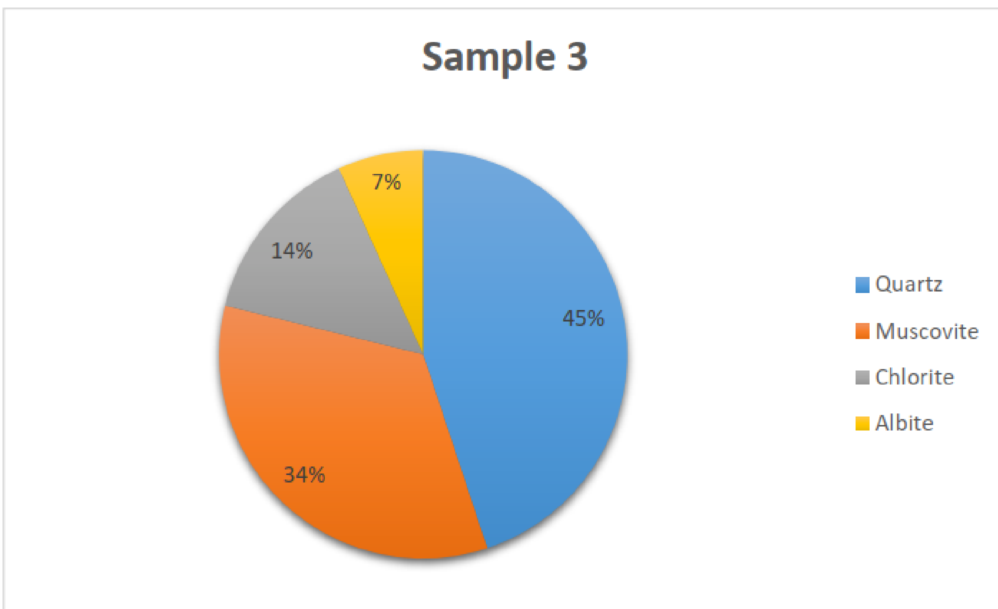


Figure 29 Percentage of Mineralogical composition for sample 3

3.2 Geometrical properties of the muck

3.2.1 Grain size distribution of the muck-sieving method

Assessing the muck is one of the primary criteria for determining whether it is suitable for reuse or not. The particle size distribution was performed under UNI EN 933-1:2012 Standard Part 1. Each sample used in this test should be dried in the oven for some hours to make them fit for the test, which follows the EN 932-2 Standard. In this test, the dried muck is separated into several particle size classes in decreasing order thanks of a set of sieves. The number of sieves and their openings have been chosen based on how the muck will be used and its type (Figure 30).

Figure 30 Sieve shaker used to perform the test

Tests were performed on two samples of material taken from the tunnel excavation process, weighing around 500 g each. The sieves are arranged based on their opening in descending order; the column of sieves was located on the sieve shaker machine for about 10 minutes for each sample. This test was performed for two samples, and the weight of each sample fraction that remained on each sieve was shown as a cumulative percentage. Furthermore, the characterization of the gran-size particle can be represented by uniformity and curvature coefficients. The uniformity coefficient is defined as a ratio of sieve size in which 60% of the grain particles by weight pass through the sieve over 10% of the grain particles by weight (Equation 1):

Equation 1 $$Cu = \frac{D_{60}}{D_{10}}$$

In addition, the coefficient of curvature is obtained according to the Equation 2:

Equation 2 $$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}}$$

- *D60* is the dimension corresponding to 60% of the passing aggregate in the particle size distribution curve.
- *D30* is the dimension corresponding to 30% of the passing aggregate in the particle size distribution curve.
- *D10* is the dimension corresponding to 10% of the passing aggregate in the particle size distribution curve.

3.2.1.1 Results

The results given in Table 4 can be used to produce the grain size distribution curves.

Table 4 Sieving results to determining the passing percentage of particle size

Sieve Diameter	Sample 1			Sample 2		
	Weight	fraction	cum. Passing	Weight	Fraction	Cum. Passing
4	5.9	1.19	100.00	4.4	0.86	100.00
2	96.7	19.47	98.81	91.4	17.94	99.14
1	72.7	14.64	79.34	74.1	14.55	81.19
0.5	52.2	10.51	64.71	53	10.40	66.65
0.25	42.3	8.52	54.20	44	8.64	56.24
0.125	44.3	8.92	45.68	46.1	9.05	47.61
0.075	37.1	7.47	36.76	37.3	7.32	38.56
0.063	16	3.22	29.29	17.9	3.51	31.23
<0.063	129.5	26.07	26.07	141.2	27.72	27.72
Total	496.7	100.00		509.4	100.00	

The cumulative retained percentage is shown in Figure 31. This information can be used as a primary classification and characterization of geometrical parameters.

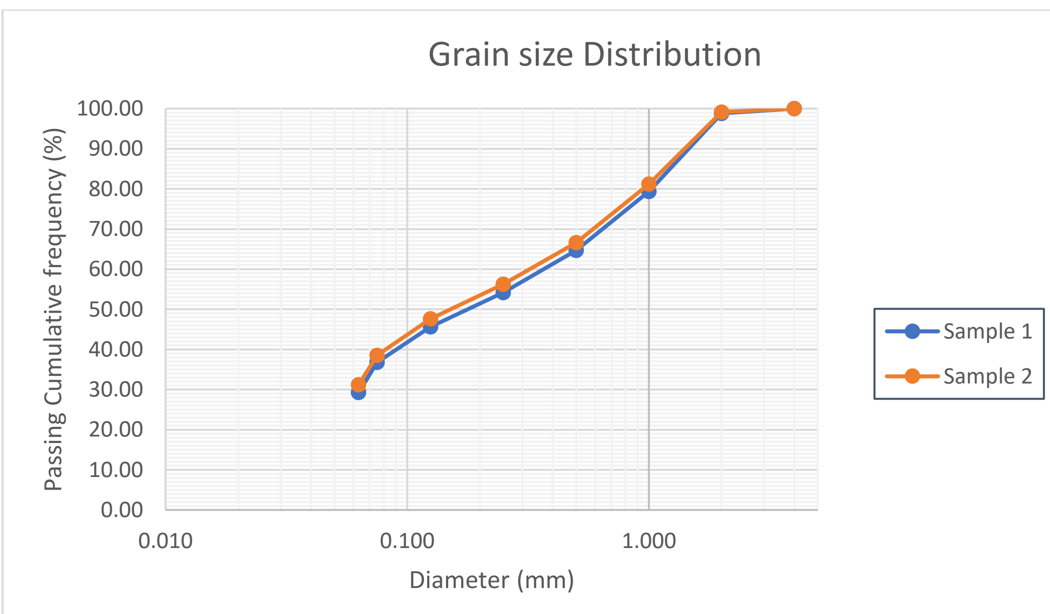


Figure 31 Grain size distribution curve obtained from the test

Furthermore, in this test campaign, another grain size distribution curve was used which was related to the experimental work previously conducted in the DIATI Laboratories (Figure 32) (Sakatadi, 2022).

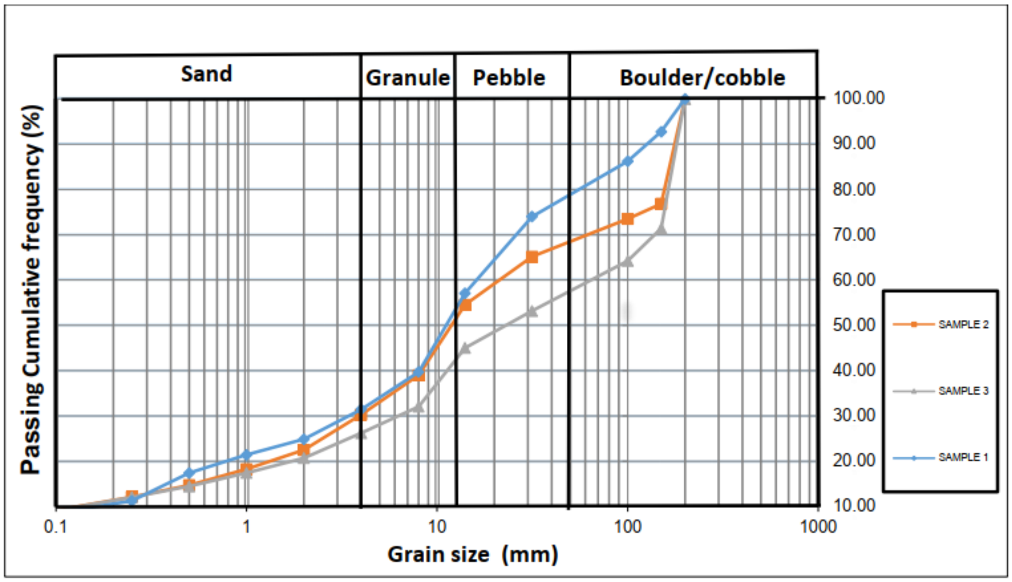


Figure 32 Grain size distribution obtained from a previous experimental campaign (Sakatadi, 2022)

3.3 Calculation of specific gravity

Specific gravity is used to determine the density of the solid grains. The test was conducted in compliance with the standard ASTM D854-14. The specific gravity of the solid soil, Gs, is the ratio of the mass of the unit volume of the soil to the mass of the same volume of distilled water at 20°C.

The test is performed with a pycnometer with a minimum capacity of 250 ml (pycnometers should have a volume of at least two to three times larger than soil volume). Initially, the weight of an empty pycnometer is measured. Then, water is added to the mark point on the pycnometer, measuring the total mass of the pycnometer and water at calibration temperature (24.3°C); the total volume of the pycnometer was obtained by using the Equation 3:

Equation 3 $V_p = \frac{M_{pw,c} - M_p}{\rho_{w,c}}$

where:

$\mathrm{M_{pw,c}}$ **-** the mass of the pycnometer and water at the calibration temperature (g)

$\mathrm{M_p}$- the average mass of the dry pycnometer at calibration (g)

$\rho_{\mathrm{w,c}}$- the mass density of water at the calibration temperature (g/mL)

After that, considering the mass of each soil sample (oven-dried sample), first reduce the amount of the water inside the pycnometer. Then after adding this soil sample to the pycnometer, again fill it with water to the mark point on the pycnometer and measuring the total weight of the mixture (soil, water at a specific temperature, and pycnometer). The specific gravity of the sample at a specific temperature is obtained according to the Equation 4 and finally, considering the temperature coefficient (K), the specific gravity of the soil at 20°C is obtained (Equation 5):

Equation 4 $G_s = \frac{M_o}{M_{pw,t} - (M_{pws,t} - M_o)}$

Equation 5 $G_{s(20°c)} = G_s \times K$

Table 5 shows that the average specific gravity for the two samples was 2.79.

Table 5 Calculation of the Specific Gravity

Calibration		**SAMPLE 1**	**SAMPLE 2**
Mass of pycnometer	Mp (g)	672.4	674.5
Mass of pycnometer + water at c	$M_{pw,c}$ (g)	1888.8	1895.9
Temperature of calibration	T_c (°C)	24.3	24.3
The density of water at c temperature	$r_{w,c}$ (g/ml)	0.99723	0.99723
The volume of the pycnometer (calibrated)	Vp (ml3)	1219.78	1224.79
Mass of soil	M_0 (g)	497.6	510.9
Mass of pycnometer + water + soil at t	$M_{pws,t}$ (g)	2208.6	2223.6
Temperature of test	T_t (°C)	24.6	24.2
The density of water at t temperature	$r_{w,t}$ (g/ml)	0.99715	0.99725
k coefficient	k (-)	0.99894	0.99904
Mass of pycnometer + water at t	$M_{pw,t}$ (g)	1888.70	1895.92
Specific gravity at t	Gt (-)	2.800	2.788
Specific gravity at 20 °C	G (-)	2.797	2.786
AVERAGE	2.79		

4 Test Campaign

The laboratory test campaign is based on an analysis of the properties of a two-component grout by adding the aggregates obtained from the muck of the TBM. The tests performed on component A include viscosity test, unit weight, and bleeding. On the other hand, the gel time was measured on the mixture of components A and B and finally on the hardened grout, surface compressive strength (SCS), and Uniaxial Compressive Strength (UCS) were performed.

All tests mentioned above are carried out on the construction site to assess regularly two-component grout properties. Therefore, these tests have a close operational nature. Component A was prepared according to the procedure proposed by (Todaro et al., 2019) for the laboratory scale. This procedure can replicate the batching plant grout at the construction site. Laboratory tests were carried out from late May 2022 until the end of July 2022. All tests were performed at room temperature and humidity though there were some fluctuations in these parameters. To prepare the component A, water was provided from the public water supply system, which had a temperature of around 24°C.

It was not possible to perform all the tests related to mix-design, such as viscosity, bleeding, unit weight, gel time, SCS (1 hour and 3 hours), and UCS on the same batched grout due to the limitation of production of the grout in laboratory scale (maximum 3 liters). Thus, tests referring to the same mix design were performed on different days with some temperature and humidity fluctuations.

4.1 Materials employed

- Cement

The cement employed is produced by grinding clinker (at least 95%) and gypsum, and it can be used in any field where high mechanical strength is required, as well as with a short curing time. It was Type l 52.5R produced by UNICEM BUZZI with a mechanical strength of 52.5 MPa and a unit weight of 3.1 g/cm^3. The cement follows the European Standard EN 197/1(Figure 33).

Figure 33 Cement type I

- Bentonite

The bentonite was of the type called CBS 4, produced by MAPEI, that is a sodic bentonite, which can be used to form cementitious suspensions with low permeability, high viscosity, and lubricating power for drilling fluids, ground injection, and backfilling injection with a unit weight of 2.7 g/cm3 (Figure 34).

Figure 34 Bentonite

- Water

The water was provided by the public water supply network of Torino.

- Retarding/fluidifying agent

The Mapequick CBS system 1 produced by MAPEI was used as retarding agent. Retarding agents lower the mixture viscosity, increase its stability, have a plasticizing effect, and can prevent the mix from setting, ensuring workability for up to 72 hours after batching. According to the MAPEI technical data sheet of CBS system 1, it has a density of 1.22 ± 0.03 g/cm^3 at 20 ° C and a pH value of 7 ± 2 as shown in Figure 35.

- Accelerating Agent

The Mapequick CBS system 3, produced by MAPEI, was used as an accelerating agent. It is an accelerating agent of cement-based mixes, suitable for fluid mixes with a high-water content.

According to the Mapequick CBS system 3 datasheet, this is a colorless liquid accelerating agent with turbidity lower than 30 N.T.U. at 20–25 °C, viscosity lower than 250 cps, and a density of 1.35 ± 0.03 g/cm3 at 20 °C(Figure 35).

Figure 35 Mapequick CBS system 3 accelerating agents (left); Mapequick CBS system 1 retarding agent(right)

- Aggregate

Aggregates were obtained from the muck of the TBM excavation. For the production of component A, the aggregates needed to be of a suitable size. Thus, the material was first sieved through a 5mm sieve, the aggregate smaller than 5mm was collected and sorted with a sieve shaker, and finally, the aggregates smaller than 0.5 mm were separated and used as shown in Figure 36 and Figure 37.

Figure 36 Excavated material from Maddalena exploratory tunnel (up); Sieving the aggregates with 5 mm sieve(down-left); aggregates with size less than 5 mm(down-right)

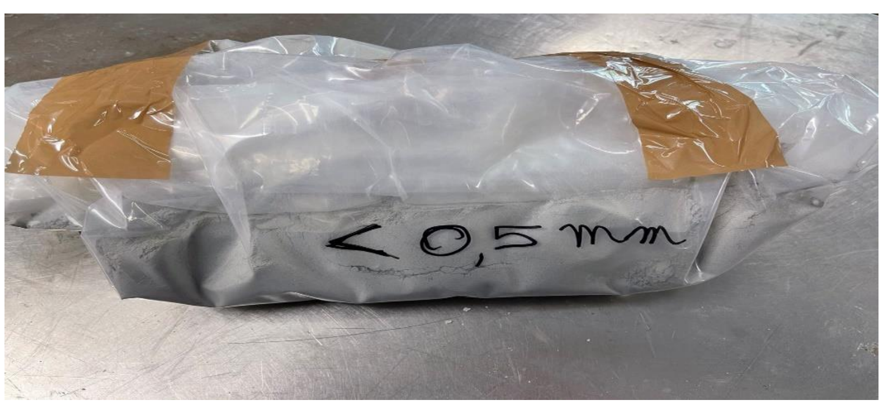


Figure 37 Aggregate with size less than 0.5 mm

4.2 Mix Design

The preparation of the two-component grout was based on the mix design suggested by (Todaro et al., 2019) since there was no fixed standard on the laboratory testing of mortar and hardened grout properties(Table 6).

