Performance requirements for two-component backfilling grout in recent mechanized tunnelling practice

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Abstract in English (max 400 parole)

The technological evolution and the increasing complexity of today's tunnel projects, together with the versatility of two-component grouts, that have proven to be an effective design solution in rather unexplored contexts, as for instance tunnels in rock or in particularly severe hydraulic conditions, led to a general tightening of the design requirements for these materials. Moreover, the increasing attention to the environmental impact of civil works encouraged research activities on durability and carbon footprint of the backfill grout and on its interaction with the surrounding environment, particularly in the case of works carried out below the water table or in lake/marine environments.

GEEG, startup of Sapienza, has been engaged for the last four years in research activities aimed at analyzing the relationships between the design mix and the characteristics of the backfilling grout, with the goal of defining for each specific project a mix design that ensures optimal performance in terms of mechanical properties, durability and environmental compatibility.

This paper describes recent trends towards which the research on two-component backfilling grout has been heading in recent years and discusses some experiences that posed challenging issues due to particular design performance requirements, which also needed innovative experimental equipment and research protocols. Several of these research activities were promoted and carried out in collaboration with WEBUILD Group. This overview is aimed at promoting a more research-oriented approach to the design of two-component backfill grout, which still has great potential for development.

Abstract in French (max 400 parole)

L'injection de back-filling grout joue un rôle décisif lors de l'excavation mécanisée de tunnels et, au fil du temps, les coulis bi-composants se sont révélés être une solution efficace et polyvalente dans différents contextes même les plus inattendus (par exemple en présences de roches ou de conditions hydrauliques particulièrement difficiles). L'évolution technologique et la complexité croissante des projets de tunnel conduisent aujourd'hui à ne plus pouvoir se contenter de matériaux aux performances de base, mais à exiger une conception minutieuse et spécifique afin d'obtenir des performances de plus en plus élevées. En outre, l'attention croissante portée à l'interaction des opérations d'excavation avec le milieu environnant a conduit à la nécessité d'assurer à ces matériaux une grande durabilité dans le temps et des rejets et interactions limités, en particulier dans le cas de travaux réalisés sous nappe phréatique ou dans un environnement lacustre/marin.

Webuild et GEEG, une start-up de l'Université « La Sapienza » à Rome, sont engagés depuis des années dans des activités de recherche visant à analyser les relations entre la formulation du mélange et les caractéristiques du coulis remplissage afin de proposer des solutions spécifiques pour les projets. L'objectif est d'obtenir une formule spécifiquement conçue pour garantir les meilleures performances en termes de propriétés mécaniques, de durabilité et de prestations environnementales.

Le présent document présente les résultats d'une série d'activités de recherche expérimentale développée ces dernières années et visant à identifier des formules spécifiques de coulis bi-composants. L'article traite aussi des expériences acquises, y compris les échecs de formulations spécifiques, qui ont permis d'établir de développer des équipements expérimentaux novateurs et de nouveaux protocoles de recherche.

Cette vue d'ensemble vise à promouvoir le potentiel des coulis de remplissage bi-composants et la nécessité d'une analyse et d'une conception minutieuses des formules pour garantir une performance adéquate, même dans des contextes et des situations non ordinaires.

1. Introduction

Filling the annular gap behind the precast concrete lining is an extremely important operation in tunnelling with TBMs. Over the last fifteen years, the two-component grout system experienced a great success and diffusion, as highlighted by the numerous studies on properties and testing procedures of this material published by several researchers, among which Thewes and Budach (2009), Pelizza et al. (2010), Antunes (2012), Youn and Breitenbücher (2014), Peila et al. (2015), Mähner and Hausmann (2017), that all contributed to build a scientific approach to an issue that previously was rather left to the jobsite practice. Aiming at standardizing targets and procedures for the backfill grout, very recently Todaro et al. (2022) collected a series of case histories and analyzed the performance requirements from completed tunnel projects worldwide.

Testing procedures and performance requirements are indeed a lively and current topic, because together with the advances in tunnelling technology, the specifications demanded from the backfill grout are rapidly shifting towards more challenging goals, promoting specific research activities and development of innovative mix designs.

