Bentonite in two-component grout applications

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Bentonite in two-component grout applications

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ABSTRACT

Two-component grout is a cement-based material, currently the most used technology for backfilling in tunnelling applications. Despite its intensive, knowledge on this material is quite limited, especially as concern the role of ingredients and their effect on the properties of fresh mortar and hardened grout. In this work, an accurate and innovative test campaign focused on the role of the bentonite was performed. Three different bentonites were used. The activation of the bentonite and its effect on both mortar stability and grout strength was investigated with the purpose to recognise the bentonite parameters useful to select, at the design stage, the best bentonite according to the designers' requirements. Swell index and Atterberg's liquid limit were recognised as useful parameters for predicting results in terms of suitable bleeding and surface compression strength.

1. Introduction to the two-component grout

Shield machines are nowadays largely used in tunnelling applications. The use of these kinds of machines, irrespective of their excavation system (Earth Pressure Balance - EPB, slurry, variable-density) required special care for the backfilling phase. In fact, during the advancement, the annulus is physiologically generated because of the difference between the drilled diameter and the linings extrados diameter [1], as reported in Fig. 1. The annulus must be completely filled in order to lock linings in the designed position, to prevent water inflow inside the tunnel increasing the waterproofing [2–5], to bear successfully the back-up load of the machine and to embed completely the linings avoiding punctual loads [6]. Beside all, in the case of shallow tunnels, a proper back-filling phase prevents or at least minimises surface settlements [7,8] even if in some case a volume higher than the annulus is injected [9].

Currently, the most frequently used material for the backfilling in tunnelling application is the two-component grout that replaced the mono-component grout because of its better attitude in the surface settlements control at short terms [10]. In fact, considering that the mono-component grout is a mortar which required some hours before to start the hardening, the two-component grout achieves just in 1 h the mechanical performances obtained commonly after 1 day by other back-filling material [11]. Differently from the mono-component, the two-component grout technology is based on two fluids called component A and component B. These fluids are kept separated for all the path from the batching plant, located outside the tunnel, till the machine. Just few centimeters from the injection nozzles, (located circumferentially on the tail of the shield) components are mixed together [12] and the obtained mortar is injected into the annulus with a pressure that decaded. This phase occurs turbulently and the obtained material loses its fluidity in few seconds [13]. In this phase the gelation process occurs and the relative time-span is commonly defined as gel time. The gel time is the crucial parameter of the two-component backfilling technology, indeed, the perfect knowing of the gel time permits the achievement of

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a proper annulus filling. After the gelation process, the obtained material starts instantaneosly to increase its mechanical performances [14], reaching uniaxial compression strength (hereinafter UCS) values of 0.03–0.5 MPa, 0.4–1.7 MPa and 2–10 MPa respectively after 1, 3 and 24 h of curing, in function of the mix design [15]. As concerns the composition, the component A is usually made up of cement, bentonite, and retarding fluidifying agent (even if recently other ingredients such latent-hydraulic blast furnace slag are started to be tested, as discussed in [16–19]) while the component B is an accelerator admixture [11].

2. Role of ingredients and the issue of the bentonite

The properties that the component A must satisfy (workability up to 3 days from the batching, fluidity assessed by using the Marsh cone within certain value, controlled bleeding, constant unit weight), the gel time and the mechanical performance of the hardened grout at short (few hours from gelation) and long curing time are strictly function of the mix design (intended as types of ingredients and dosages).

Pertaining to the role of each ingredient in the two-component grout performances, Pellegrini and Perruzza [20] and Youn at al. [21] highlighted the importance of cement and accelerator dosages in the strength achievable at short and long term. Dal Negro et al. [22] explained the role of the retarding agent for guaranteeing the required workability. Exactly as for common cementitious mortar, the bentonite plays a key role in the stability of the component A (reducing the bleeding phenomenon) as put alight by Mesboua et al. [23]. Furthermore, Pelizza et al. [24,25] and Peila et al. [26] affirmed the involvement of the bentonite in the increasing of the waterproofing capacity of the hardened grout and in the gelation phase. More details were added by Dal Negro et al. [27] which stated that the right bentonite and its appropriate dosage facilitate bleeding control: the introduction of the differentiation between different kinds of bentonite is an innovation that must be highlighted in fact, for the first time, the potential issue of the right choice and the right dosage of a certain type of bentonite is introduced. A further proof of the importance of the bentonite in the two-component grout technology can be founded also in construction site applications, as reported in [28,29]. These researchers reported the experimental approach adopted for the choice of the best bentonite, compatible with their construction site needs, describing a comparison between common and high performance bentonite (using as comparison parameters less flaking during the mix, less bleeding and the lower viscosity). Unfortunately, no more details were provided i.e. no information concerning how to differentiate a high performance bentonite from a common one have been reported. As last note worth reference, a structured research concerning the influence of the kind of the bentonite and its dosage on the bleeding and the flowability can be found in [21]. This interesting work was based on three different bentonites, but, unfortunately, the only information on the types of bentonite concerns their dominant element (sodium) and the final addition of polymer to the chemical matrix. No bentonite parameters were introduced in order to forecast or estimate the magnitude of the bleeding or flowability variability.

The lack clearly spotted by analysing the information available in the scientific literature concerns the absence of specific investigations on the role of bentonite in other aspects of the two-component technology, apart from the bleeding phenomenon. Let us suppose that also after the gelation the two-component grout continues to be fluid (an enormously viscous fluid): in this way, the gelled material should continue to require the "stability" provided by the bentonite. Assuming the validity of this hypothesis, expressly at short curing time, some questions could be asked: could the bentonite be involved also in the strength performance of the grout at short curing times? Could grouts made with different bentonites exhibit different performance in terms of strength at short curing times? Could the activation modality of the bentonite affect the strength of the grout?