The crucial factor in preparing the mix design is to realize each component's weight and unit weight, such as bentonite, cement, water, accelerating agent, and retarding agent, to prepare 1000 l (1 m^3) of the grout. To obtain the volume needed for each component, it is necessary to divide the weight of the component by the unit weight of that component. Finally, to acquire the volume of water needed, the volume of each other component should be added together and then subtracted from 1000 l. The volume of each component will then be divided by the total volume, which is 1000 l, to have the proportion of each element in the grout. Moreover, to acquire the requisite volume of grout on a laboratory scale, these fractions must be multiplied by the desired volume; hence it is essential to have the fraction of each component.

Table 6 Mix design proposed by (Todaro et al.2019)

Elements	Weight(kg)
Cement	230
Bentonite	30
Retarding Agent	3.5
Accelerating Agent	81
Water	853

4.2.1 Mix design prepared during the Laboratory test Campaign

To achieve the sustainability goal and reuse of the muck produced during the TBM excavation, some adjustments to the mix design were necessary, adding the aggregates acquired from the excavation, and consequently, following mix designs obtained during the test campaign.

A total number of 10 different mix designs were obtained. For the samples from 1 to 5, a specific amount of aggregate was selected from each container for collecting the total fine materials. It consisted of 50% of particle size fraction 0.212-0.425 mm, 25% to the fraction 0.063-0.212, and 25% from the fraction less than 0.063 mm (Table 7,Table 8,Table 9,Table 10, and Table 11). For sample number 6, the percentages have been selected to be more realistic to the reference grain size curve (Sakatadi, 2022)and are equal to: 21.4% for 0.212-0.425 mm, 52% for 0.063-0.212 mm, and 26.6% for less than 0.063 mm(Table 12).

Table 7 Sample M001

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	260	3.1	83.87	0.252	780
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	80	1.35	59.26	0.178	240
Total Fine material	80	2.79	28.67	0.086	240
Fine material a (0.212-0.425 mm)	40	2.79	0	0	0
Fine material b (0.063-0.212 mm)	20	2.79	0	0	0
Fine material c (< 0.063 mm)	20	2.79	0	0	0
Water	813.73	1	813.73	2.441	2441.18
Total volume without water			186.27		

Table 8 Sample M002

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	260	3.1	83.87	0.252	780
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	80	1.35	59.26	0.178	240
Total Fine material	120	2.79	43.01	0.129	360
Fine material a (0.212-0.425 mm)	60	2.79	0	0	0
Fine material b (0.063-0.212 mm)	30	2.79	0	0	0
Fine material c (< 0.063 mm)	30	2.79	0	0	0
Water	799.39	1	799.39	2.398	2398.17
Total volume without water			200.61		

Table 9 Sample M003

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	260	3.1	83.87	0.252	780
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	80	1.35	59.26	0.178	240
Total Fine material	100	2.7	35.84	0.108	300
Fine material a (0.212-0.425 mm)	50	2.7	0	0	0
Fine material b (0.063-0.212 mm)	25	2.7	0	0	0
Fine material c (< 0.063 mm)	25	2.7	0	0	0
Water	806.56	1	806.56	2.420	2419.68
Total volume without water			193.44		

Table 10 Sample M004

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	100	1.35	74.07	0.222	300
Total Fine material	100	2.79	35.84	0.108	300
Fine material a (0.212-0.425 mm)	50	2.79	0	0	0
Fine material b (0.063-0.212 mm)	25	2.79	0	0	0
Fine material c (< 0.063 mm)	25	2.79	0	0	0
Water	801.4	1	801.4	2.404	2404.26
Total volume without water			198.58		

Table 11 Sample M005

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material	100	2.79	35.84	0.108	300
Fine material a (0.212-0.425 mm)	50	2.79	0	0	0
Fine material b (0.063-0.212 mm)	25	2.79	0	0	0
Fine material c (< 0.063 mm)	25	2.79	0	0	0
Water	806.98	1	806.98	2.421	2420.93
Total volume without water			194.22		

Table 12 Sample M006

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	90	1.35	66.67	0.2	270
Total Fine material	120	2.79	43.01	0.133	360
Fine material a (0.212-0.425 mm)	25.68	2.79	0	0	0
Fine material b (0.063-0.212 mm)	62.4	2.79	0	0	0
Fine material c (< 0.063 mm)	31.92	2.79	0	0	0
Water	801.66	1	801.66	2.405	2404.98
Total volume without water			198.34		

Then a new quantity of aggregate with particle size less than 0.5 mm was selected and the analysis of grain size distribution curve was done on this (which was faithful to the particle size distribution existing on the conveyor belt of the excavation machine). Next, new mixes were prepared, and these mixes were identified with the letter “G”(Table 13,Table 14,Table 15,Table 16, and Table 17). The first mix which was created was quoted as M005G and it was identical to the mix M005 in terms of composition.

Table 13 Sample M005G

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material (<0.5)	100	2.79	35.84	0.108	300
Water	806.98	1	806.98	2.421	2420.93
Total volume without water			194.22		

Table 14 Sample M007G

Elements	Weight (kg)	Unit Weight (kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material (< 0.5)	120	2.79	44.44	0.133	360
Water	798.4	1	798.4	2.395	2395.12
Total volume without water			201.6		

Table 15 Sample M008G

Elements	Weight (Kg)	Unit Weight (Kg/L)	Volume (l)	Volume for 3l	Weight for 3l
Cement	230	3.1	74.19	0.223	690
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material (<0.5)	150	2.79	55.56	0.167	450
Water	787.3	1	787.3	2.362	2361.79
Total volume without water			212.74		

Table 16 Sample M009G

Elements	Weight (Kg)	Unit Weight (Kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	200	3.1	64.52	0.194	600
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material (<0.5)	120	2.79	44.44	0.133	360
Water	808.1	1	808.1	2.424	2424.16
Total volume without water			191.9		

Table 17 Sample M010G

Elements	Weight (Kg)	Unit Weight (Kg/l)	Volume (l)	Volume for 3l	Weight for 3l
Cement	200	3.1	64.52	0.194	600
Bentonite	28	2.7	10.37	0.031	84
Retarding Agent	5	1.22	4.1	0.012	15
Accelerating Agent	92.5	1.35	68.52	0.206	277.5
Total Fine material (<0.5)	150	2.79	55.56	0.167	450
Water	796.9	1	796.9	2.391	2390.8
Total volume without water			203.1		

4.3 Computation of the amount of the component B for tests

A simple Equation 6 was used to determine the amount of accelerating agent required:

Equation 6 $$A : A_{mix\ design} = B : B_{mix\ design}$$

$A_{\text{mix design}}$ - the amount of component A obtained from mix design (g).

A- the required amount of component A that needed to be mixed with component B (g).

$B_{\text{mix design}}$ - the amount of component B obtained from mix design (g).

B- the required amount of component B that needed to be mixed with component A (g).

Thanks to this proportion the component B needed for gelation and casting has been calculated.

4.4 Preparation of component A

The preparation of component A was made according to (Todaro et al., 2019), which proposed a laboratory scale that emulates the batching grout preparation at the construction site. The goal is to prepare the component A with properties similar as much as possible to those of that one produced at the construction site. Due to the limitation on the size of laboratory equipment, the amount of component A that can be obtained has a range between 1.5 to a maximum of 3 liters. Moreover, for grout less than 1.5 liters, the lack of homogeneity could be faced. To obtain a correct component A with good homogeneity, it is necessary to consider the following points:

- The tank's volume should be 2 or 3 times higher than the volume of the mortar.
- The impeller should have an inclined blade, half the diameter of the tank, located at the center to create a good turbulence.
- The distance between the impeller and the bottom of the tank should be minimum, to avoid contact during the rotation.

4.4.1 Mixing equipment

1. **Tank**

A simple tank is needed, to insert and mix the elements and obtain the required component A (Figure 38).

2. **Containers**

One container for the required amount of bentonite, cement, and inert element is needed, and two smaller containers for retarding/fluidifying agent (Figure 39).

Figure 38 Tank with lid

Figure 39 Containers (left); Small containers (right)

3. Mixer

A mixer is a device that can rotate the impeller at different speeds per minute, ranging between 800 and 2000 rpm as shown in Figure 40.

Figure 40 Mixer

4. **Impeller**

An impeller to homogeneously mix the elements (Figure 41).

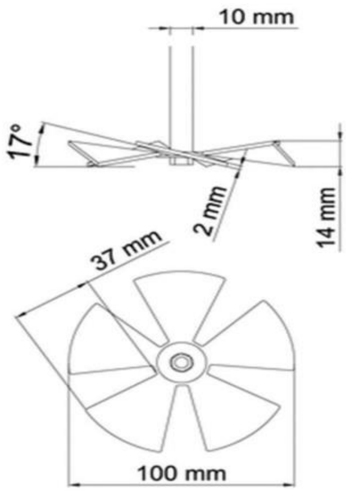


Figure 41 Figure from Todaro et al.2019(left); impeller used for the test(right)

5. **Vacuum cleaner**

The vacuum cleaner is used to suction the dust that is generated during the mixing of the elements (Figure 42).

Figure 42 Vacuum cleaner

6. Scale

A precise scale weighs the different elements used for the production of the mix. The scale that was used has an accuracy of ± 0.01 g (Figure 43).

Figure 43 Precise scale

4.4.2 Weight of the elements

1. Cement

The cement container is tared, and the cement is added until it reaches the desired amount.

2. Bentonite

The container of the bentonite is tared, and bentonite is added until it reaches the needed amount.

3. Water

The water container is tared, and water is added until it reaches the wanted weight.

4. Retarding/fluidifying agent

First, a certain amount of the retarding agent is poured inside one of the containers. Then, it is poured inside a second container while the first container is rotated, to ensure that all parts of the inner side of the first container is wet by the agent. This procedure is necessary to add the correct amount of the retarding agent to the mixture, since the slight changes in the amount of the retarding agent can significantly affect the properties of the obtained grout. Thus, after this procedure, the first container is tared, and the needed quantity of the retarding agent is added.

4.4.3 Mixing Operation

First, the preliminary check should be done. In this process, the water tank is located under the mixer, then the mixer is turned on, and the speed is raised to 800 rpm, then it is increased to 2000 rpm, and finally, it is reduced to 800 rpm again. It is necessary to check the correct placement and installation of the impeller and the mixer. An impeller installed incorrectly, such as too close to the tank bottom, results in vibrations in the entire system.

Once the impeller speed is raised to 800 rpm, the bentonite is poured into the tank gradually, increasing the impeller speed to 2000 rpm. Mixing continues according to the activation time of the bentonite. After that, the cement and aggregates are added, and mixing continues for 3 minutes. Finally, the retarding agent is added, and mixing continues for 2 minutes. The whole process lasts 12 minutes. The process is outlined in (Table 18)(Todaro et al., 2019). This process in this test campaign modified according to Table 19.

Table 18 Redrawn of mixing operation for component A according to Todaro et al. (2019)

Mixing operation	Impeller rotation speed	Duration(min)
Locate the tank filled with water and start the mixer	800	–
Add bentonite	800 —> 2000	7
Add cement	2000	3
Add retarding/fluidifying agent	2000	2

Table 19 Mixing operation of component A using aggregate

Mixing operation	Impeller rotation speed	Duration(min)
Locate the tank filled with water and start the mixer	800	–
Add bentonite	800 —> 2000	7
Add cement and aggregate together	2000	3
Add retarding/fluidifying agent	2000	2

4.5 Tests Characterization

Several experiments were carried out on component A, a combination of components A and B (gelled grout), and the hardened grout to assess the qualities of the mixes acquired based on varying proportions of the ingredients. In the following, the procedure adopted is explained.

4.5.1 Tests on Component A

1. Viscosity

To evaluate the viscosity of component A, the time needed for 1 liter of component A to flow out from the nozzle of the marsh funnel is measured. The test is carried out using the Marsh funnel procedure in compliance with the standard UNI 11152-13:2005.

Component A is poured into the marsh funnel until the notch point inside the cone. If there are air bubbles inside the mix, they must be removed by tapping the outer surface of the Marsh funnel, then the mixture is let go out from the nozzle of the marsh funnel, and the time required to fill 1 liter is measured (Figure 44).

Figure 44 Standard marsh cone with notch (left); one-liter container with a notch (right)

2. Unit weight

To measure the unit weight, the container of the precision scale is filled with component A, and the cap is placed, then the surplus of component A pours out from a tiny hole in the middle of the cap. The poured-out component A from the cap is removed with the flow of water, while the hole in the cap is closed with a finger. Then, the precision scale is placed on its box and measured after a timed lap of 5 minutes to allow the air bubble to rise (Figure 45).

The unit weight of component A is measured in compliance with the standard EN 1015-6:1998 (Methods of test for mortar for masonry. Part 6: Determination of Bulk Density of Fresh mortar), using a precision scale with a resolution of ± 0.005 g/cm^3.

Figure 45 Precision scales in its box to measure the unit weight of component A, without the cap (up), with the cap (down)

3. Bleeding test

The bleeding can be performed following the standard UNI 11152-11. One liter of component A inserted into a graduated cylinder according to the geometry defined in the related standard, and then it is sealed with a stopper, for instance, plastic tape, to avoid the evaporation of the water. The bleeding can be evaluated by measuring the height of exudate water over the primary volume in different time settings. The measurement is done at 10', 20', 30', 40', 50', 60', 90', 120', 180’, and after 24 hours. The bleeding should be less than 5-6% after 24 hours.

It should be considered that the amount of cement and water/cement ratio influences the bleeding, especially in the long term (24 hours). The higher the ratio, the lower the bleeding (Equation 7):

$$\text{Equation 7} \quad Bleeding(\%) = \frac{V_{exudate\,water}}{V}$$

where:

$V_{\text{exudate water}}$ - *the volume of exuded water (m^3)*

V - *the fixed volume of 1 l of component A (m^3)*

4.5.2 Test on the gelled grout

1. Gel time

The amount of time between the beginning of mixing component A into component B and the point at which the mixture grout ceases being fluid is known as the gel time. The procedure adopted is that proposed by (Todaro et al., 2019), since no standard procedures are available.

In this procedure, two containers with a capacity of 0.4 l are used (Figure 46). One of them is filled with 200 g of component A, while another container is filled with a corresponding amount of component B according to the mix design. Then component A is poured into the container of component B, acquiring good turbulence and, consequently, uniform mixing of the two components. Adding component B to the container of component A would not result in a homogeneous mixture. To obtain a reliable gel time, it is recommended to perform the gel time test at least three times to obtain an average value as gelation time.

Figure 46 Six containers with capacity of 0.4 l to perform the gel time tests

4.5.3 Test on hardened grout

4.5.3.1 Two-component grout sample casting

Since two-component grout exhibits a mechanical behavior like a hard clay at a short curing time and as a weak concrete at a long curing time, there are no standards available to properly cast samples of two-component grout(Todaro et al., 2020).

In the past, the most common method for filling an annular gap was to use a mono-component filling method (mortar and fine aggregate) precisely aligned to be tested with UNI EN 196-1:16. Although mono-component technology is less common today, all parties involved in the tunneling industry adhere to this guideline. Thus, with some adjustments, the UNI EN 196-1:16 for the two-component grouts can be used. Due to the lack of standards, the short-term compressive strength of a two-component grout is evaluated according to the procedure proposed in the paper of (Todaro et al., 2020).

Samples are rectangular prisms with dimensions of 40 x 40 x 160 mm and are cast in non-deformable molds. First, if there is a hole inside the lower part of the mold, it should be closed with a paper tape to avoid the flow out of the grout from the hole. In the second step, two containers are filled with component A and the other one with component B. Finally, component A is poured into the container of component B (on the contrary, the proper turbulence is not generated). The operation is repeated, and the obtained admixture is poured inside the mold, creating a homogenous and continuous flow. All samples should be filled with a single layer, since any correction could result in a heterogeneous sample. Once the mold is filled with samples, 30-60 seconds wait is necessary, using a spatula to scrape the sample's surface in a single and continuous movement to obtain a flat surface. As a final step, the mold is sealed to prevent evaporation of water and allowed to cure for a specified time (Figure 47).

Due to the short gelation, the creation of air bubbles inside the grout trapped during the casting phase is unavoidable, and it would be better to do the pour and cast quickly. Hence, air bubbles tend to ascend to the surface of the grout before the hardening of the grout. Furthermore, the amount of the mixture should be at least 20% higher than the volume of the mold (0.256 l) to perform a proper casting. The additional amount permits casting the mold in a single flow without material losses due to the adhesion to the inner part of the container or due to inaccurate pouring.

Figure 47 Standard mold to cast three samples(up-left); Three samples casted and then scraped by spatula (up-right); Two molds hermetically sealed with their cap (down)

4.5.3.2 Surface Compressive Strength (SCS) test

In the short term, backfilling should lock the segments in the desired position and bear the back-up weight during the advancement. The surface compressive strength is adopted to evaluate the grout's short-term compressive strength.

The test follows the procedure of a penetrometer test and follows the standard ASTM C403/C403M-16 (Standard test method for time of setting of concrete mixtures by penetration resistance), conveniently modified to fit the characteristics of two-component grout, which has a quick setting time. These changes are related to the bit's surface area and penetration thickness (Todaro et al., 2020).