This article provides an overview of the trends towards which the research on two-component backfilling grout has been heading in recent years and briefly reports, for each topic, some experimental results, hoping to offer some key elements for understanding the potential and limitations of the two-components back-filling materials and contribute to inspire future studies. This work is based on the experience of the authors with ongoing tunnel projects in Australia, Canada, Norway and Italy and is aimed at the promotion of a more design-conscious use of this technological solution in TBM tunnelling worldwide.

2. The role of the back-filling grout

In the mechanized excavation of tunnels with Tunnel Boring Machines (TBM), the filling of the annular gap that is created between the cut diameter and the extrados of the lining segments plays an important role.

The main function of the backfill grout is to avoid settlements at the ground surface and assure a good embedment of the lining. The backfill can be made with different grout mixtures, active or inert [7], suitable for different backfilling systems. In fact, grouting can be made through ports in the segment lining, leaving the void unfilled for a certain amount of time, thus allowing some settlements, or through the tailskin, providing immediate contrast to the settlements in exchange for a higher risk of tubes clogging [4]. Two-component grouts were developed to avoid this risk and achieve good pumpability and workability as well as a quick setting, all necessary features when excavating with TBMs in soft grounds, which require a continuous filling of the annular gap as the machine advances.

Two-component mixtures consist of two fluids: a component A (cement, bentonite, water and a retarding agent) and a component B (accelerator, usually sodium silicate), which together are able to produce a gel within seconds from the moment they are combined, i.e. the injection. Being conceived as a sort of extension of the ground surrounding the tunnel, these mortars are not designed to achieve high strength and stiffness values [9], but, if compared to one-component mortars, they provide an early strength capable of counteracting possible movements or misalignments of the rings and washouts by the groundwater. These mortars must achieve certain requirements in terms of pumpability, workability, setting time and mechanical properties that may vary from jobsite to jobsite, depending on the TBM injection plant and the specific needs of each project, but, beyond what mentioned above, they have several advantages with respect to single-component mixtures, such as easier batching, transportation and maintenance [4].

3. The evolution of the requirements for two-component back-filling grout

Until a few years ago these mixtures were mainly used in soft grounds, thus in most tunnel projects the technical specifications for two-component backfill grouts were tied to minimum requirements on the properties of the component A, to ensure pumpability, stability and workability of the fresh mixture, on the gelling time and on the early strength, while the requirements on the hardened grout were usually limited to a threshold UCS value at 28 days.

Together with the technological progress that has led to the use of TBMs in increasingly complex geological contexts, the boundaries of two-component grout applications are rapidly expanding to tunnels in rock or under significant lithostatic and hydraulic loads, making these mixtures the backfill material of choice in most projects, also thanks to their many operational advantages.

New applications go hand-in-hand with more challenging requirements and an increasing focus on the performances of two-component grout. The latter are currently being dealt with by several research studies aimed at developing specific and innovative mix designs. The following section summarizes the main grout characteristics undergoing a significant change, promoted by designers as well as contractors.

3.1. Mechanical performance

The strength of two-component grouts is often in the range between 0.1 to 0.3 MPa at 1 hour and between 1 to 3 MPa at 28 days [10]. Tunneling in hard rock and under high hydraulic loads is leading to a progressive demand for higher compressive strengths, that went from values of UCS at 28 days greater than 5 MPa, requested for the Follo Line in Oslo [8], to over 20 MPa for the inclined pressure shaft of the Snowy 2.0 project [17]. The same case histories are first examples of specifications on the elastic modulus E, that had to be more than 100 MPa at 28 days and more than 5 GPa, respectively for the two tunnels. Such a marked variation in performance required a substantial change in the mix design and the replacement of some components (i.e. bentonite) or the introduction of others (i.e. filler), which are meant to impart "structure", decreasing the liquid/solid ratio of the mixtures.