Furthermore, there is the need to find an engineering instrument i.e. a parameter, able to guide tunnelling engineers in the choice of the best bentonite for certain technical requirements, as for example the bleeding of the component A and the strength of the gelled grout.

In this work, three different commercial bentonites were considered. One mix design was established as valid for all the research

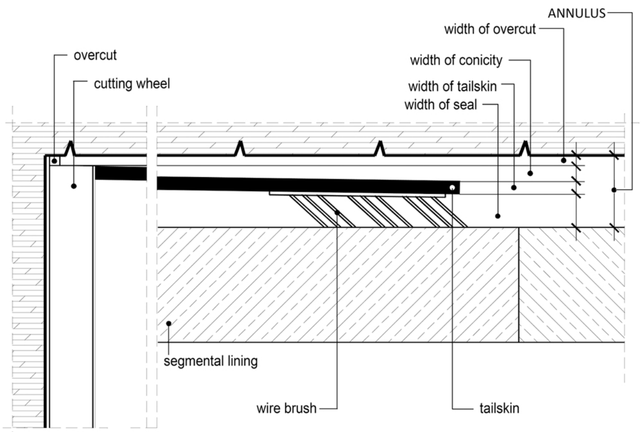

Fig. 1. Geometrical scheme of the annulus (modified from [1]).

and the procedure for the component A production was parametrically modified as concern the bentonite activation thereby the impact of the activation time on the component A parameters (bleeding, gel time and flowability) was assessed, according to the testing protocol described in [30]. Furthermore, the role of bentonite in the surface compression strength (SCS) was studied. As final step, the potential relation between swell index (hereinafter SWI) and Atterberg's liquid limits (hereinafter LL), the component A features and the SCS of hardened grout are highlighted and discussed.

3. Materials and component A production

The mix designed used for the component A production is reported in Table 1.

The sample production was performed in laboratory, according to [30]. The procedure adopted for the component A production (impeller rotation speeds and durations for each step) and the ingredients adding order is summarised in Table 2. The accelerator is a water solution of sodium silicate. It should be remarked that despite unneglectable differences between the construction site turbo-mixers (able to produce usually 1 – 2 m^3 of component A in a few minutes) and the used laboratory impeller (not more than 3 L with a needed time of 12 min), the studied component A can be considered significantly similar that one produced in construction site, as reported in [31].

Taking into account the second step, the word "activation" is a jargon expression, common for figures involved in engineering applications where bentonite is used. In these contexts, it indicates the process of hydration, which permits to bentonite particles to incorporate the water, increasing their volume. The activation of the bentonite can be obtained naturally, by leaving the bentonite in water and waiting long enough (the natural hydration of the bentonite and its use in the construction site of Bolaños-Campobecerros, NE-N High Speed Railway Line in Galicia-Spain, is described by [32]) or forcedly, by increasing the turbulence of the water–bentonite. This second modality has been chosen in this research. In Fig. 2 the used bentonites are showed, identified by numbers 1–3. Products have been provided powdered and dry, in the same condition as usually supplied to construction site. Bentonites number 1 and 3 are products expressly prepared for the two-component grout application and really adopted in construction site, while bentonite 2 is a natural bentonite composed by a percentage of smectite close to 98% (at the present never used for the two-component grout in tunnelling). The dominant element of all bentonites is Na.

4. Testing and procedures

In the following paragraphs, the complete structure of the work is reported. Due to the complexity of the research, it has been deemed useful to summarise the research path, whereupon each test and its related procedure are briefly explained.

4.1. Research path

Three different bentonites, were considered for the study. Bentonite 1 was used in a France construction site, while bentonite 3 was used for tunnelling construction sites in Italy. Unfortunately, no specific information related to bentonites 1 and 3 are available because the related construction sites are already completed. Bentonite 2, at the present time, was not used for two-component grout applications. One mix design was established as valid for all the research: the dosage and the commercial type of each ingredient (bentonite kind excluded) were kept equal for the whole test campaign. The procedure for the component A production reported in Table 2 was modified according to the research purpose: the phase related to the bentonite activation was parametrically changed in time duration. 0 min (no activation), 2, 4 and 7 min of bentonite activations were tested. Thereby, four different components A for each kind of bentonite were obtained and, consequently, four complete component A characterisation were performed for each bentonite. This first step of the research was developed in order to verify the impact of the activation time on the bentonite hydration and, consequently, on the component A parameters. The testing protocol foresaw determinations of bleeding and flowability, that are the most used tests for characterise the component A [30,33,34]. A second step concerned the production of two-component grout samples. After the assessment of the gel time (considered as the first test related to both components A-B and their interaction), casted samples were tested at the curing times of 1 and 3 h (short curing time). This second research phase aimed to highlight the role of bentonite in the SCS. Finally (third phase of the research), the SWI and LL were used for characterise the bentonites. A potential connection between results of first and second phases of the research and the kinds of used bentonites (characterised by certain values of SWI and LL) has been recognised and discussed. All the laboratory procedure have been performed at a fixed temperature equal to 23 ± 2 °C.

Table 1
Used mix design.

	Ingredients	Dosage (kg/m^3)
Component A	Water	853
	Bentonite	30
	Cement type I 52.5 R	230
	Retarding/fluidifying agent - Mapequick CBS1	3.5
Component B	Accelerator - Mapequick CBS3	81

Table 2
Laboratory procedure for the component A production.