The measurement is done on a two-component sample with 1 hour and 3 hours, respectively. A mold allows a cast of 3 samples and 3 surface compressive strength tests can be carried out along each sample. As a result, there will be 9 SCS tests per mold. Despite their proximity, the SCS values obtained for the same sample do not show any correlation or dependence (Todaro et al., 2020).

The SAUTER GmbH Ziegelei 1 D-72336 Balingen digital model dynamometer (maximum force of 1000 N, 0.5N of resolution) was used for penetration tests. It is equipped with a flat circular bit with a surface of 177.9 mm^2 and a thickness of 5 mm. The dynamometer is placed perpendicularly to the sample casting surface, and a growing pressure is applied manually with a constant advancement speed. If the applied pressure is not entirely perpendicular to the surface, the recorded strength will be lower than the actual one. The peak force that allows penetration of the bit thickness for 5mm into the two-component mortar is measured (Figure 48,Figure 49).To evaluate the surface compressive strength, the ratio between the measured peak force and the area, which is the area of the bit, should be measured, according to the Equation 8:

Equation 8 $$SCS = \frac{F}{A}$$

where:

SCS - the surface compressive strength (MPa)
F-the measured peak force (N)
A- the area of the bit (mm^2)

The area of the bit is equal to 177.9 mm^2.

Figure 48 SAUTER GmbH Ziegelei 1 D-72336 Balingen digital model dynamometer (left); Detail of the bit (Todaro et al., 2020) (right)

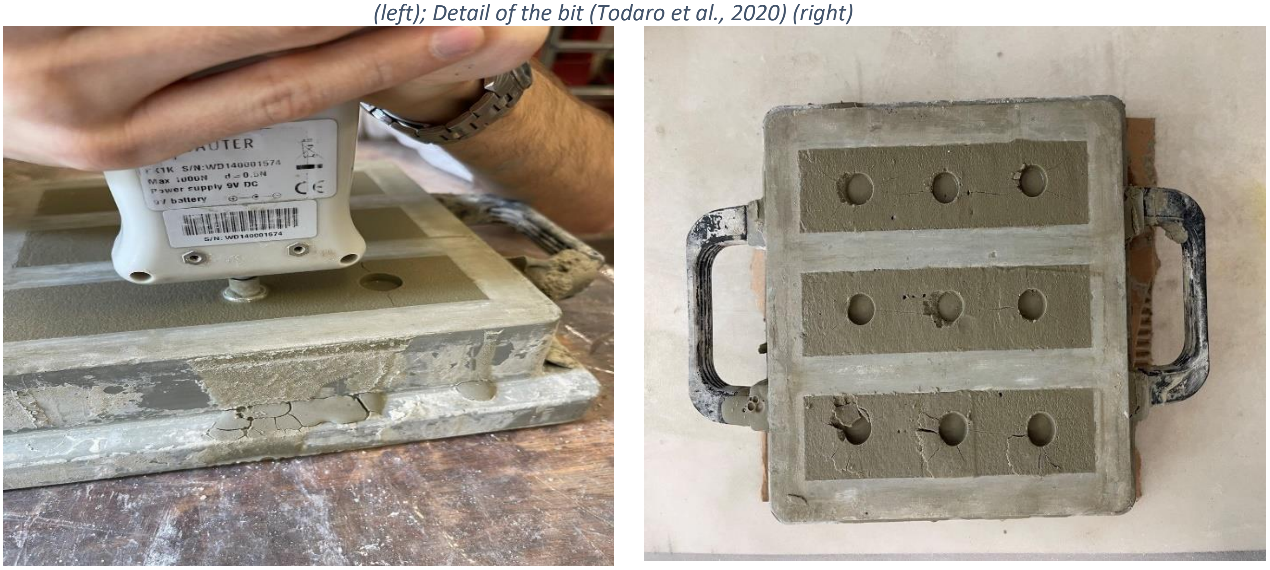


Figure 49 SCS tests performed on the surface of samples inside their mold (left); The marks left by the test are visible (right)

4.5.3.3 Uniaxial Compressive strength (UCS) test

For a complete description of the two-component grout at some construction sites, the uniaxial compressive strength is evaluated after 24 hours, 7 days, and 28 days. Two-component grout has a mechanical behavior, such as clay with a short curing time and weak concrete with a long curing time. As a result, some adjustments are needed, to carry out the UCS test in accordance with UNI

EN 196-1:2016 (Methods of testing cement. Part 1: Determination of strength). (Todaro et al., 2020).

Samples were cast according to the procedure explained in sample casting, and samples were cured in the water for 24 hours, 7 days, and 28 days, respectively. Each sample was first put through three-point flexural testing (except the sample for 24 hours of curing time), which divided each sample in half. Once all samples were cut into half, the UCS test was performed on each half (Figure 50,Figure 51).

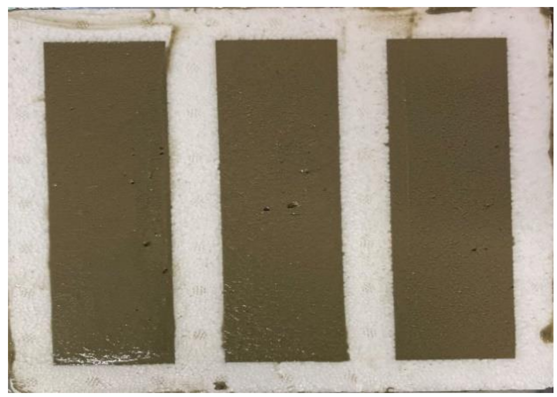


Figure 50 Special mold for casting and easy removing of samples (up-left); Casted two-component grout (right); Extracted samples put into water for curing

Figure 51 Three-point flexural test on sample (left); UCS test on half of the sample (right)

4.6 Result of the laboratory tests

As mentioned in 4.2.1, 10 different samples were made during the test campaign, and various tests were done on each sample. The result of each test will be explained in the following.

The viscosity test

Viscosity of the mortar guarantees the compatibility of mortar with pumps. From the analysis of the data obtained from the component A, since the typical normal range of the flowability must be between 30-45 second, it can be seen, according to the result, that there is no significant change in the flowability of the mixtures, which ranged between 32.8 and 36.8. If the amount of aggregates increase, the viscosity decrease. The viscosity should be measured at time zero which is after the preparation of the mortar, after 24 hours, after 48 and finally after 72 hours and it should have a good degree of flowability. For the first three samples (M001, M002, M003), the viscosity was measured until 48 hours, and these samples were fluid after 72 hours. Then, the viscosity also measured for other samples (M004 to M010G) at time zero (exactly after the preparation of the mortar). The Table 20 and Figure 52 show the data obtained from viscosity test:

Table 20 Flow time of different samples

N.sample	Flowability[T0] (s)
M001	35
M002	36
M003	35.8
M004	34.1
M005	33.1
M006	36.5
M005G	32.8
M007G	34.4
M008G	33.8
M009G	36.8
M010G	34.5

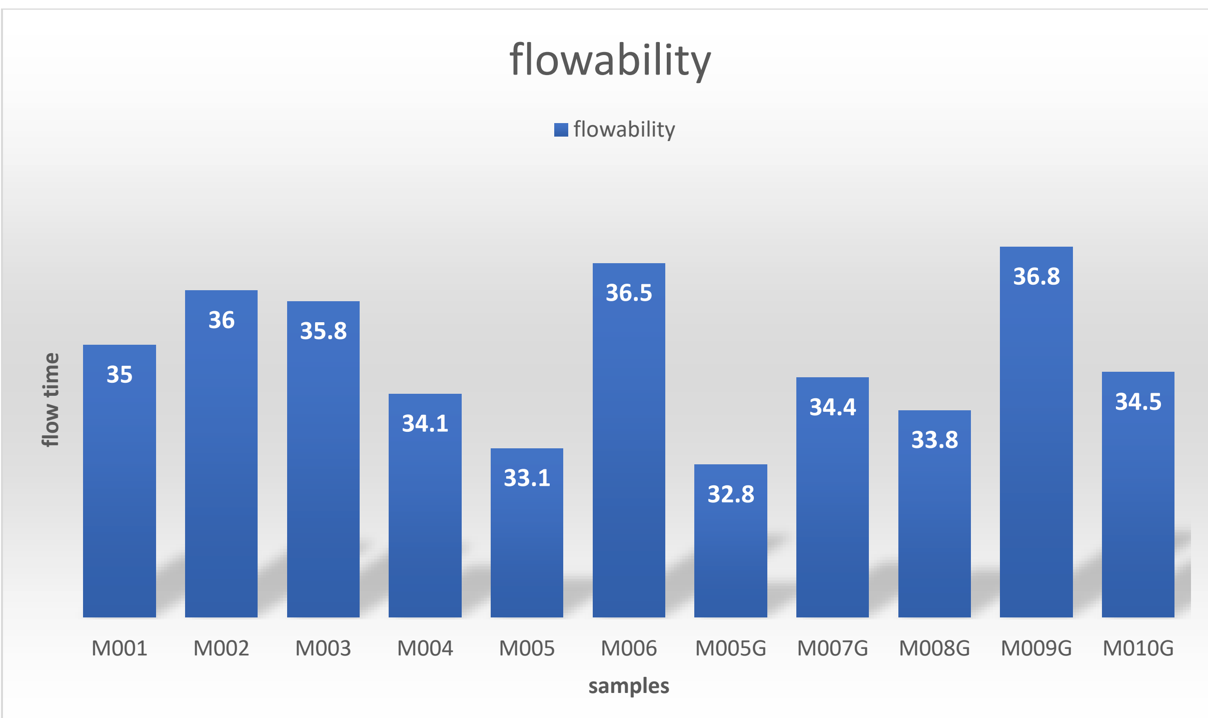


Figure 52 Range of flow time for different samples

The unit weights

The unit weight of component A must usually be between 1.13 and 1.18 g/cm^3, though, due to the presence of the aggregate, it increases the unit weight of the mortar more than usual, and it can be said that by increasing the aggregates, the unit weight increases. The results can be seen in Table 21.

Table 21 Result of the unit weight

N.sample	Unit weight (g/cm^3)
M001	1.24-1.25
M002	1.27-1.28
M003	1.26-1.27
M004	1.25
M005	/
M006	1.25
M005G	1.25-1.26
M007G	1.25
M008G	1.28-1.29
M009G	1.24
M010G	1.26-1.27

The Bleeding

The stability of the mortar is fundamental for ensuring a homogenous backfill annulus and should always be verified: it is linked with the transportation of the mortar to the job site. It should be noted that bleeding decreases as the aggregate increases. The bleeding was measured for samples M001, M002, M003, and M010G. Furthermore, it should be mentioned that a standard Becker was not used for the measurement of bleeding of sample M003, and bleeding related to sample M010G was measured after 6 hours and not 24 hours in the primary test. Table 22,Table 23 show the data related to the bleeding test.

Table 22 Result of the bleeding test

N.sample	Bleeding (%) 30 min	Bleeding (%) 60 min	Bleeding (%) 3 hours	Bleeding (%) 24 hours
M001	0	0	0.7	3.8
M002	0	0	0.3	3.1
M003	0	0	0.3	2.8
M004	/	/	/	/
M005	/	/	/	/
M006	/	/	/	/

Table 23 Result of the bleeding test

N.sample	Bleeding (%) 30 min	Bleeding (%) 60 min	Bleeding (%) 3 hours	Bleeding (%) 6 hours
M005G	/	/	/	/
M007G	/	/	/	/
M008G	/	/	/	/
M009G	/	/	/	/
M010G	0	0	1	1.7

Most of the samples show less than 6% bleeding after 24 hours.

The gel time

In the first 3 samples (M001, M002, and M003) the gelation was excessively low. M004 showed a higher quantity of the accelerating agent, characterized by a gel time in an acceptable range (6.8 s). Mix M005 is characterized by a lower quantity of accelerating agent and showed a total gel time equal to 6 s. Mix M006 was designed with higher amounts of aggregate with different particle size distributions and lower quantity of the aggregate and, as a result, the gel time was extremely low. Despite the reduction of the accelerating agent, the gel time variation could be attributed to the aggregate used and specifically to the particle size distribution. For sample

M005G, which is identical to M005 but with a different particle size distribution, the gel time equals 6.3 s. Then, considering the mix M007G, it has a higher quantity of aggregate (120 kg/m^3). As a result, the gel time was low, and the mixing of components A and B were non-homogenous. Both mixes M008G and M009G represented a peculiarity during the gel test as a significant part of component A gelled almost instantly in contact with component B, while the remaining part gradually reached the gel state as usual. Mix M010G is characterized by a reduced amount of cement (200 kg/m^3) and greater aggregate quantity. The components A and B mix was very homogenous and regular, with a gel time of 6.4 s. Table 24 shows the data related to the gel time test.

Table 24 Result of the gel time

N. sample	gel time [s]
M001	5
M002	/
M003	/
M004	6.8
M005	6
M006	< 5
M005G	6.3
M007G	5.8
M008G	6.4
M009G	6.9
M010G	6.4

Surface Compressive Strength (SCS) test results.

Due to the low gelation time, the SCS test was not performed on the first three samples (M001, M002, and M003). Furthermore, for mixes M008G and M009G, the heterogeneous mixing between components A and B compromised the casting of the s specimens. On the other hand, this test was done on the samples M004, M005, and M007G after 1 hour and 3 hours, but The resistance showed by sample M004 was excessively high compared to the typical values from the literature (Todaro et al., 2022).

In addition, SCS was measured for the samples M005G, M009G, and M010G after 1 hour. Table 25 indicate the data related to surface compressive strength tests.

Table 25 Result of the surface compressive strength test

N.sample	M001	M002	M003	M004	M005	M006	M005G	M007G	M008G	M009G	M010G
SCS 1H	/	/	/	0.87	0.57	/	0.81	0.74	/	0.7	0.78
SCS 3H	/	/	/	>2.8	1.91	/	/	>2.7	/	/	/

The complete results of test related to each sample are provided in Annex 1.

After these tests, M005, M005G, and M010G could be considered the most promising mixtures. To maximize the amount of aggregate used in the mix, M010G could be the best candidate. In addition, it consists of a lower amount of cement (30 kg/m^3 less than M005, M005G).

Then, the properties of mixes M005G and M010G were retested to obtain more accurate data. Therefore, different quantities of mixtures were prepared for M005G and M010G. Since the maximum quantity of the mixture that could be prepared in the lab was 3 l, sequential ordinal numbers were used to distinguish between the same mix designs.

The mix M005G (1) was subjected to a viscosity test after preparation of the mixture, after 24 hours, 48 hours, and 72 hours but the test was subjected to an error of overestimation. Since it was not possible to fill the marsh cone with the exact quantity of the required mixture, which must be 1.5 l, it was slightly lower (around 1.3-1.4 l).

Mix M005G (2) was characterized by higher viscosity and lower gel time while maintaining a perfect mix between components A and B. The fluctuation could be attributed to atmospheric conditions (high humidity due to rainfall).

For mix M010G (1) and M010G (2), both were prepared on the same day, and they showed similar values in comparison with M010G with an exception for the viscosity, which was higher for M010G (2) and specific weight, which was lower (this could be probably due to presence of a significant quantity of the air during mixing). These two mixtures were characterized by higher gelation time. In addition, the bleeding was reduced for M010G (1).

Mix M010G (3) provided the same values as previous mixtures, while SCS measured was equal to 0.96 MPa, which was approximately 0.2 MPa higher than previous mixtures. The SCS after 3 hours gave a very high value, equal to 2.5 MPa.

Both mixes provided 24 hours of bleeding less than 4.5% (Figure 53). Considering that after 72 hours it remained smooth, the measured time for viscosity was equal to 38.9 s for M010G and 42.9 for M005G.


Figure 53 Bleeding test after 24 hours for M005G (left) and M010G (right)

Mix M005G is characterized by a mixing between components A and B better than M010G. It should be noted that environmental parameters such as temperature and humidity could affect the gelation time and gelation process itself.

Table 26,Table 27,

Table 28, and Table 29show the numerical data related to the primary mix designs of samples M005G and M010G and those related to secondary tests.