As design specification started to include strict limitations regarding the stiffness of the material, such measurements began to be performed on a regular basis, rising questions about the proper standards for testing two-component grouts, as already pointed out by Pelizza et al. in 2010 and Antunes in 2012 regarding other important parameters as the gel time and the early strength.

Furthermore, following the development of modern numerical models, capable of capturing the interaction between lining and soil/rock mass, strength and stiffness of the backfilling grout are being often included in the analyses and verifications of the tunnels, becoming *de facto* design parameters, with clear consequences on the advance in laboratory testing and research on the behavior of the support system composed by backfilling and lining [5].

In some instances, where high deformations and convergences may be expected, the research is focusing not so much on achieving particularly high performances, but on the production of a deformable grout, able to reduce the loads transferred on the lining, as already stated by Thewes and Budach [7]. One way to obtain this desired behavior may be the introduction of aerating additives in the design mix to generate air bubbles, which would collapse under certain stress states allowing deformations in the material. The crushed material in its final configuration, due to the reduced porosity, could provide better strength and stiffness than the initial undisturbed grout with its honeycomb structure.

3.2. Durability

The long-term behavior of the two-component grout under site conditions is rarely dealt with by research studies. Standard investigations for assessing the durability of concrete and single-component mortars when exposed to aggressive environments involve a series of tests that cannot be applied to two-component grouts, due to procedures that require oven drying. In fact, as whoever works with two-component grout knows, these materials can suffer serious degradation when exposed to air. It is therefore quite clear that standard practices cannot be applied to two-component grouts.

Under usual operating conditions, i.e. underground and below the water table, the exposure to air should not be an issue, in fact the available case histories [11] show that the two-component grout of real tunnels was found intact after years from the injection; however, when tunnelling in a permeable ground or a fractured rock mass, or where oscillations of the water table must be expected, this aspect should be further investigated.

Information on the temperatures recorded at the jobsite (especially for shallow tunnels) and on the chemical profile of the groundwater that will come in contact with the grout may guide the selection of particular curing conditions to which subject the samples before mechanical tests, in order to assess the effect of the temperature on the development of strength, as well as the influence of acid or salty water.

In applications where two-component grout has never been considered before as backfilling material, as hydraulic pressure tunnels repeatedly subjected to variations of pressure, of which Snowy 2.0 project represent the first example, the concept of durability can be also viewed as resistance against fatigue.

Protecting the integrity of the backfill in the long-term is also a step forward in terms of sustainability, safety and cost-efficiency of a tunnel; investments in research activities on the durability and on site verification of the backfill grout would improve the quality of all the support system made by lining and backfilling, and would enhance the overall technological progress.

3.3. Environmental impact

Regulating emissions to prevent the global average temperature from rising and ensuring sustainable consumption and production patterns are Sustainable Development Goals (SDG) of the 2030 Agenda, set up in 2015 by the United Nations General Assembly. After this turning point many national governments took action with initiatives and laws to improve sustainability and to reach carbon neutrality, as done by the European Commission in 2019 with the Green Deal. The concrete industry and particularly the cement production, responsible for about 5% of the total global carbon dioxide emissions, are strongly involved in this process. The European Cement Association individuated three main approaches to reduce emissions: adopting alternative fuels and high efficiency kilns; using low-clinker cements, innovative binders and innovative concrete solutions; developing carbon capture and storage/use technologies.

Driven by an impulse that has pervaded the entire sector, the study of the environmental impact of backfilling mortars is experiencing growing interest from the scientific community, while the new instruments for assessing sustainability, resiliency, and equity in civil works (Envision, LEED and others) are inviting designers and contractors to research on green solutions, for instance mix designs with low carbon footprint.

However, the environmental impact of two-component mortars is not represented solely by the embodied carbon but includes also the interaction between the grout and the surrounding environment. In detail, the presence of the sodium silicate used as accelerator, together with the cement hydration reactions, locally alter the pH and the chemical profile of the groundwater, a fact that may assume particular importance for tunnel projects crossing protected areas.

4. Experimental results

On par with the increasing technical complexity of modern day's tunnel projects, research activities carried out to provide design teams with innovative solutions have become increasingly complex, together with the studies on two-component grout. The following section will briefly describe some experiences made by the authors conducting different research activities dealing with the topics described above, faced rather frequently in the last few years.