Operation	Impeller rotation speed (rpm)	Duration (min)
Fill the tank with water and start the mixer	800	/
Add the bentonite, increasing the propeller	from 800 to 2000	0.5
speed at a constant rate (bentonite activation)	2000	6.5
Add the cement	2000	3
Add the retarding/fluidifying agent	2000	2

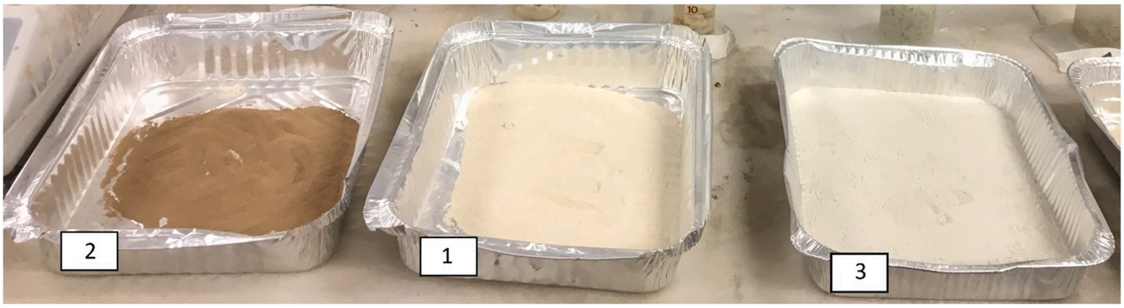

Fig. 2. Used bentonites.

4.2. Unit weight and flowability assessment

The assessment of the unit weigh and the flowability were performed on the fresh component A, namely within 3 min from the production. The unit weight was assessed by using a mud balance (Fig. 3, on the left). This test, easily performed both at the laboratory scale and in construction site, is a quick way for verifying the compliance of the produced component A with the technical document indeed big differences permit easily to recognise batching problems or metering mistakes. The flowability was assessed daily up to 72 h by using a Marsh cone (Fig. 3, on the right), according to [35]. This test permits to verify if the produced component A is workable, hence useful for the backfilling, after a certain time from the production.

4.3. Bleeding assessment

The bleeding test aims to assess the stability of the component A. Tests have been performed according to [35]. A graduated cylinder of 1 L of capacity is completely filled till the notch (Fig. 4, on the left), whereupon it is sealed for the all test long. The bleeding value is a percentage value computed as the ratio between the volume of the bleeding water V_w (Fig. 4, on the right) and the initial mortar volume (1000 mL) (1).

$$bleeding(\%) = \frac{V_w(mL)}{1000(mL)} * 100 \tag{1}$$

Longer is the curing time, higher is the bleeding. This test is fundamental for assessing the component A stability without mixing actions and, commonly, is the first test performed in laboratory for setting up a new two-component grout mix design. It can be stated that higher is the dosage of bentonite, lower is the bleeding [23].

4.4. Gel time assessment

The gel time is defined as the time lapse between the first contact between component A and component B and the loosing of the fluidity of the obtained mix. For the gel time assessment, currently a recognised standard is not available. Anyway, the procedure

Fig. 3. Mud balance (on the left) and the Marsh cone(on the right).
Pictures modified from [30].

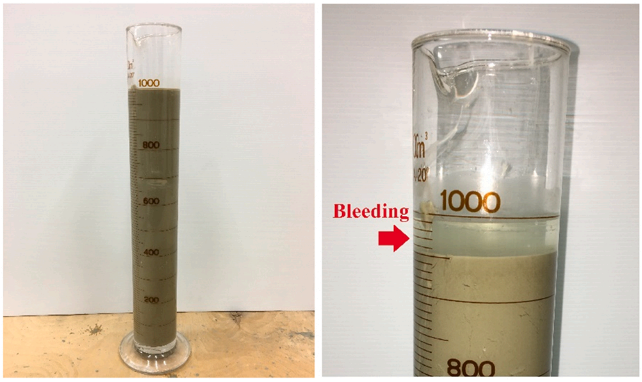

Fig. 4. Bleeding test. Before to start the curing (on the left) and test ending (on the right). The arrow indicates the bleeding water. Figures modified from [26].

described in [36] can be followed. Briefly, once the right quantities of both components has been weighted and put in two separated thanks (quantities are metered according to the reference mix design), the component A is poured in the component B (the time counter starts), the obtained mix is poured once again in the empty tank and so on till the grout is not more able to flow.

4.5. Sample production

Samples of two-component grout have been produced according to [37]. The used shape of 160 * 40 * 40 mm respects the standard regulation for mortars [38] (Fig. 5). It should be signalled that even if this standard regulation was born for standard mortar (that strongly differs from the two-component grout for the longer setting time, smaller water/cement ratio and also for the presence of aggregates), it is currently used also for the two-component grout.

In Fig. 5, the shaping phase of samples, performed after the casting, is depicted.

4.6. SCS assessment

The SCS assessment is a quick and simple test but of crucial importance, since it permits to roughly predict the UCS at short term (from 1 to 3 h of curing). Currently, it is widely adopted both at laboratory and construction site scale. Starting from [39], Todaro et al. [37] introduced some changes respect of the original standard for facing the not negligible differences between a standard mortar and the two-component grout. Without going into details on the processing factor able to convert SCS in UCS and vice-versa (further details can be found in [37]), in this context the testing procedure and the reference equation are reported. Samples casted according to EN 196–1 can be used, without demoulding them. Moulds have to be rigid (PVC, steel mould or anyway contrast support can be used for constrain displacements). The pocket dynamometer is equipped with a circular and flat bit (A_b = 177.9 mm^2) and placed perpendicularly to the sample casting surface (Fig. 6). The bit is pushed on the casting surface. Increasing pressure is applied. During the test, the peak force ($F_{p\text{-}pen}$) is recorded. Finally, by computing the ratio between the peak force ($F_{p\text{-}pen}$) expressed in N and the bit area (A_b) expressed in mm^2, it is possible to compute the SCS in MPa (2).

$$SCS(MPa) = \frac{F_{p-pen}(N)}{A_b(mm^2)} \tag{2}$$

Fig. 5. Shaping phase of two-component grout samples after the casting. Mould in compliance to [31].