Table 26 Results of the unit weight for two final candidate samples

N.sample	M005G	M005G (1)	M005G (2)	M010G	M010G (1)	M010G (2)	M010G (3)
Unit Weight (kg/m3)	1.25-1.26	1.25-1.26	1.25-1.26	1.26-1.27	1.27	1.25-1.26	1.27

Table 27 Result of the bleeding for two final candidate samples

N.sample	Bleeding (%) 30 min	Bleeding (%) 60 min	Bleeding (%) 3 hours	Bleeding (%) 24 hours
M005G	/	/	/	/
M005G (1)	0	/	0.7	4.3
M005G (2)	/	/	/	/
M010G	/	/	*1*	/
M010G (1)	/	/	0.5	4.2
M010G (2)	/	/	/	/
M010G (3)	/	/	/	/

Table 28 Result of flowability for two final candidate samples

N.sample	T0(s)	T24(s)	T48(s)	T72(s)
M005G	32.8	/	/	/
M005G (1)	33.2	38.7*	40*	42.9*
M005G (2)	36.5	/	/	/
M010G	34.5	/	/	/
M010G (1)	33.9	/	/	/
M010G (2)	36.7	37	37.9	38.9
M010G (3)	35.5	/	/	/

* Error due to that the amount of grout was lower than the capacity of marsh funnel

Table 29 Result of the surface compressive strength for two final candidate samples

N.sample	SCS 1hour (MPa)	SCS 3hours (MPa)
M005G	0.81	/
M005G (1)	/	/
M005G (2)	0.68	2.56
M010G	0.78	/
M010G (1)	0.76	/
M010G (2)	0.78	/
M010G (3)	0.96	2.50

As a result, M005G and M010G are both characterized by high stability (24 hours bleeding less than 4.5%); M005G has a slightly lower specific weight (1.25-1.26 kg/l). Furthermore, M005G seems to be characterized by mixing components A and B, leading to a more homogenous and uniform gelation.

After obtaining appropriate results on M005G and M010G, which confirmed the available data, uniaxial compressive strength (UCS) and three-points flexural strength were measured. The UCS was measured for curing time of 1 day,7 days and 28 days while three-points flexural strength was measured for curing time of 7 days and 28 days. Both of these tests are in accordance with the standard UNI EN 196-1:2016: method for testing cement part 1.

Specimens with a curing time of 24 hours were subjected to the UCS test, while the specimens with a curing time of 7 days and 28 days were subjected to a 3-point flexural test and subsequently to the UCS test.

For each flexural test, 3 specimens were used from each mix at the end of the test. The two ends of the specimen obtained due to breakage were subjected to the UCS test. The two ends are subsequently named sides "a "and "b ".

Table 30,Table 31,Table 32,Table 33,and Table 34 show the numerical values measured during the execution of UCS and 3-point flexural tests. The graphical representation of UCS for mixture M005G and M010G versus different curing time is shown in Figure 54.

The 1-day and 7-days UCS tests were carried out on specimens from the same quantity of mortar, while specimens subjected to 28 days tests were cast using a quantity of subsequently batched mortar (both quantities were packed at the same time).

Table 30 Uniaxial compressive strength for samples cured 24 hours

Specimens	side	UCS M005G(MPa)	UCS M010G(MPa)
Specimen 1	a	1.12	1.11
	b	0.93	0.96
Specimen 2	a	1.04	0.95
	b	1.28	0.98
Specimen 3	a	1.12	1.04
	b	1.00	1.01
Mean value		1.08	1.01

Table 31 Three-points flexural test for samples cured for 7 days.

Specimens	M005G(MPa)	M010G(MPa)
Specimen 1	0.40	0.49
Specimen 2	0.47	0.54
Specimen 3	0.52	0.56
Mean Value	0.46	0.53

Table 32 Uniaxial Compressive Strength test for samples cured for 7 days

Specimens	Side	UCS M005G(MPa)	UCS M010G(MPa)
Specimen 1	a	1.52	1.51
	b	1.63	1.42
Specimen 2	a	1.66	1.44
	b	1.63	1.52
Specimen 3	a	1.61	1.51
	b	1.66	1.5
Mean value		1.62	1.49

Table 33 Three-points flexural test for samples cured for 28 days

Specimens	M005G(MPa)	M010G(MPa)
Specimen 1	0.65	0.41
Specimen 2	0.56	0.44
Specimen 3	0.49	0.4
Mean Value	0.56	0.42

Table 34 Uniaxial Compressive Strength test for samples cured for 28 days

Specimens	Side	UCS M005G(MPa)	UCS M010G(MPa)
Specimen 1	a	1.94	1.05*
	b	2.09	1.46
Specimen 2	a	1.96	1.28
	b	2.02	1.55
Specimen 3	a	1.9	1.32
	b	1.9	1.53
Mean value		1.97	1.43

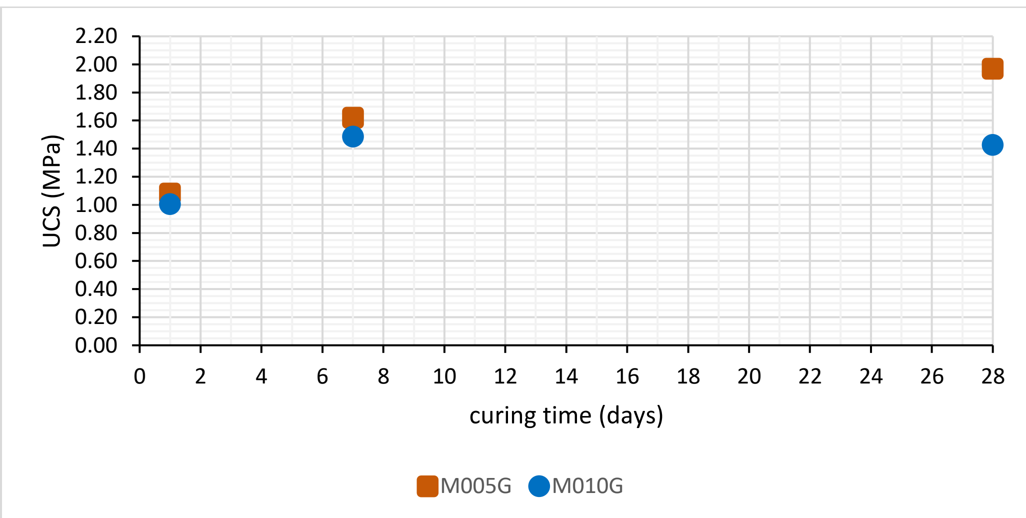


Figure 54 UCS vs curing time

The complete results related to these two samples and their graphs are given in Annex 2 and Annex 3.

5 Discussion and conclusion

After performing all the tests on the two final samples (M005G and M010G), it can be understood that both the two mix designs are good to use instead of the mix design without aggregates in terms of meeting the sustainability objective and reuse of the excavated material.

According to the test performed on component A, for sample M010G, the amount of cement was reduced 30 kg/m^3 in comparison with M005G (from 230 kg/m^3 to 200 kg/m^3) while the amount of aggregate increased to150 kg/m^3, which is 50 kg/m^3 is higher than M005G.

The results of viscosity test show that both samples have good degree of fluidity after 72 hours. In addition, the density of these two samples is close and is around 1.26 kg/l. Furthermore, the results obtained from the bleeding test depicted that the amount of bleeding after 25 hours is less than 6% (4.3 and 4.2 for M005G and M010G respectively).

Considering the test done on both components A and B, the gel time was in acceptable range (6.3 s for M005G and 7 s for M010G). According to the Surface Compressive Strength, both samples showed good results for 1h and 3h tests and they were in a close range (except M010G (3), that was 0.2 MPa higher for SCS 1 hour test). The results of the Uniaxial Compressive Strength show that the UCS of both samples are in a good range for 24 hours and 7 days. Also, the result of UCS for 28 days is in a good range, though there is a reduction in the sample M010G. Again, it should be mentioned that the first two tests (24 hours and 7 days) were obtained from the same batched, while the test on 28 days was done on a different batched mortar.

Here also, to confirm the results obtained from the Uniaxial Compressive Strength, the results of this test campaign is compared with some classic two-components grout according to Table 35 (Todaro et al., 2022).

The most used testing times were 1 hour, 24 hours, and 28 days. So, considering the data obtained from the test campaign developed (24 hours, 7 days, and 28 days), the comparison is just done on 24 hours and 28 days. Table 35 shows the UCS data obtained from different case histories at 24 hours ,7 days, and 28 days.

Table 35 UCS values for different case histories related to 7 days and 28 days curing time

Cases	UCS 24H (MPa)	UCS 28 DAYS (MPa)
2	/	5.1
3	1.5	/
10	1.04	1.64
11	1.21	2.02
13	0.7	3
15	1.5	4
18	1	2
20	0.8	2
21	0.8	2
22	0.8	2.5
23	1.5	3
Mean value	1.09	2.73

As a result, the mean value of UCS is 1.09 MPa and 2.73 MPa for 24 hours and 28 days respectively. Comparing these results with the result obtained during the test campaign and knowing that the typical range for UCS should be less than 5-6 MPa, the UCS results in the campaign for both samples are in a good range (Figure 55).

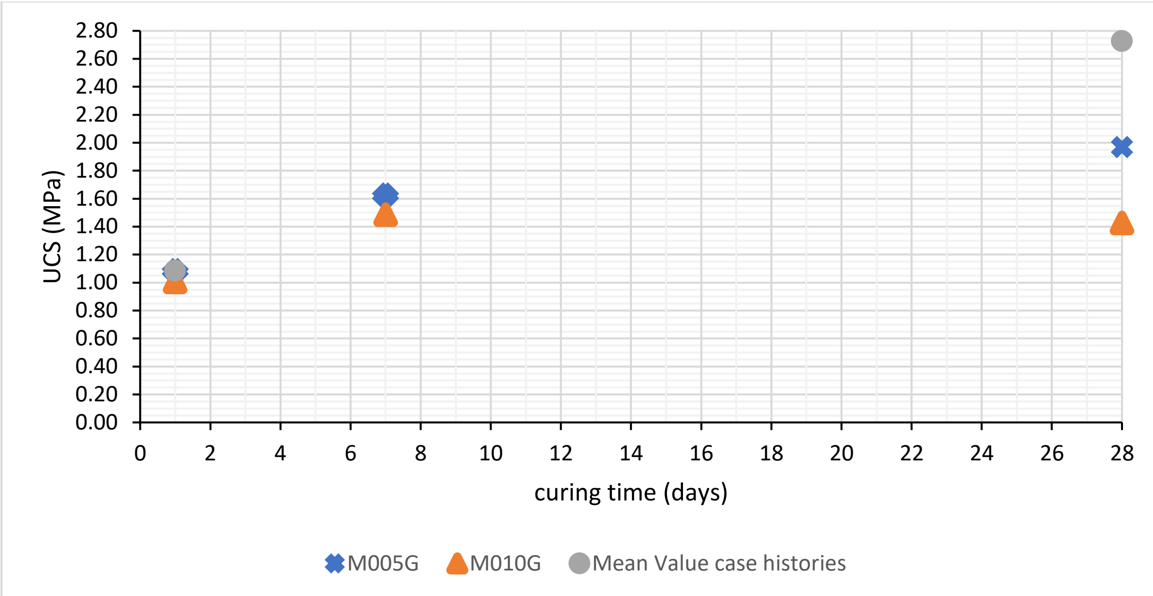


Figure 55 Comparison between UCS for prepared samples and mean value of UCS for case histories vs curing time

Reference

1. Bellopede, R. (2011). Main Aspects of Tunnel Muck Recycling. *American Journal of Environmental Sciences*, *7*, 338–347. https://doi.org/10.3844/ajessp.2011.338.347
2. Bilgin, N., Copur, H., & Balci, C. (2013). *Mechanical Excavation in Mining and Civil Industries*. CRC Press. https://doi.org/10.1201/b16083
3. Bilotta, E., Casale, R., Prisco, C., Miliziano, S., Peila, D., Pigorini, A., & Pizzarotti, E. (2022). *Handbook on Tunnels and Underground Works: Volume 1: Concept – Basic Principles of Design*. https://doi.org/10.1201/9781003256175
4. Cho, J.-W., Jeon, S., Yu, S.-H., & Chang, S.-H. (2010). Optimum spacing of TBM disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method. *Tunnelling and Underground Space Technology*, *25*(3), 230–244. https://doi.org/10.1016/j.tust.2009.11.007
5. EFNARC. (2005). *Specification and Guidelines for the use of specialist products for Mechanised Tunnelling (TBM) in Soft Ground and Hard Rock.* www.efnarc.com
6. Gertsch, L., Fjeld, A., Nilsen, B., & Gertsch, R. (2000). Use of TBM muck as construction material. *Tunnelling and Underground Space Technology*, *15*, 379–402. https://doi.org/10.1016/S0886-7798(01)00007-4
7. Goel, R. K., & Singh, B. (2011). Engineering Rock Mass Classification. In *Engineering Rock Mass Classification*. https://doi.org/10.1016/C2010-0-64994-7
8. Hashimoto, T., Brinkman, H., Konda, T., Kano, Y., & Feddema, A. (2006). *Simultaneous Backfill Grouting, Pressure Development in Construction Phase and in the Long-Term*. *1995*. https://doi.org/10.1201/9781439834268.ch15
9. ITAtech. (2014). *Guidelines on Best Practices for Segment Backfilling. ITAtech Activity Group Excavation. ITAtech Report n°4 – Guidelines on Best Practices for Segment Backfilling – N°ISBN 978-2-9700858-5-0: May 2014.*

10. Oggeri, C. (2010). *Investigation and Test for Reuse of Muck in Tunnelling*.

11. Olbrecht, H., & Studer, W. (1998). *Use of TBM chips as concrete aggregate. Materials and Structures/Materiaux et Constructions, Vol. 31, April, pp 184-187, CH-8600 Diibendotf, Switzerland*.

12. Ozdemir, L. (1992). *Mechanical excavation techniques in underground construction. Short course notebook, vol 1. Istanbul Technical University, Istanbul, pp 1-49*.

13. Peila, D., Borio, L., & Pelizza, S. (2011). *The behaviour of a two-component backfilling grout used in a Tunnel-Boring Machine*. https://core.ac.uk/display/11421901?source=4

14. Reschke, A., & Noppenberger, C. (2011). Brisbane Airport Link Earth Pressure Balance Machine Two Component Tailskin Grouting – A New Australian Record. *NEW ZEALAND*, 9.

15. Rispoli, A., Ferrero, A. M., Cardu, M., Brino, L., & Farinetti, A. (2016). *Hard Rock TBM performance: Preliminary study based on an exploratory tunnel in the Alps*. https://doi.org/10.1201/9781315388502-80

16. Riviera, P., Bellopede, R., Marini, P., & Bassani, M. (2014). Performance-based re-use of tunnel muck as granular material for subgrade and sub-base formation in road construction. *Tunnelling and Underground Space Technology*, *40*, 160–173. https://doi.org/10.1016/j.tust.2013.10.002

17. Sakatadi, G. (2022). *Characterization of muck from TBM excavation aimed to its sustainable reuse*.

18. Thewes, M., & Budach, C. (2009). Grouting of the annular gap in shield tunneling – an important factor for minimization of settlements and for production performance. *Proceedings of the ITA-AITES World Tunnel Congress*.

19. Todaro, C., Bongiorno, M., Carigi, A., & Martinelli, D. (2020). Short term strength behavior of two-component backfilling in shield tunneling: Comparison between standard penetrometer test results and UCS. *Geoingegneria Ambientale e Mineraria*, *159*, 33–40.

20. Todaro, C., Martinelli, D., Boscaro, A., Carigi, A., Saltarin, S., & Peila, D. (2022). Characteristics and testing of two-component grout in tunnelling applications. *Geomechanics and Tunnelling*, *15*(1), 121–131. https://doi.org/10.1002/geot.202100019

21. Todaro, C., Peila, L., Luciani, A., Carigi, A., Martinelli, D., & Boscaro, A. (2019). *Two component backfilling in shield tunneling: Laboratory procedure and results of a test campaign* (pp. 3210–3223). https://doi.org/10.1201/9780429424441-340

22. Voit, K., & Zimmermann, T. (2015). Characteristics of selected concrete with tunnel excavation material. *Construction and Building Materials*, *101*, 217–226. https://doi.org/10.1016/j.conbuildmat.2015.10.016

Standard

- ASTM C403/C403M-16 (2016). Standard test method for time of setting of concrete mixtures by penetration resistance
- ASTM 854-14 (2016). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer
- UNI EN 933-1, 2012 Part 1. Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method
- EN 1015-6:1998 (1998). Methods of Test for Mortar for Masonry. Part 6: Determination of Bulk Density of Fresh Mortar
- UNI 11152-11:2005 (2005). Sospensioni acquose per iniezioni a base di leganti idraulici - Caratteristiche e metodi di prova. Parte 11.
- UNI 11152-13:2005 (2005). Sospensioni acquose per iniezioni a base di leganti idraulici - Caratteristiche e metodi di prova. Parte 13
- UNI EN 196-1:2016 (2016). Methods of testing cement. Part 1: Determination of strength.