To perform these studies, a dedicated testing equipment was set up to:

- simulate the mixing of the 2 components with the geometry/flow/pressure of the TBM two-components back-filling injection plant;
- perform tests on both fresh and hardened grout;
- develop small-scale and meso-scale studies;
- accurately control the curing conditions of the samples over time;
- perform mechanical, chemical and environmental tests.

The objective of this broad overview is to present some promising outcomes of innovative studies on two-component grouts, while showing how research activities had to be adapted to provide reliable information to support the design process.

4.1. Mechanical performance

As of today, the most demanding project in terms of performance requirements for the backfill is certainly Snowy 2.0, which started a still ongoing research activity that pushed the potential of two-component technology to its limits.

Table 1 reports the dosages of a reference two-component grout that reaches a uniaxial compressive strength (UCS) of about 1.5 MPa at 28 days, together with those of a mix designed to obtain high-performances.

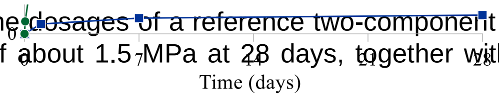

Figure 1 shows UCS values at different curing times. As it can be seen, a very significant increase of the mechanical properties was achieved using a cement/slag binder, limiting the bentonite to a minimum and improving the solid skeleton by a dramatic reduction of the water/binder ratio and the introduction of a filler. These changes resulted in the necessity of adding a superplasticizer to preserve the fluidity of the fresh component A, and in a significant increase of the dosage of accelerator to keep the gel time into an acceptable range.

Table 1. Reference and high-performance mix designs. Dosages in kg/m^3.

Materials	Reference mix	Snowy 2.0 Type 2+ High-performance mix [17]
Cement	295	243
Slag	-	365
Water	818	518
Bentonite	35	2.8
Filler	-	339
Retarder	5	11.3
Superplasticizer	-	3.6
Accelerant	87	176
w/b	2.77	0.85*

*defined by European standard EN 206-1 for supplementary cementitious materials

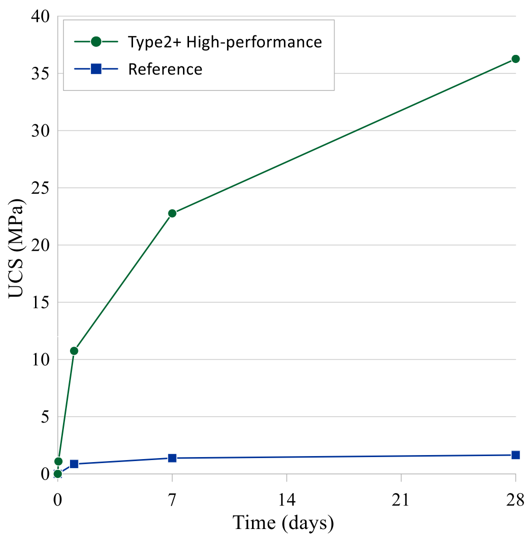

Figure 1. Development of strength over time for reference and high-performance grouts.

As can be expected, the stiffness is also significantly increased by the same adjustments of the mix design. Figure 2 shows two examples of strain-stress paths recorded on cylindrical samples of each grout mix in Table 1Table 2, corresponding to tangent Young's elastic moduli at 50% of UCS equal to 1 GPa for the reference grout mix and 10 GPa for the high-performance one. Except for the first 24 hours after preparation, two-component grouts usually exhibit a brittle behavior.

The rather recent practice of giving specifications on the elastic modulus has modified the experimental activity for verifying (and optimizing) two-component grout mixes, as regards the shape and size of the specimens and the method for measuring sample deformations. Reliable measurements of the deformations are performed by means of LVDT transducers or strain gauges, both to be attached to cylindrical specimens, instead of the usual cubes 40x40x40 mm^3 or 50x50x50 mm^3 (ASTM C109).