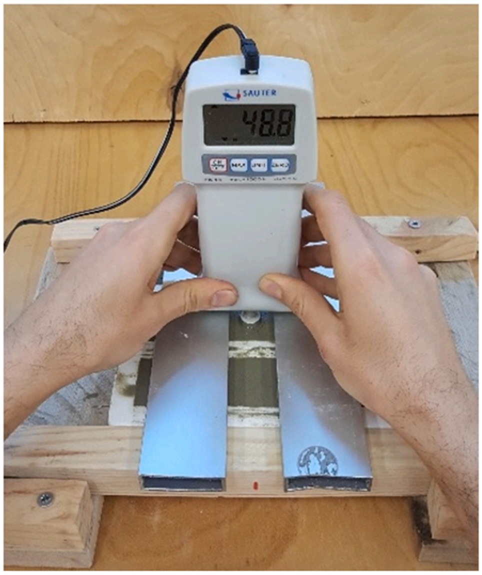

Fig. 6. Penetration phase performed by using the described pocket penetrometer. The depicted mould is made of polystyrene and the displacements are constrained with a wood block device [30].

4.7. SWI and LL

Swell index is assessed according to [40]. This test method permits the evaluation of the swelling properties of a clay mineral. Briefly, after a dried phase, 2 g of bentonite are added to 90 mL of distilled water with step of 0.1 g every 10 min. Once the bentonite adding phase is ended, the water is increased reaching 100 mL. After at least 16 h from the last adding of bentonite, the swell index is computed as the ratio between the swelled bentonite volume and the amount of 2 g, according to (3):

$$SWI = \frac{V(mL)}{2(g)} \tag{3}$$

Fig. 7 depicts the observed swelling phenomenon 20 h after the last bentonite addition (bentonite 1).

For the assessment of the liquid limit, [41] was taken as reference.

5. Results

The outcomes are presented in the following. In order to make the work clearer to readers, three different sections are presented. The first is dedicated to the data obtained concerning component A and the second is related to the SCS assessments. Finally, in the third section, the outcomes pertaining to SWI and LL are presented.

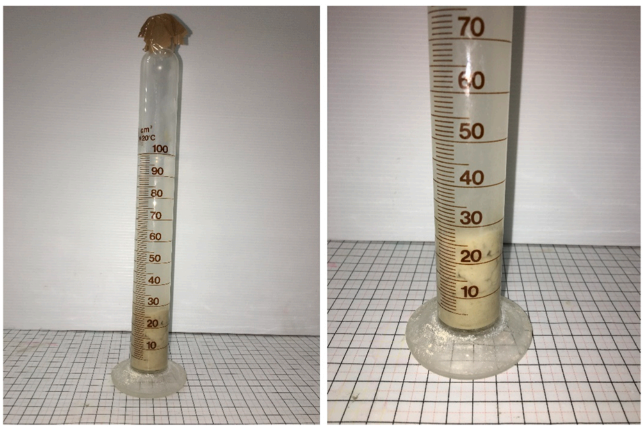

Fig. 7. Bentonite swelling phenomenon. Photo taken 20 h after the last bentonite increment. Bentonite 1.

5.1. Component A

Table 3 presents an overview of the outcomes concerning the characterisation of the different components A, in terms of flow time, gel time and unit weight. It should be noted that the flow time was assessed only on the fresh mortar. Fig. 8, Fig. 9 and Fig. 10 are charts related to the bleeding assessment respectively for bentonite 1, 2 and 3. In each chart, the four trends related to the different bentonite activation times are reported.

5.2. SCS as a function of the bentonite activation

Fig. 11 and Fig. 12 report the SCS result related to samples cured 1 and 3 h of curing respectively. Each type of bentonite used (1, 2 and 3) is characterised by four columns, one for each bentonite activation time (0 min, 2 min, 4 min and 7 min). Each value is the average of the measurements performed (at least 5 determinations) and the standard deviation of the assessed SCS values is lower than 0.1 MPa.

5.3. SWI and LL

The obtained data pertaining to the SWI assessment and Atterberg's liquid limits are summarised in Table 4. Measurements of SWI were carried out 20 h after the last addition of bentonites in the cylinders. In Table 4, w (%) indicates the natural water content of the material as provided by the suppliers.

6. Comments on results

6.1. Component A

Before proceeding with discussion of the outcomes it should be signalled that, taking into account the flowability and the gel time assessments, a fluctuation of ± 1 s is not meaningful if all the determinations have been performed by the same operator. Similarly, if different operators have performed tests due to unforeseeable circumstances, a larger fluctuation, equal to ± 2 s, should likewise not be considered meaningful. This second scenario reflects the real working conditions of tests that are going to be discussed. Taking into account Table 3, the first parameter considered is the gel time. The component A produced with the bentonite 3 unequivocally exhibits a gel time independent of the bentonite activation time, with a value equal to 6 s for each determination. A constant trend can be identified also in the case of bentonite 1, with a measurement range of 2 s.