ANNEX 1

ID: M001

Date	5/30/2022
Activation time (min)	7
environment temperature	Normal
water temperature	Normal
humidity	dry

Bleeding		
(min)	(mm)	(%)
10	0.0	0.0
20	0.0	0.0
30	0.0	0.0
40	0.0	0.0
50	0.0	0.0
60	0.0	0.0
90	1.0	0.3
120	1.5	0.5
180	2.0	0.7
86400	11.0	3.8

Flow time (s)			
t0 h	t24 h	t48 h	t72 h
35	35	36.8	/

Gel time (s)		
Test 1	Test 2	Test 3
5.2	5.1	4.6
AVERAGE		5.0

ID: M002

Data	5/30/2022
activation time (min)	7
environment temperature	Normal
water temperature	Normal
humidity	dry

Bleeding		
(min)	(mm)	(%)
10	0.0	0.0
20	0.0	0.0
30	0.0	0.0
40	0.0	0.0
50	0.0	0.0
60	0.0	0.0
90	0.5	0.2
120	1.0	0.3
180	1.0	0.3
86400	9.0	3.1

Flow time (s)			
t0 h	t24 h	t48 h	t72 h
36	37.8	39.3	/

ID: M003

Data	5/30/2022
Activation time (min)	7
Environment temperature	Normal
Water temperature	Normal
Humidity	Dry

Bleeding		
(min)	(mm)	(%)
10	0.0	0.0
20	0.0	0.0
30	0.0	0.0
40	0.0	0.0
50	0.0	0.0
60	0.0	0.0
90	0.0	0.0
120	0.8	0.2
180	1.0	0.3
86400	10.0	2.8

Flow time (s)			
t0 h	t24 h	t48 h	t72 h
35.8	37.5	38.7	/

ID: M004

Data	6/6/2022
Activation time (min)	7
Environment temperature	Normal
Water temperature	Normal
Humidity	Dry

Gel time (s)		
Test 1	Test 2	Test 3
6.7	6.3	7.5
AVERAGE		6.8

SCS 1h (N)			AVERAGE
162.0	/	"97.0"*	162.0
181.5	151.5	165.5	166.2
/	134.0	133.0	133.5
			153.9

* Failed during measuring

SCS 1h (MPa)			AVERAGE
0.91	/	/	0.91
1.02	0.85	0.93	0.93
/	0.75	0.75	0.75
			0.87

ID: M005

Date	6/8/2022
Activation time (min)	7
Environment temperature	Hot
Water temperature	Normal
Humidity	A little humid

Gel time (s)		
Test 1	Test 2	Test 3
6.2	5.9	6.0
AVERAGE		6.0

SCS 1h (N)			AVERAGE
106.5	99.5	102.0	102.7
92.5	104.0	105.5	100.7
-	-	-	-
			101.7

SCS 1h (MPa)			AVERAGE
0.60	0.56	0.57	0.58
0.52	0.58	0.59	0.57
-	-	-	-
			0.57

SCS 3h (N)			AVERAGE
330.0	/	350.0	340.0
-	-	-	-
-	-	-	-
			340

SCS 3h (MPa)			AVERAGE
1.85	/	1.97	1.91
-	-	-	-
-	-	-	-
			1.91

ID: M005G

Data	6/15/2022
Activation time	7
Environment temperature	Hot
Water temperature	Normal
Humidity	a little humid

Gel time (s)		
Test 1	Test 2	Test 3
6.1	6.8	5.9
AVERAGE		6.3

SCS 1h (N)			AVERAGE
151.0	137.5	146.5	145.0
143.0	144.5	144.0	143.8
-	-	-	-
			144.4

SCS 1h (MPa)			AVERAGE
0.85	0.77	0.82	0.82
0.80	0.81	0.81	0.81
-	-	-	-
			0.81

ID: M007G

Date	6/15/2022
Activation time (min)	7
Environment temperature	Warm
Water temperature	Normal
Humidity	a little humid

Gel time (s)		
Test 1	Test 2	Test 3
5.9	5.3	6.1
AVERAGE		5.8

SCS 1h (N)			AVERAGE
129.0		148.5	138.8
124.5	124.0	"105.5"	124.3
-	-	-	
			131.5
SCS 1h (MPa)			AVERAGE
0.73	/	0.83	0.78
0.70	0.70	"0.59"	0.70
-	-	-	
			0.74

SCS 1h (N)			AVERAGE
133.5	134.0	154.0	140.5
157.5	114.5	110.5	127.5
123.5	"106.5"*	/	123.5
			130.5
SCS 1h (MPa)			AVERAGE
0.75	0.75	0.87	0.79
0.89	0.64	0.62	0.72
0.69	"0.60"*	/	0.69
			0.73

* Failed during measuring

SCS 3h (N)			AVERAGE
> 430.0	> 400.0	> 400.0	> 410.0
> 400.0	> 400.0	> 400.0	> 400.0
/	402.5	400.0	> 401.3
			> 403.8
SCS 3h (MPa)			AVERAGE
> 2.42	> 2.25	> 2.25	> 2.30
> 2.25	> 2.25	> 2.25	> 2.25
/	2.26	2.25	> 2.26
			> 2.27

ID: M008G

Date	6/16/2022
Activation time (min)	7
Environment temperature	warm
Water temperature	Normal
Humidity	a little humid

Gel time (s)		
Test 1	Test 2	Test 3
6.7	5.8	6.8
AVERAGE		6.4

ID: M009G

Date	6/17/2022
Activation time (min)	7
Environment temperature	
Water temperature	
Humidity	

Gel time (s)		
Test 1	Test 2	Test 3
6.6	7.4	6.7
AVERAGE		6.9

SCS 1h (N)			AVERAGE
/	128.0	"68.0"*	128.0
141.0	129.5	83.5	118.0
137.0	118.0	121.5	125.5
			123.8
SCS 1h (MPa)			**AVERAGE**
/	0.72	"0.38"*	0.72
0.79	0.73	0.47	0.66
0.77	0.66	0.68	0.71
			0.70

* Failed during measuring

ID: M010G

Data	6/17/2022
Activation time (min)	7
Environment temperature	
Water temperature	
Humidity	

Bleeding		
(min)	(mm)	(%)
10	0	0.0
20	0	0.0
30	0	0.0
40	0	0.0
50	0	0.0
60	0	0.0
90	1	0.3
120	1.7	0.6
180	3	1.0
360	5	1.7
86400	-	0.0

Gel time (s)		
Test 1	Test 2	Test 3
6.6	6.2	6.5
AVERAGE		6.4

SCS 1h (N)			AVERAGE
135.5	150.5	141.5	142.5
121.0	133.5	152.0	135.5
129.0	141.5	152.0	140.8
			139.6
SCS 1h (MPa)			AVERAGE
0.76	0.85	0.80	0.80
0.68	0.75	0.85	0.76
0.73	0.80	0.85	0.79
			0.78

ID: M010G (1)

Date	6/20/2022
Activation time (min)	7
Environment temperature	
Water temperature	
Humidity	

Bleeding		
(min)	(mm)	(%)
10	0	0.0
20	0	0.0
30	0	0.0
40	0	0.0
50	0	0.0
60	0	0.0
90	1	0.3
120	1	0.3
180	1.5	0.5
86400	12	4.2

Gel time (s)		
Test 1	Test 2	Test 3
7.1	7.2	7.3
		7.2

SCS 1h (N)			AVERAGE
171.0	148.0	140.5	153.2
131.0	123.0	119.5	124.5
132.0	127.5	127.0	128.8
			135.5
SCS 1h (MPa)			AVERAGE
0.96	0.83	0.79	0.86
0.74	0.69	0.67	0.70
0.74	0.72	0.71	0.72
			0.76

ID: M010G (2)

Date	6/20/2022
Activation time(min)	7
Environment temperature	
Water temperature	
Humidity	

Gel time (s)		
Test 1	Test 2	Test 3
7.5	6.6	8.3
AVERAGE		7.5

SCS 1h (N)			AVERAGE
151.0	137.5	127.5	138.7
			138.7
SCS 1h (MPa)			AVERAGE
0.85	0.77	0.72	0.78
			0.78

ID: M005G (1)

Date	6/20/2022
Activation time(min)	7
Environment temperature	
Water temperature	
Humidity	

Bleeding		
(min)	(mm)	(%)
10	0	0.0
20	0	0.0
30	0	0.0
40	0	0.0
50	-	-
60	-	-
90	-	-
120	1.5	0.5
180	2	0.7
86400	12.5	4.3

Flow time (s)			
t0 h	t24 h	t48 h	t72 h
33.2	38.7	40.0	42.9

Gel time (s)		
Test 1	Test 2	Test 3
6.5	6.8	7.0
AVERAGE		6.8

ID: M010G (3)

Date	6/21/2022
Activation time(min)	7
Environment temperature	
Water temperature	
Humidity	

Gel time (s)		
Test 1	Test 2	Test 3
7.0	6.7	6.9
AVERAGE		6.9

SCS 1h (N)			AVERAGE
157.0	144.5	150.0	150.5
185.0	164.0		174.5
195.5	"150"*	177.0	186.3
			170.4
SCS 1h (MPa)			**AVERAGE**
0.88	0.81	0.84	0.85
1.04	0.92		0.98
1.10	"0.84"*	0.99	1.05
			0.96

* Failed during measuring

SCS 3h (N)			AVERAGE
390.0	507.0	453.5	450.2
472.5	> 440	404.5	438.5
497.5		394.0	445.8
			444.8
SCS 3h (MPa)			**AVERAGE**
2.19	2.85	2.55	2.53
2.66	> 2.47	2.27	2.46
2.80		2.21	2.51
			2.50

ID: M005G (2)

Date	6/22/2022
Activation time(min)	7
Environment temperature	
Water temperature	
Humidity	Very humid(rainy)

Gel time (s)		
Test 1	Test 2	Test 3
5.9	6.0	5.6
AVERAGE		5.8

SCS 1h (N)			AVERAGE
112.5	134.0	142.0	129.5
"88.0"*	114.5	"87.5"*	114.5
122.0	"91.0"	117.0	119.5
			121.2
SCS 1h (MPa)			**AVERAGE**
0.63	0.75	0.80	0.73
"0.49"*	0.64	"0.49"*	0.64
0.69	"0.51"	0.66	0.67
			0.68

* Failed during measuring

SCS 3h (N)			AVERAGE
> 400.0	470.0	480.0	475.0
478.5	443.0	432.5	451.3
436.0	432.0	454.0	440.7
			455.7
SCS 3h (MPa)			**AVERAGE**
> 2.25	2.64	2.70	2.67
2.69	2.49	2.43	2.54
2.45	2.43	2.55	2.48
			2.56

ANNEX 2

General Tests

Viscosity test with Marsh cone		
Time (s)	**M005G**	**M010G**
t_0	33.2	36.7
t_1= 24 h	38.7	37.0
t_2 = 48 h	40.0	37.9
t_3= 72 h	42.9	38.9

Gel time		
Time (s)	**M005G**	**M010G**
t_{gel} (sec)	6.3	6.40
t_{gel} (sec)	6.8	7.20
t_{gel} (sec)	5.8	7.50
t_{gel} (sec)	-	6.90
t_{gel} mean(sec)	6.3	7.0

Density (kg/l)		
	M005G	**M010G**
density (kg/l)	1.255	1.265

During the bleeding test the Beckers are sealed.

Capacity (ml)	1000
Height of 1000 ml (mm)	289

M005G			
	mm of exuded water	ml of exuded water	bleeding (%)
t= 1 h			
t_1= 3 h	2	6.92	0.7
t_2 = 24 h	12.5	43.25	4.3

M010G			
	mm of exuded water	ml of exuded water	bleeding (%)
t= 1 h	0	0	0.0
t_1= 3 h	1.5	5.19	0.5
t_2 = 24 h	12	41.52	4.2

SCS (SURFACE COMPRESSIVE STRENGTH) 1h and 3h

Date	6/15/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M005G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	151.0	137.5	146.5	143.0	144.5	144.0			
Compressive Strength (MPa)	0.85	0.77	0.82	0.80	0.81	0.81			
Mean value (MPa)	0.81								

Date	6/22/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M005G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	112.5	134.0	142.0		114.5		122.0		117.0
Compressive Strength (MPa)	0.63	0.75	0.80		0.64		0.69		0.66
Mean value (MPa)	0.70								

Date	6/22/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	3h

M005G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	> 400	470.0	480.0	478.5	443.0	432.5	436.0	432.0	454.0
Compressive Strength (MPa)	> 2.25	2.64	2.70	2.69	2.49	2.43	2.45	2.43	2.55
Mean value (MPa)	2.55								

SCS (SURFACE COMPRESSIVE STRENGTH) 1h and 3h

Date	6/17/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M010G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	135.5	150.5	141.5	121.0	133.5	152.0	129.0	141.5	152.0
Compressive Strength (MPa)	0.76	0.85	0.80	0.68	0.75	0.85	0.73	0.80	0.85
Mean value (MPa)	0.78								

Date	6/20/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M010G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	171.0	148.0	140.5	131.0	123.0	119.5	132.0	127.5	127.0
Compressive Strength (MPa)	0.96	0.83	0.79	0.74	0.69	0.67	0.74	0.72	0.71
Mean value (MPa)	0.76								

Date	6/20/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M010G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	151.0	137.5	127.5						
Compressive Strength (MPa)	0.85	0.77	0.72						
Mean value (MPa)	0.78								

Date	6/21/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	1h

M010G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	157.0	144.5	150.0	185.0	164.0		195.5		177.0
Compressive Strength (MPa)	0.88	0.81	0.84	1.04	0.92		1.10		0.99
Mean value (MPa)	0.94								

Date	6/21/2022
Specimen dimension (mm)	40x40x160
Area of Specimen	1600
Height of Specimen	40
Maturation	3h

M010G									
TEST MADE WITH PENETROMETER									
Bit Area (mm^2)	177.9								
TEST	1	2	3	4	5	6	7	8	9
Force (N)	390.0	507.0	453.5	472.5	> 440.0	404.5	497.5		394.0
Compressive Strength (MPa)	2.19	2.85	2.55	2.66	> 2.47	2.27	2.80		2.21
Mean value (MPa)	2.50								

Results of UCS for 24 hours

	C_0
M005G	1.12
	0.93
	1.04
	1.28
	1.12
	1.00
average	1.08
standard deviation	0.111223

	C_0
M010G	1.11
	1.00
	0.96
	0.95
	0.98
	1.04
average	1.01
standard deviation	0.049815

Results of UCS for 7 Days

	C_0
M005G	1.52
	1.63
	1.66
	1.63
	1.61
	1.66
average	1.62
standard deviation	0.046901

	C_0
M010G	1.51
	1.42
	1.44
	1.52
	1.51
	1.50
average	1.49
standard deviation	0.034166

Results of UCS for 28 Days

	C_0
M005G	1.94
	2.09
	1.96
	2.02
	1.90
	1.90
average	1.97
standard deviation	0.066612

	C_0
M010G	*1.05**
	1.46
	1.28
	1.55
	1.32
	1.53
average	1.43
standard deviation	0.099364

*** This result did not used in the calculation**

Results of Three-points flexural test for 7 days

	T_0
M005G	0.40
	0.47
	0.52
average	0.46
standard deviation	0.048162

	T_0
M010G	0.49
	0.54
	0.56
average	0.53
standard deviation	0.029249

Results of Three-points flexural test for 28 days

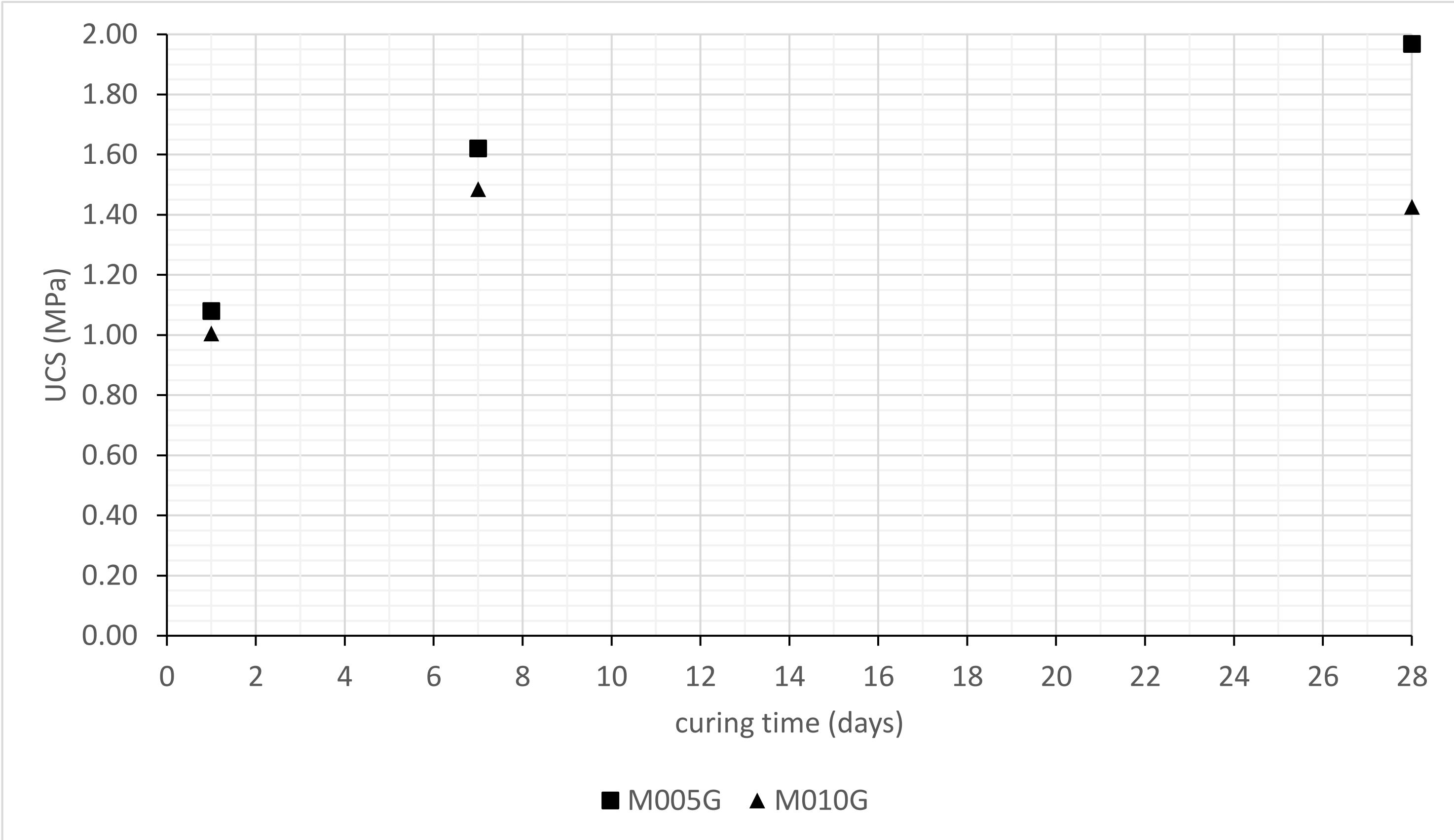
	T_0
M005G	0.65
	0.56
	0.49
average	0.56
standard deviation	0.06398