When only small cubic samples are available or when tests have to be performed at few fours of curing time, it's very difficult to correctly apply the strain gauges as well as the LVDT transducers, so that a viable way to estimate E would be only by dynamic measurements [16], i.e. V_P and V_S waves velocities, knowing that they provide higher values than the static ones. Other measurement methods, as LVDT transducers between the press plates, are too influenced by the adjustments of the spherical joints and the friction at the contact steel plates/sample to provide reliable measurement, as shown in Figure 3, which displays a comparison between three measuring methods.

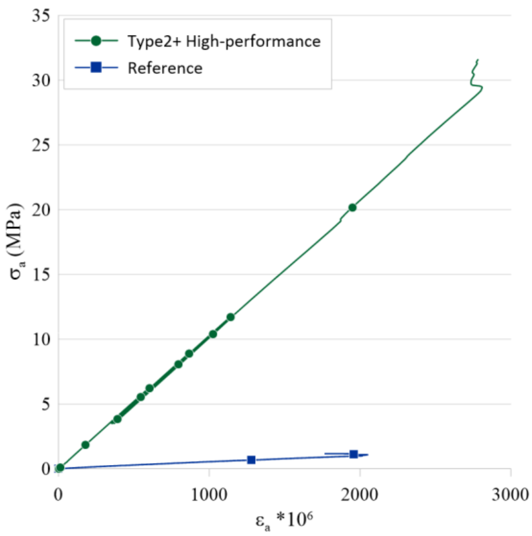

Figure 2. Stress-strain curves from UCS tests on reference and high-performance grout samples.

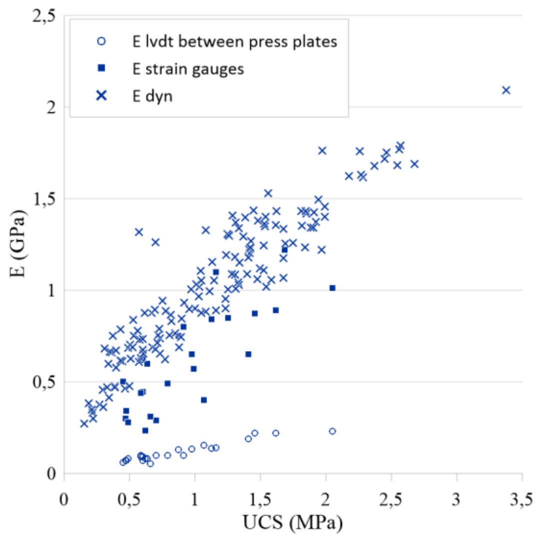

Figure 3. UCS value vs elastic moduli measured with different methods.

4.2. Durability

Lacking specific standards, the design of two-component grout mixes with respect to durability issues is proceeding with a site-specific approach, considering the conditions, peculiar for each jobsite, that may damage or threaten the integrity of the backfill over time and tailoring the experimental activity accordingly. Pure waters, sea waters and sulphate-rich waters are known to promote an aggressive action against cement matrices, but their effects have been proved to be less important in two-component grouts, that has a far lower porosity than concrete and doesn't have aggregates. However, if an evaluation is needed, samples can be cured in water prepared with the same concentrations of chlorides, sulphates and other compounds recorded on the jobsite.

Instead, during the experimental activity carried out for two recent projects (among which Snowy 2.0 [1]), it was observed that curing in cold water hinders the development of strength, while prolonged exposure to air causes a physical and mechanical degradation that proceeds from the external surface towards the core of the samples with a speed that depends on the mix design. It is then possible to conduct tests after curing in air at the expected humidity or in dry soil (Figure 4).