The component A manufactured using bentonite 2 exhibits more scattered measurements. The fluctuation range is equal to 3 s and the gel time seems to decrease from 7 s to 5 s and eventually settles close to 8 s as a function of the increasing activation time. This set of data is plainly not accurate because, in the author's experience, the gel time trend can be managed only by changing the mutual volume percentage between components A and B; also, an inversion of the gel time as a function only of a change of the bentonite activation time makes no sense. It can consequently be speculated that slight weighing errors were made when preparing the amounts of components. In conclusion, also the gel time trend for the component A produced with the bentonite 2 can be deemed constant, with an average value of 7 s.

From another point of view, by considering each bentonite activation time individually, it can be observed that all the measurement ranges (max value – min value) are between 1 s and 2 s (Table 5). This result highlights that the component A exhibits the same gel time, independently of the kind of bentonite used. Consequently it can be stated that bentonite is not involved in the reaction of gelation.

Taking into account the unit weight assessment, independently of the bentonite used and of the activation time, a constant specific weight of 1.17–1.19 kg/L was observed. It can be consequently affirmed that the density was very stable, as preliminary supposed, having all bentonites approximately the same unit weight. Furthermore, a fluctuation of 0.02–0.03 kg/L by using the mud balance is intrinsic of the assessment.

As concerns the flow time assessed on the fresh mortar, it was not possible to recognise a unique trend for the three bentonites as a

Table 3
Outcomes concerning the components A characterisation.

		Bentonite activation time (min)			
		0	2	4	7
Bentonite 1	Flow time (s)	27	30	34	35
	Gel time (s)	6	7	7	8
	Unit weight (kg/L)	1.17	1.18	1.18	1.18
Bentonite 2	Flow time (s)	29	30	32	31
	Gel time (s)	7	6	5	8
	Unit weight (kg/L)	1.19	1.17	1.17	1.17
Bentonite 3	Flow time (s)	33	36	36	35
	Gel time (s)	6	6	6	6
	Unit weight (kg/L)	1.17	1.16	1.17	1.17

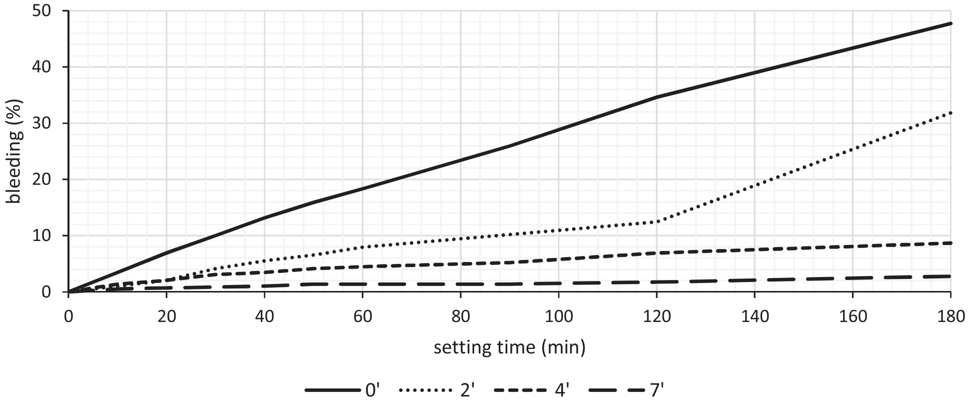

Fig. 8. Bleeding outcomes concerning the bentonite 1. Different activation times.

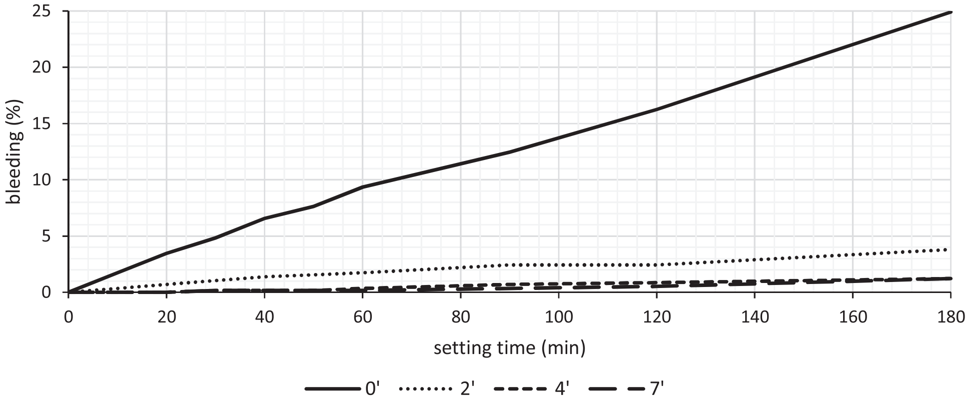

Fig. 9. Bleeding outcomes concerning the bentonite 2. Different activation times.

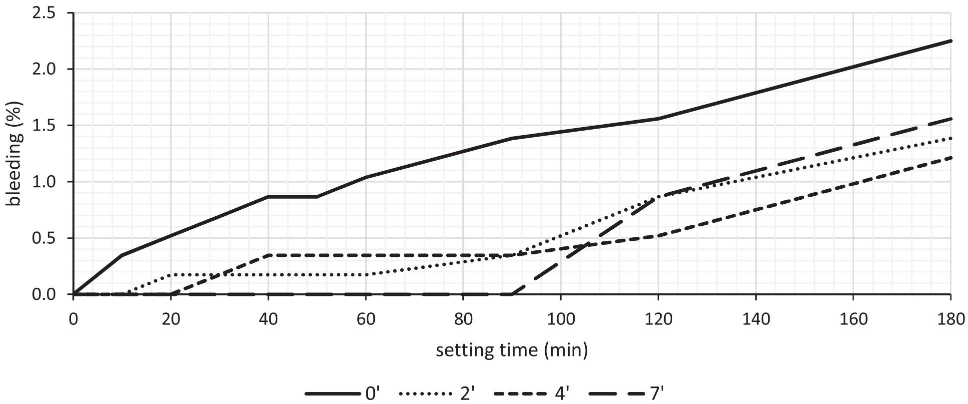

Fig. 10. Bleeding outcomes concerning the bentonite 3. Different activation times.