	T_0
M010G	0.41
	0.44
	0.40
average	0.42
standard deviation	0.017101

UCS Charts

M005G	
curing time (days)	Mean Value C_0
1	1.08
7	1.62
28	1.97

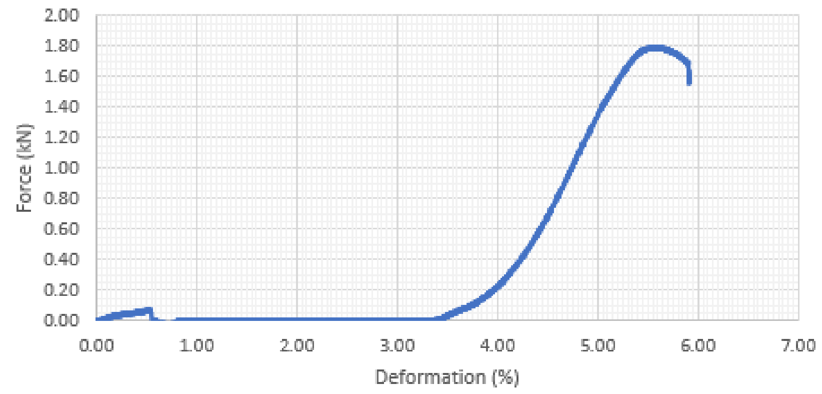
M010G	
curing time (days)	Mean Value C_0
1	1.01
7	1.49
28	1.43



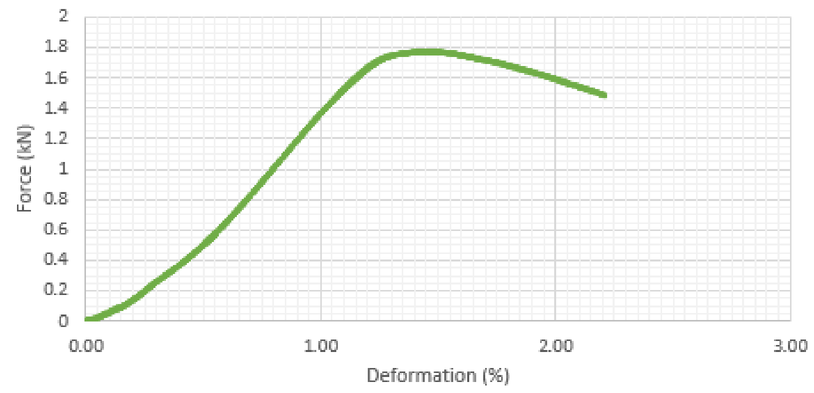
ANNEX 3

UCS CHARTS FOR 24 HOURS	
M005G	M010G

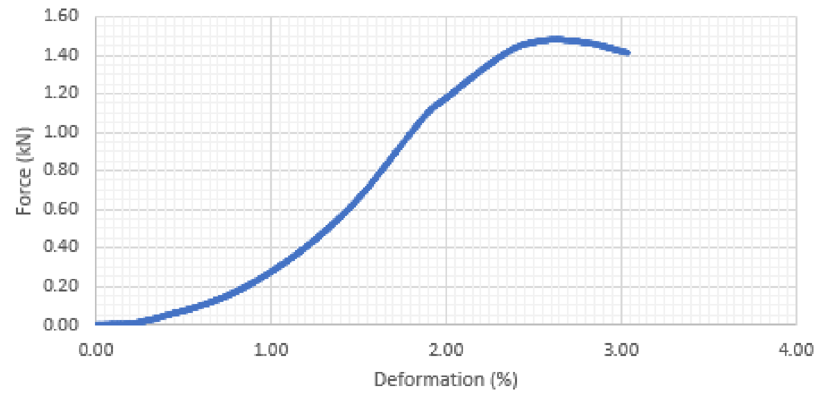
SPECIMEN 1A



SPECIMEN 1A



SPECIMEN 1B



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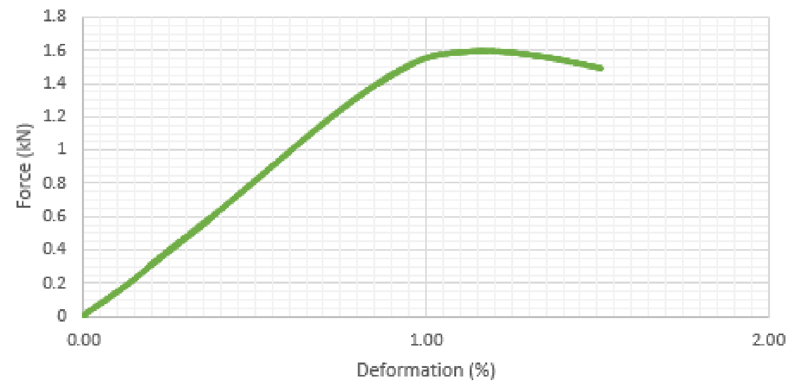

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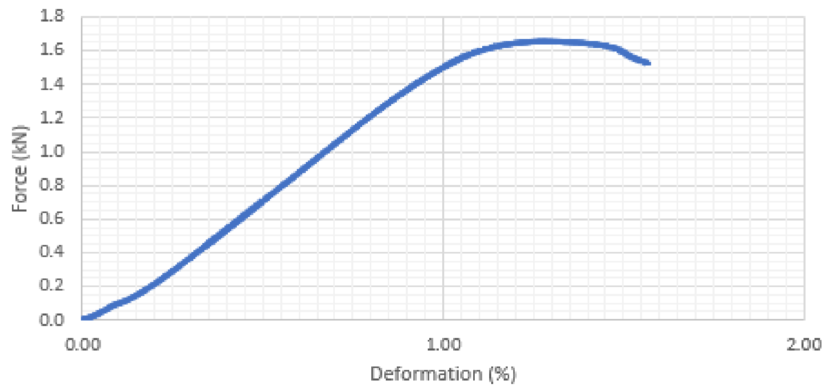

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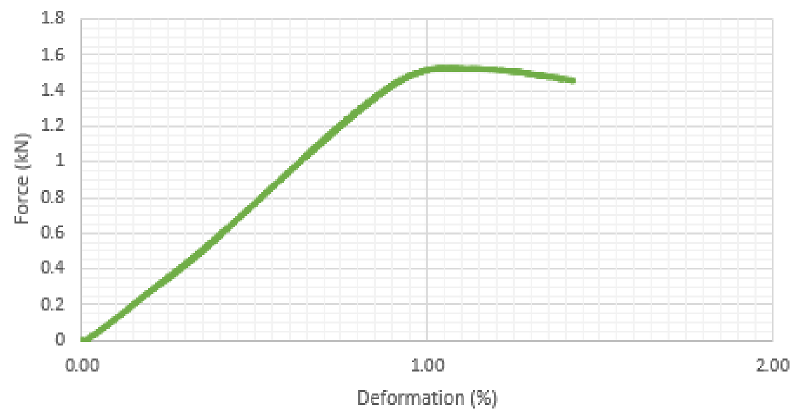

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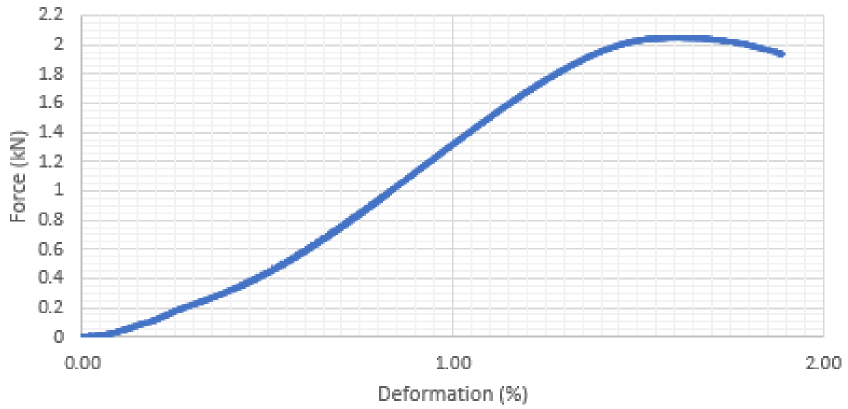

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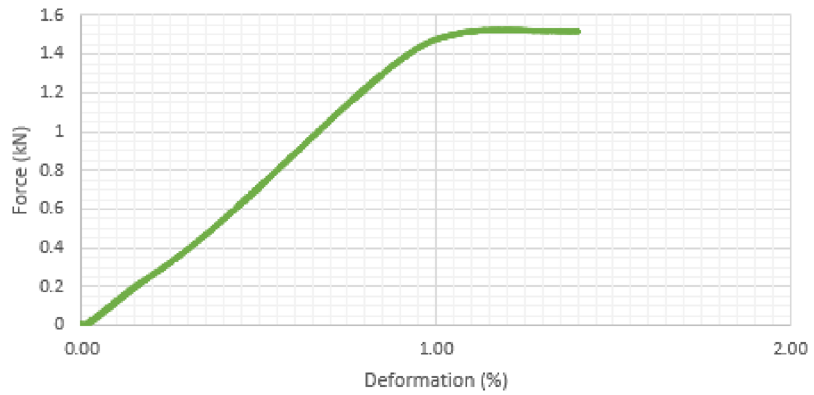

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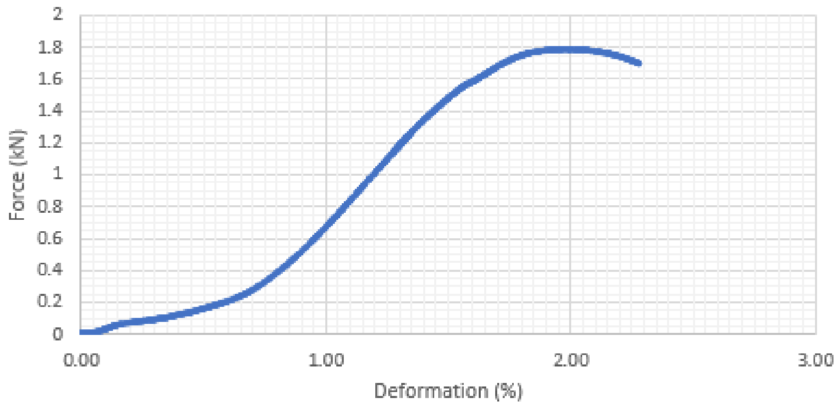
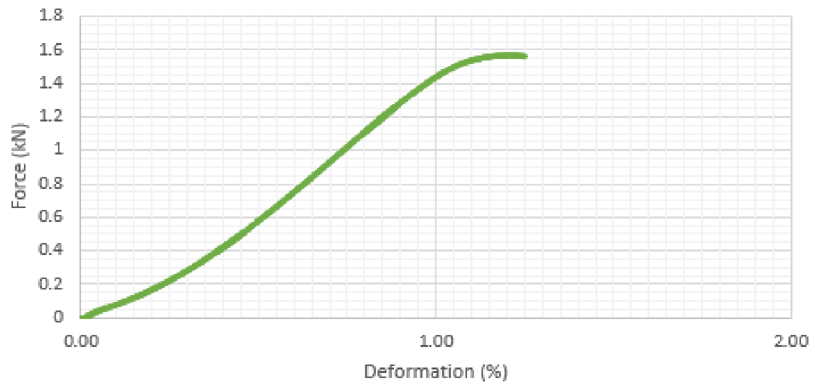


SPECIMEN 3A



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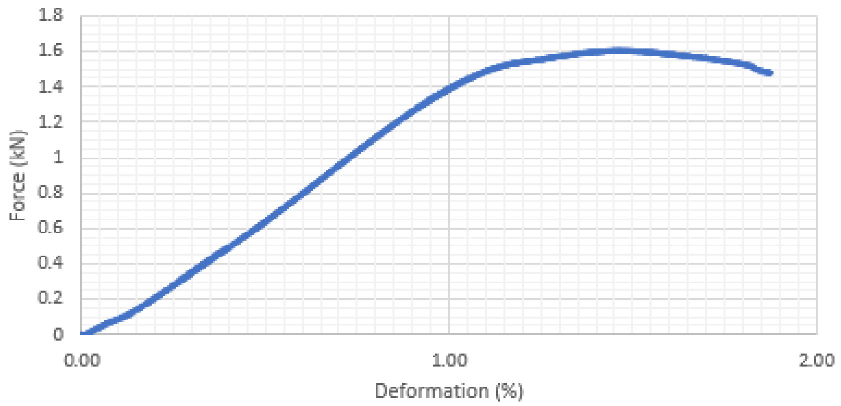
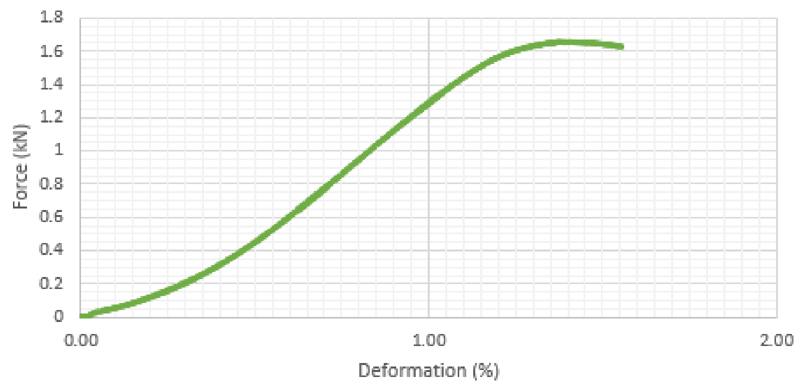


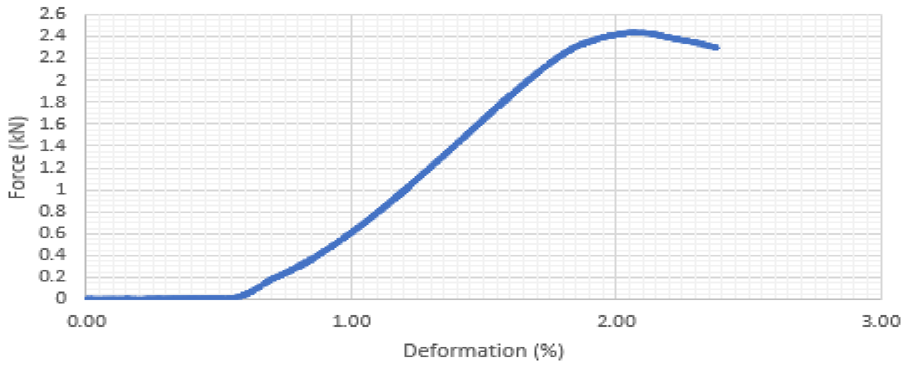
SPECIMEN 3B



UCS CHARTS FOR 7 DAYS

M005G	M010G

SPECIMEN 1A



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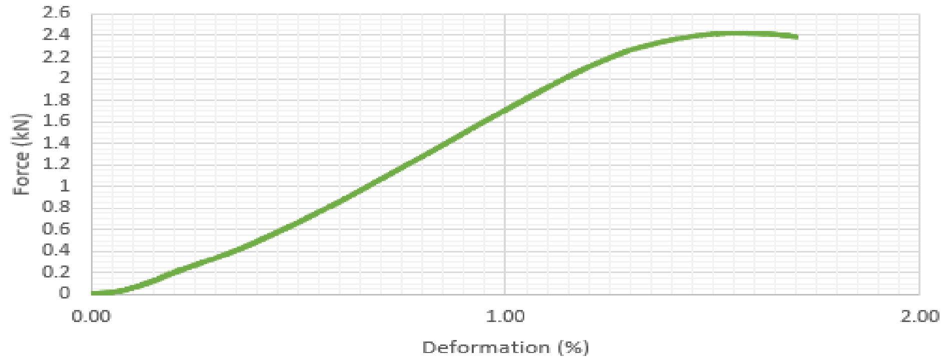