function of the activation time, although a general growing tendency could be identified. The component A produced with bentonite 1 showed a clearly and regularly rising trend: from 27 s for 0 min of activation to 35 s for 7 min. Also the component A manufactured with bentonite 3 exhibited a growing trend, although there was a step of 3 s between 0 min and 2 min, after which the flow time was closely aligned with values of 35–36 s. Also concerning the component A produced with bentonite 2, a slight increase of the flow time could be observed.

The parameter markedly influenced by the bentonite activation time is bleeding (Fig. 8, Fig. 9 and Fig. 10). The first interesting aspect that can be pointed out concerns the strong bleeding reduction that can be obtained by increasing the activation time, irrespective of the considered bentonite. As example to better highlight the phenomenon, Table 6 reports for each bentonite the proper

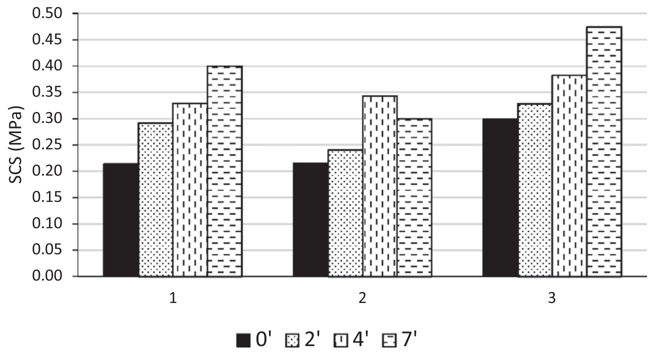

Fig. 11. SCS after 1 h of curing pertaining to the studied bentonites. Different activation times.

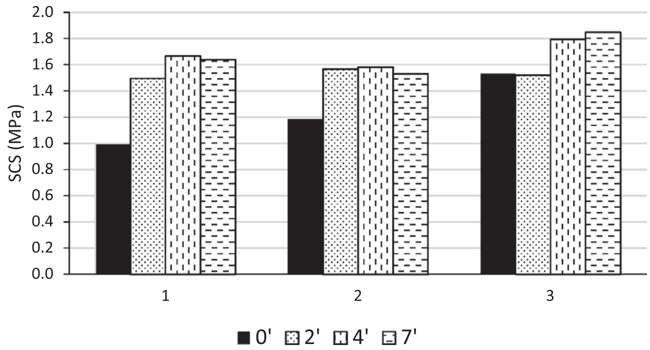

Fig. 12. SCS after 3 h of curing pertaining to the studied bentonites. Different activation times.

Table 4
Outcomes related to the swell index test campaign.

Bentonite	w (%)	SWI (mL/2 g)	LL (%)
1	10.73	14	427
2	12.65	13	525
3	10.98	23	445

Table 5
Range of gel time measurements for the four bentonite activation times.

Bentonite activation time (min)	Min value (s)	Max value (s)	Range (s)
0	6	7	1
2	6	7	1
4	5	7	2
7	6	8	2

Table 6
Decrement in percentage of the bleeding value computed between 0 min and 7 min of bentonite time activation. Assessment performed after 3 h of setting.

	Setting time = 3 h		
Bentonite	Bleeding value with 0 min of bentonite activation (%)	Bleeding value with 7 min of bentonite activation (%)	Δ (%)
1	47.75	2.77	94.2
2	25.00	1.20	95.2
3	2.25	1.50	33.3

bleeding values assessed without activation and with 7 min of activation. 3 h of setting was selected as the reference value for the comparison.

Components A produced with bentonites 1 and 2 exhibit a reduction of bleeding close to 95%, while bentonite 3 shows a lower percentage reduction, close to 33%.

In order to compare the used bentonites, the limit bleeding value (b_L) equal to 1.5% is considered. This value corresponds on average to the bleeding exhibited by component A, which is used in practice on construction sites, after 3 h of setting [15]. The component A produced with bentonite 1 (Fig. 8) exhibits the highest bleeding values between the studied cases. The value close to 50% for the inactivated bentonite is the highest of all the test campaigns. There is a bleeding reduction as a function of the increasing of the activation time, but on no occasion were bleeding values lower than b_L reached. Concerning the component A manufactured with bentonite 2 (Fig. 9), the value close to 25% obtained without activation is strongly reduced to less than 5% by activating the bentonite for just 2 min. Furthermore, bentonite activated for 4 min and 7 min exhibits a bleeding value lower than b_L. The component A produced with bentonite 3 (Fig. 10) is the most stable. Without activation, a bleeding slightly higher than 2% is reached. Furthermore, by activating the bentonite (2 min, 4 min or 7 min) bleeding values smaller than b_L are reached.

6.2. SCS as a function of the bentonite activation

The role played by the bentonite in the strength of the two-component grout in the first hours after casting has opened a new line of research that is potentially able to increase the importance of the bentonite in the two-component grout applications. Considering the outcomes depicted in Fig. 11, the increasing of the SCS as a function of a longer bentonite activation time is plainly represented, independently of the type of bentonite. In Table 7, the computed increment of SCS (%) between 0 min and 7 min of activation is reported.