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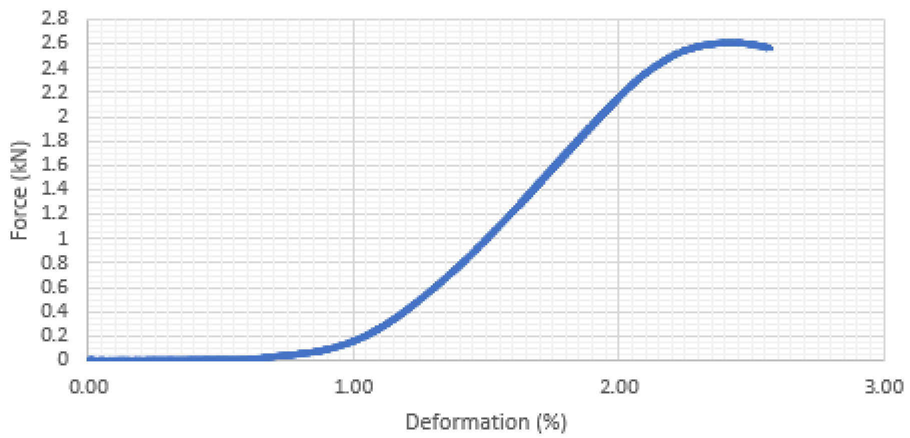

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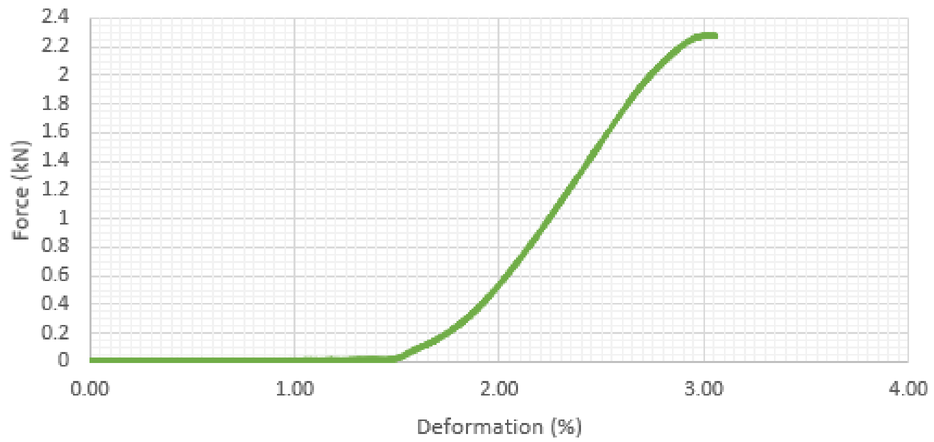

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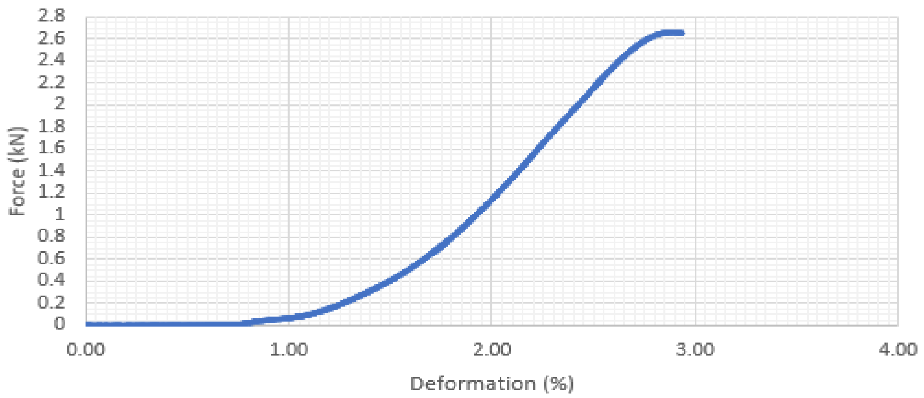

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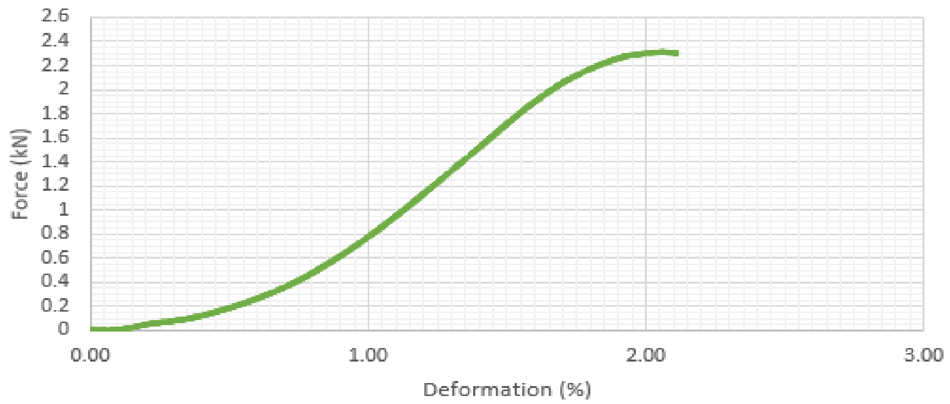
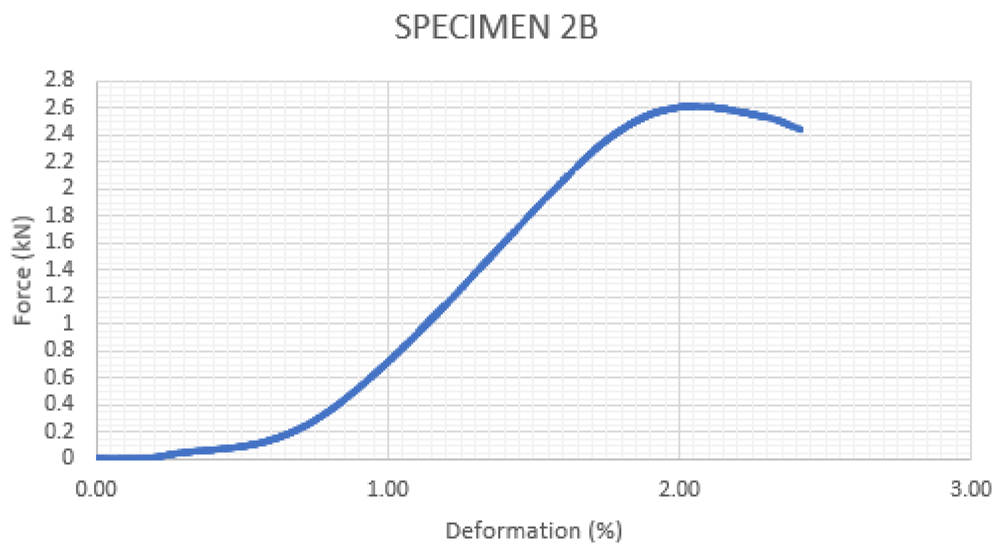
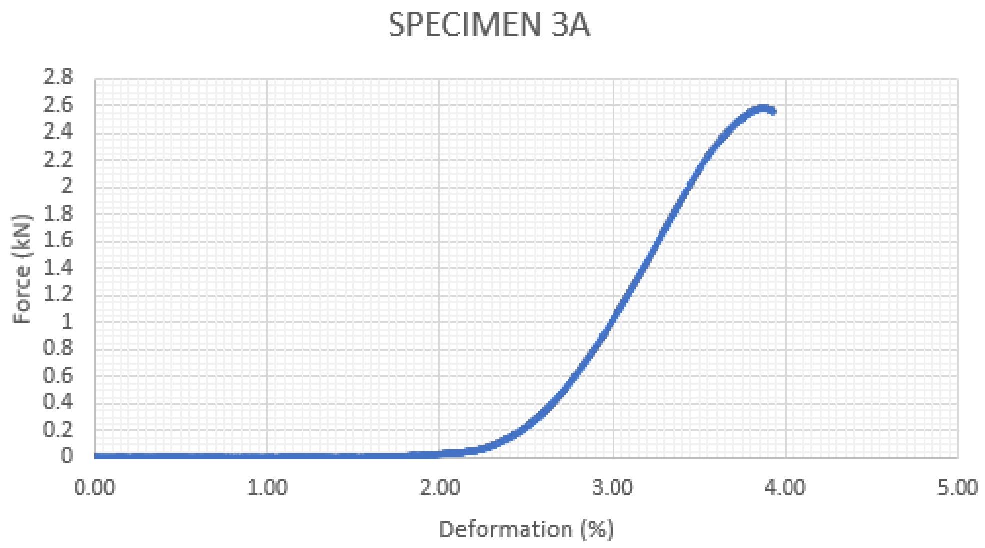
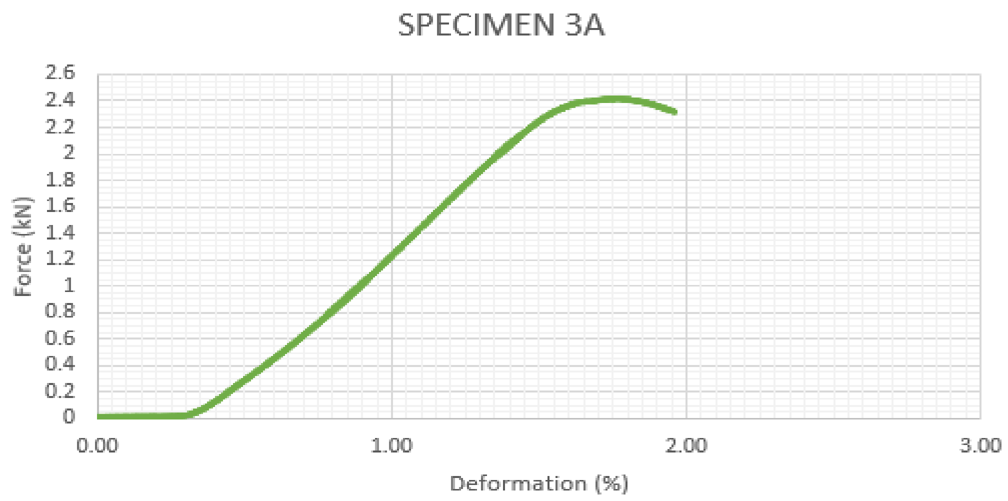
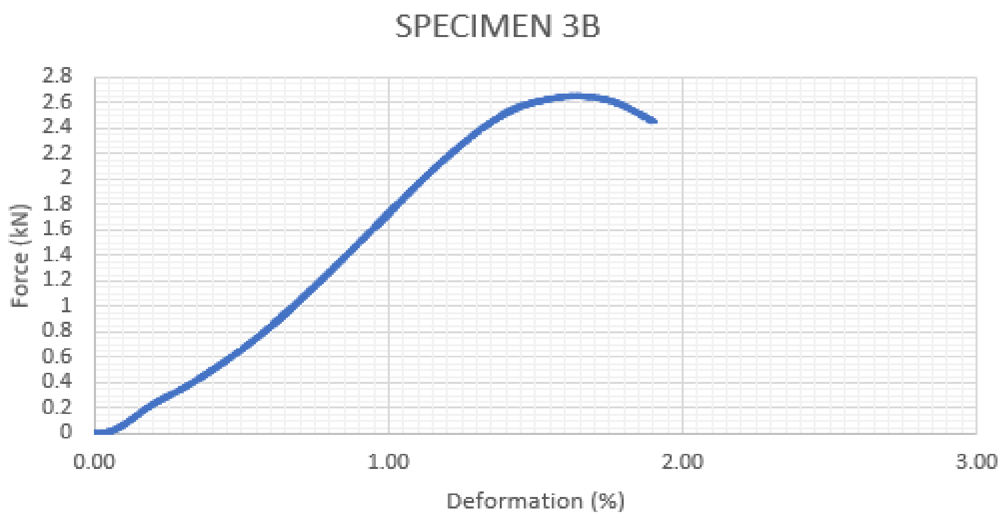


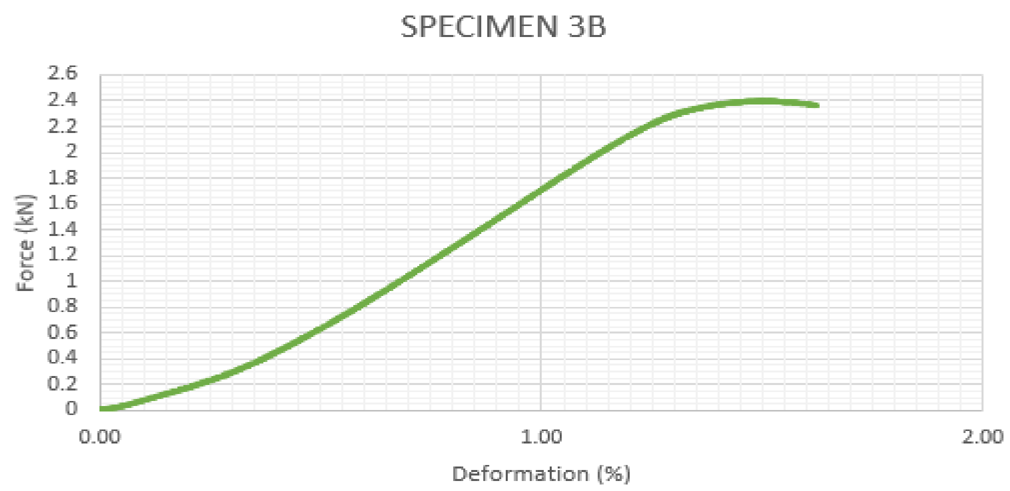

SPECIMEN 2B
Force (kN)
Deformation (%)


SPECIMEN 2B
Force (kN)
Deformation (%)

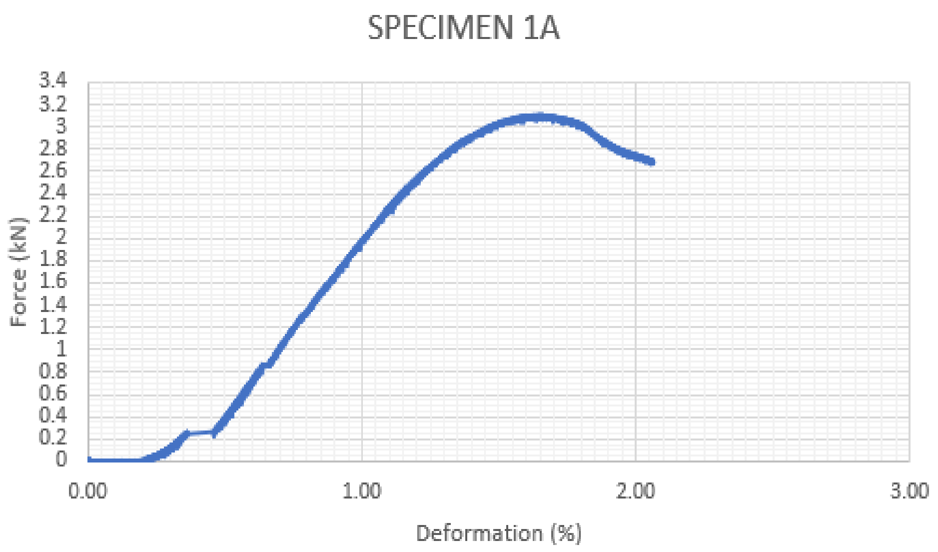

SPECIMEN 3A
Force (kN)
Deformation (%)