However, a trend inversion can be seen for bentonite 2: the forecast SCS value for an activation time of 7 min was higher than the previous activation times but the results did not confirm expectations. This inconsistency should be ascribed to mismanagement of the sample casting phase. From a general comparison, the two-component grout produced with bentonite 3 exhibits the highest SCS values, while bentonite 1 is found to be the most sensitive to the activation process (almost doubling the SCS from 0 to 7 min of activation).

Taking into account data reported in Fig. 12 for 3 h of curing time, the increasing of the SCS as a function of longer bentonite activation times is not regular as in the case of 1 h of curing and, furthermore, the magnitude of the phenomenon is more moderate. Table 8 reports the computed increment of SCS (%) between 0 min and 7 min of activation.

For bentonites 1 and 2, activating the bentonite for 2 min, 4 min, or 7 min led to SCS values close to 1.6 MPa.

A different trend can be seen for bentonite 3: two different SCS values can be identified. For this bentonite, a negligible difference is recognised between not activating the bentonite and with an activation time of 2 min, while a marked rise in the SCS occurs for the activation time of 4 min (a step of 0.2 MPa), with a final SCS close to 1.8 MPa. As in the case of 1 h of curing, bentonite 3 exhibits the highest SCS value, with 1.85 MPa obtained with 7 min of bentonite activation time. Again confirming the data for 1 h, bentonite 1 has the greatest sensitivity to the activation time.

6.3. SWI and LL

The swell index test campaign indicated that all the determinations were performed on material originally characterised by a very similar moisture content (10–13%). Bentonites 1 and 2 exhibited very similar values, exactly 14 and 13 respectively. Bentonite 3, instead, was characterised by a markedly different value of SWI, 10 points higher than the other ones. Pertaining to LL, the test campaign to assess the liquid limits highlighted very high values, over 400% for all bentonites. Specifically, bentonite 2 exhibited the highest value while the lowest value was for bentonite 1.

7. Final remarks

From the analysis of the component A, it can be summarised that by modifying the bentonite activation time no marked variations of unit weight and gelling time can be observed. The flowability could increase, so it is always advised to verify the flow time experimentally. Undoubtedly, the parameter most strongly linked to the bentonite activation is bleeding. By increasing the activation time, without changing the mix design or the kind of bentonite, better results in term of bleeding, i.e. stability, can be obtained for the component A. Similarly, taking into account the SCS, benefits can be obtained by increasing the activation time even if, the growing trend is more evident at 1 h of curing that is the crucial curing time in the full-face mechanised excavation.

According to the results obtained, it can be clarified that, for a fixed mix design (fixed dosages), the kind of bentonite does not play a key role in the gelling time and unit weight. Taking into account the swell index and considering the original procedure for the component A production (i.e. 7 min of bentonite activation), it is possible to assert that high values of SWI correspond to high SCS. In the specific case of bentonite 3, characterised by the highest SWI, the test campaign carried out on the two-component grout samples provided the highest values of SCS at both 1 and 3 h of curing. A more complex scenario was observed for the bleeding phenomenon. Although also for this aspect the bentonite with the highest SWI was confirmed as the best performing (also with a null activation time the bleeding for the mortar produced with bentonite 3 was lower than 2.5%), the mortar manufactured by using bentonite 2 also exhibited a bleeding value lower than b_L, by just applying a medium (4′) activation time of the bentonite. Considering that the SWI of bentonite 2 is substantially equal to that of bentonite 1 and that the respective bleeding performances are markedly different, it is

Table 7
SCS increment between 0 min and 7 min of bentonite activation concerning two-component grouts produced with different bentonites. 1 h of curing.

Curing time = 1 h	
Bentonite	Δ (%)
1	87
2	40
3	59

Table 8
SCS increment between 0 min and 7 min of bentonite activation concerning two-component grouts produced with different bentonites. 3 h of curing.

Curing time = 3 h	
Bentonite type	Δ (%)
1	64
2	29
3	21

evident that another bentonite-dependent parameter should be taken into account: the Atterberg's liquid limit. Indeed, considering that bentonite 2 has a higher liquid limit than bentonite 1, it can be stated that a higher liquid limit leads to a lower value of bleeding, for a certain constant testing procedure and for an equal value of SWI. Hence, concerning the bleeding, the limit liquid should also be considered in addition to the SWI.

To conclude, a high value of SWI is a necessary but not sufficient condition for choosing a suitable bentonite, from both the strength and bleeding points of view. A high SWI corresponds to a high level of SCS, but if different bentonites exhibit the same SWI, the assessment of the liquid limit can determine the choice of the better bentonite also from the bleeding point of view. In Fig. 13, a flow chart reports the steps for the choice of the most suitable bentonite for a two-component grout application.

In any case, at least two bentonites should be selected at the end of the path reported in Fig. 13. In conclusion, it is strongly advised to perform a complete laboratory test campaign similar to the one described in this paper, aiming to verify the SCS and bleeding for choosing the best bentonite for certain technical provisions.

Finally, a reflection on the economic aspect is of value. Different types of bentonites are available on the market and the cost range for this product is wide. Concerning the two-component backfilling applications, once the grout targets have been established, it should be considered that a bentonite with a high SWI may satisfactorily fulfil the requirements of bleeding with a lower dosage than a bentonite with a lower SWI. Consequently, as suggested by Ivantchev & Del Rio [28], an expressly scheduled test campaign should always be performed at the construction site, in order to verify the influence of the bentonite on the two-component grout, to optimise the batching station and to verify the behaviour of the bentonite also at the real scale. Furthermore, staying in the construction site field, a last aspect should be discussed: if a bentonite with a suitable SWI value has been chosen, the possibility of obtaining good performance in terms of bleeding and SCS also without a complete activation process of the bentonite is an interesting option that could be of paramount importance in the critical case of an immediate demand for component A over the mean. In this case, also reducing or completely cutting the bentonite activation time during the component A production, the manufactured product might still ensure the minimal required parameters for a satisfactory backfilling operation. On the other hand, if a certain bentonite does not satisfy the construction site requirement for minimal fluctuations of values, engineers should know that, by increasing the duration of the activation phase, there is room for improvement of both the SCS and the bleeding, maybe enough to satisfy the provisions.