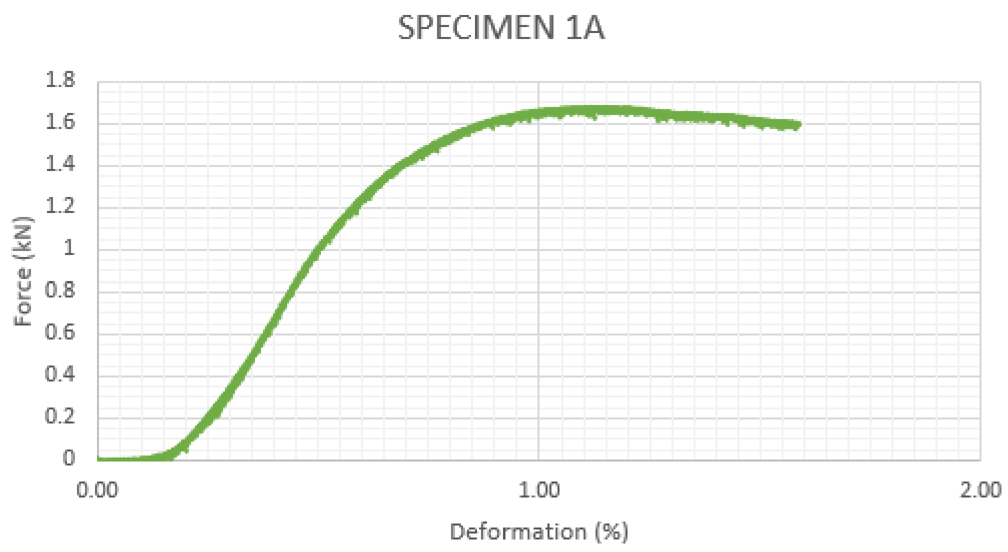

SPECIMEN 3A
Force (kN)
Deformation (%)

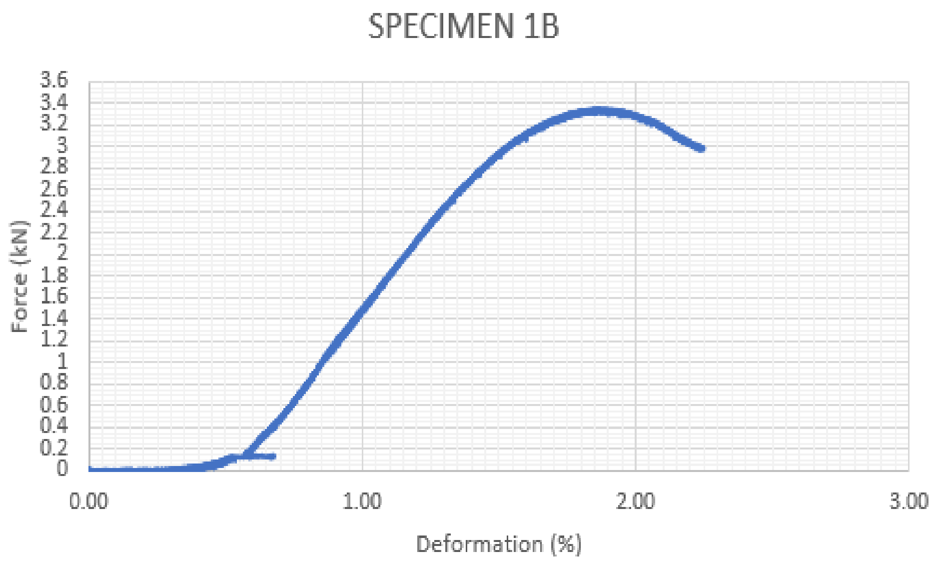

SPECIMEN 3B
Force (kN)
Deformation (%)

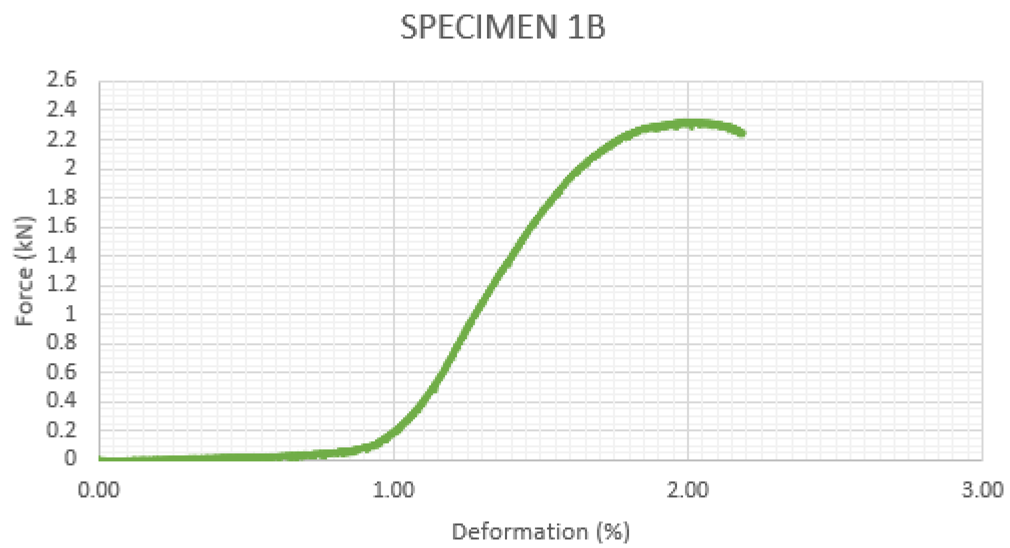

SPECIMEN 3B
Force (kN)
Deformation (%)

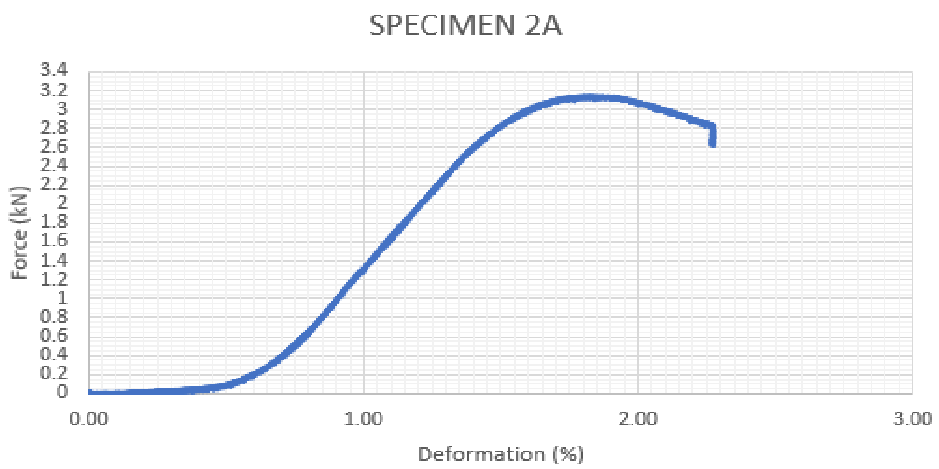
UCS CHARTS FOR 28 DAYS	
M005G	M010G

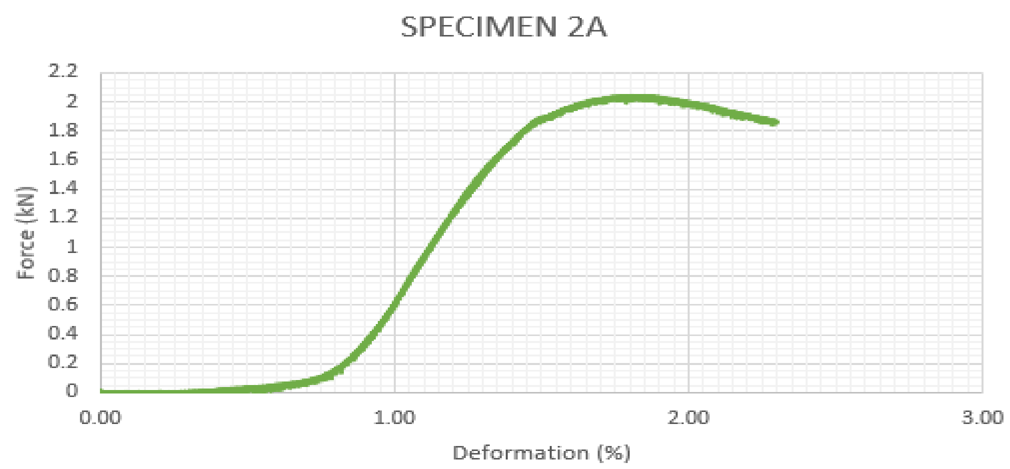


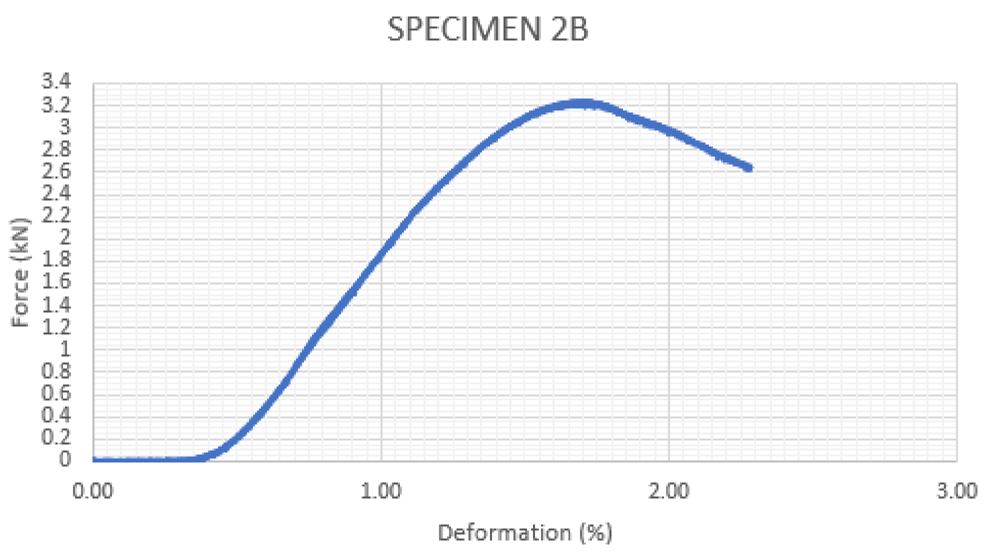


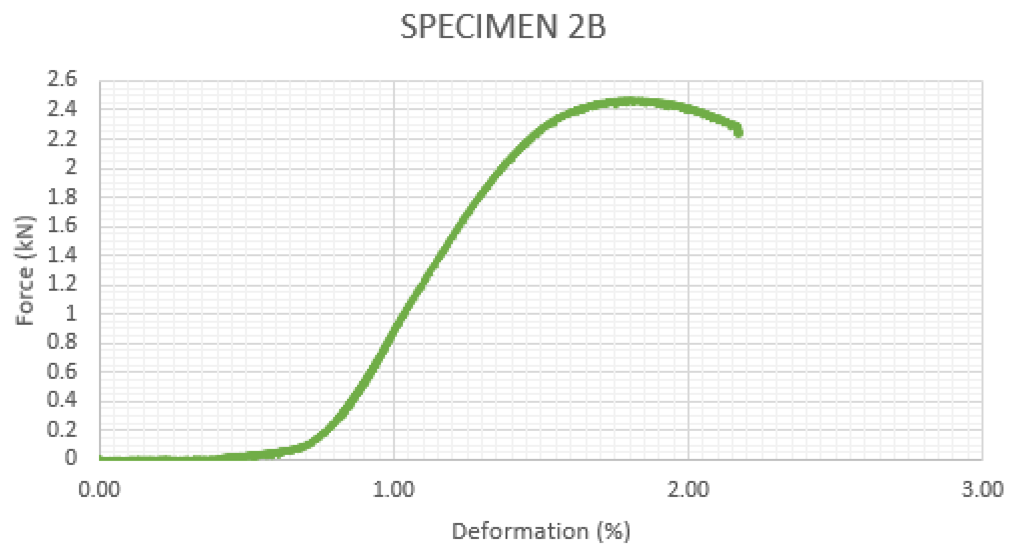


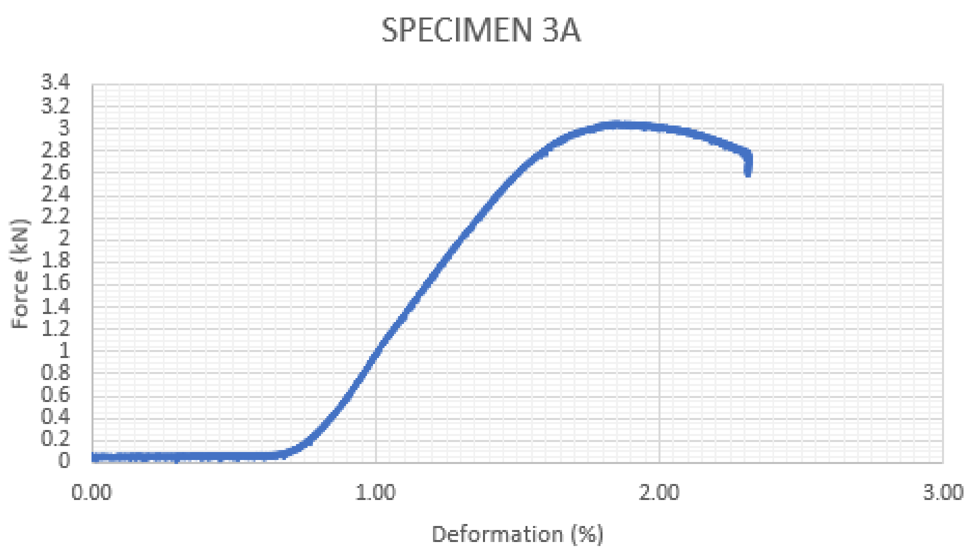


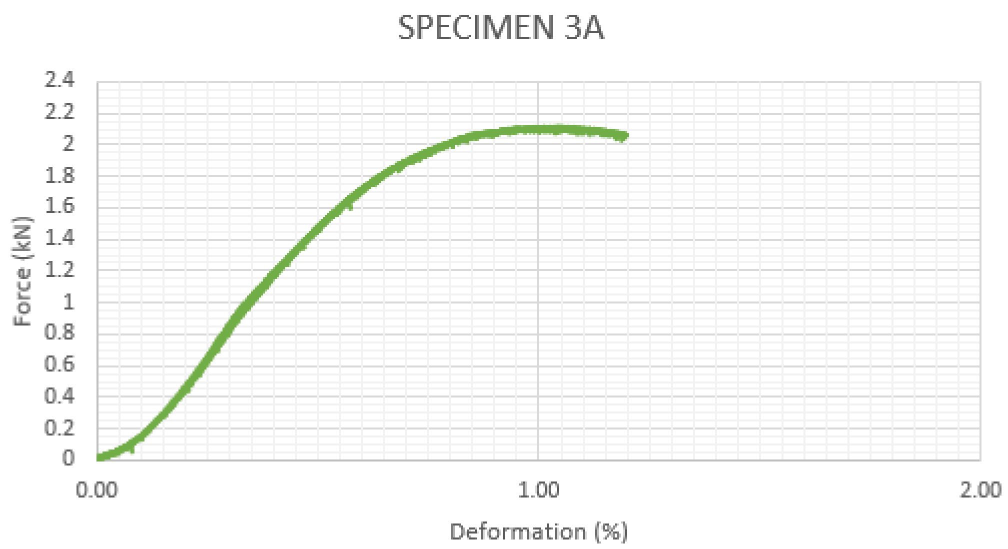


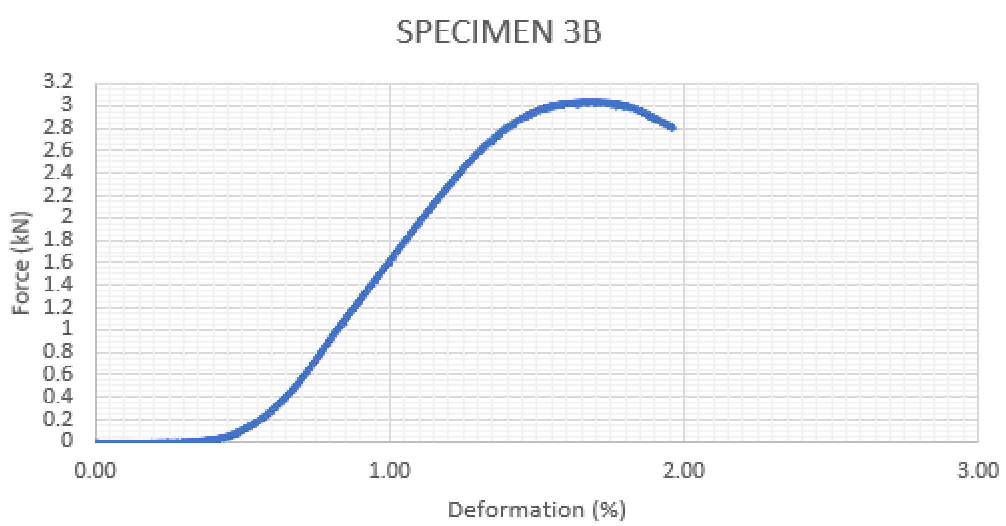



SPECIMEN 2B
Force (kN)
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
3.00
Deformation (%)


SPECIMEN 2B
Force (kN)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
3.00
Deformation (%)


SPECIMEN 3A
Force (kN)
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
3.00
Deformation (%)


SPECIMEN 3A
Force (kN)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
Deformation (%)


SPECIMEN 3B
Force (kN)
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
3.00
Deformation (%)


SPECIMEN 3B
Force (kN)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
1.00
2.00
Deformation (%)