8. Conclusions

This research was performed with the aim to understand the role of the bentonite in the two-component grout application. The literature review highlighted the involvement of the bentonite in the stabilisation of the mortar suspension, controlling and minimising the bleeding phenomenon. In this work, simple test put alight that bentonite has a crucial importance in the two-component grout technology and influences the behaviour of both the component A and the hardened grout, even if not all bentonites are similar. The role of bentonite in the stabilisation of the component A and its effect on reducing the bleeding were plainly confirmed even if, the effect of the activation time cannot be neglected. According to the authors' knowledge, this work is the first one that put alight the bentonite role in the two-component grout strength at short curing time and this innovation will raise the importance of the selection phase of raw ingredients for the backfilling operation. Considering that short curing time (from the casting to 3 h of curing) is the time lap commonly most studied in mechanised tunnelling (all construction site testing protocols require strength testing at this curing time), the selection of the best bentonite could optimise the backfilling performance. According to the present work, swell index and

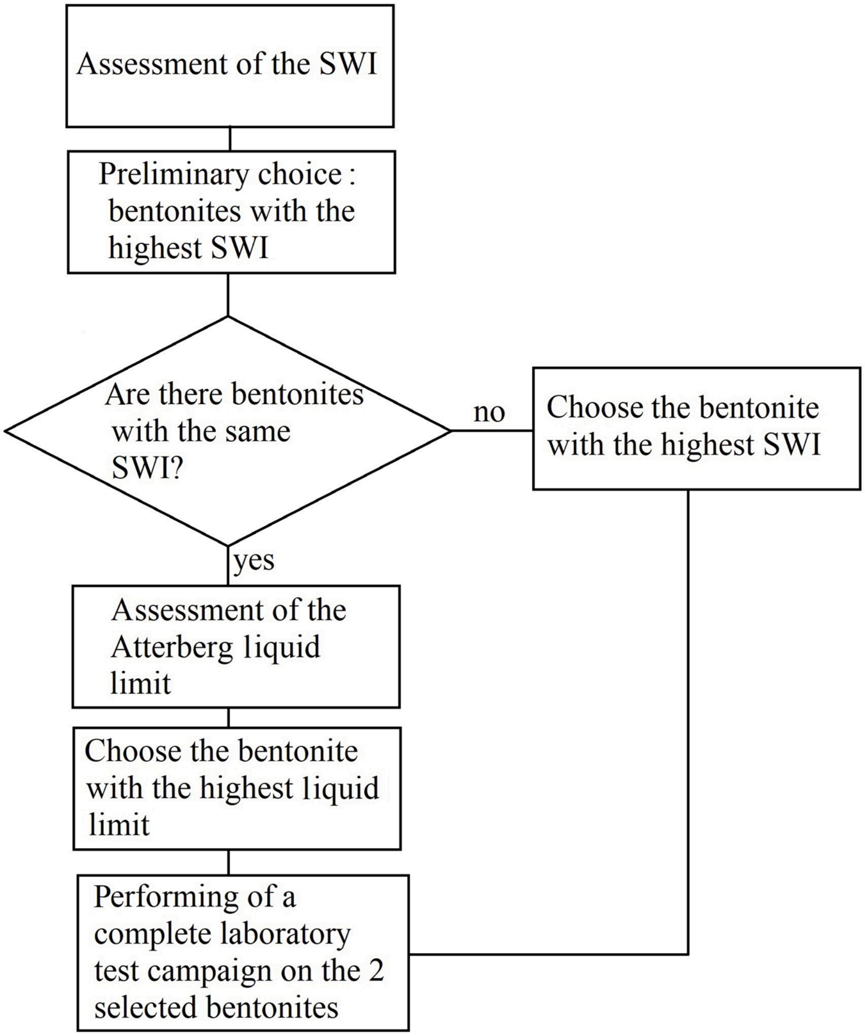

Fig. 13. Flow chart for the choice of the most suitable bentonite for a two-component grout application.

Atterberg's liquid limit are useful test that can be used for preliminary select the best bentonites for a certain two-component grout application. It should be reported that more specific analysis on bentonites (i.e. mineralogical analysis or chemical ones) could undoubtedly help for the final selection but are not common for the tunnelling world. Usually, the only available information concerning bentonites is that one provided by suppliers but not always this information is directly linked to the real performance potentially obtained on the site. This uncertainty is due to the unicity of each construction site, in fact, its peculiarities (concrete, water, chemicals, machine equipment, batching station) undoubtedly can affect the final performance of certain bentonite.

In conclusion, it has been decided to base the work by selecting two base test (SWI ad LL) that can be simply performed at the construction site scale.

Finally, it is due to report that no comparison studies are available in scientific literature, consequently, the continuation of the experimental tests is very important. It should be signalled that further investigations on other types of bentonites should be performed. Both natural bentonite or "expressly prepared for the two-component grout" ones should be tested, in order to highlight the pros and cons of each type. However, at the present time and according to this study, only the reproduction of the proposed test path could lead to the proper selection of the bentonite in the two-component grout applications.

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