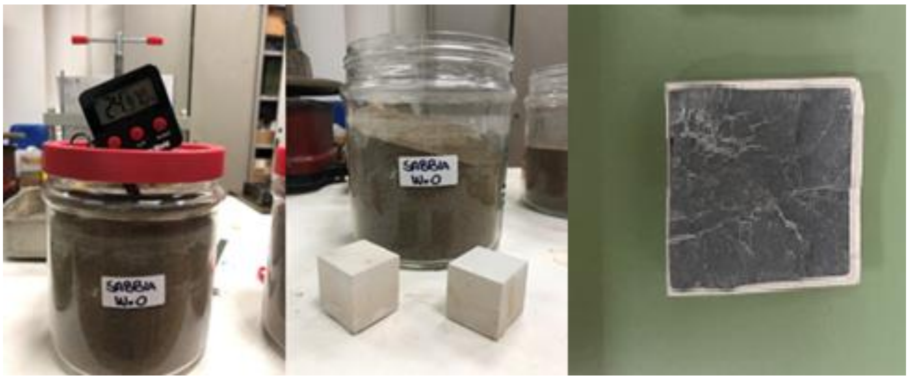

Figure 4. Curing in soil. Aspect of the internal surface of a sample showing external discoloring.

Recently, the study of the durability of the backfill grout was approached with great attention during the design process of the Snowy 2.0 Project [1], developing *ad hoc* testing equipment and procedures to support the designers in the selection of a mix design able to face severe and cyclic stresses without significant deterioration throughout the plant lifetime.

The research activity on this topic [17] is still ongoing, pushing the investigation up to 1 million loading/unloading cycles with a 2 s period (0.5 Hz frequency). The execution of these tests took about 25 days, a long period of exposure to air during which was very important to preserve the samples from damages due to drying, so that cyclic loading had to be performed in a room at controlled temperature and humidity, 25°C and 98% respectively. The loads had to be applied with a pneumatic system to avoid using electrical devices in a high-humidity environment. At the end of the cycles, UCS and E were measured on the samples and no decay of the performance was observed.

In the direction of preserving the integrity and the lifetime of the material, it is worth mentioning the research on two-component grouts with self-healing properties that the authors are conducing to improve the long-term hydraulic seal of a tunnel project in Italy, under particularly problematic hydraulic conditions. Self-healing additives – already used in concrete with good results – are added to the autogenous self-repair properties that cement pastes already possess, due to the presence of cement particles which remain anhydrous even after the hydration reactions have ended and that react when put in contact with new water by the formation of cracks. In two-component grouts the use of self-healing additives is theoretically hindered by the high water/cement ratio, that doesn't leave much room for the existence of anhydrous cement, and by the presence of sodium silicate which probably consumes the same reaction products necessary to these additives to work. The experimental activity on the effectiveness of self-healing additives in this kind of grout is rather promising (Figure 5), focusing mainly on the assessment of the cracks sealing by means of flow measurements and mechanical tests.

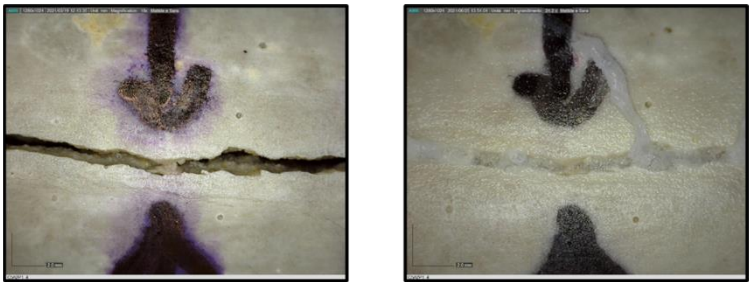

Figure 5. Pictures of a crack in two-component grout before and after self-healing (at 90 days).

4.3. Environmental impact

A full evaluation of the sustainability of concrete and mortar should go through a Life Cycle Assessment, which entails the analysis of their impact from resource extraction ('cradle') to use and disposal phase ('grave'); however, in a preliminary phase, different grout mixes may be compared in terms of emissions considering the GWP (Global Warming Potential) in kgCO_2e/ton of their single constituents in the “cradle to gate” frame. Obviously, a detailed calculation of the overall emissions associated with a two-component grout is very complex and depends on many jobsite-specific factors as logistic, geography, supply chain and so on, but this simple approach can be followed rather easily, having the Environmental Product Declaration (EPD) of each constituent, and allows an optimization of the mixes.

An example of this estimate is presented in Table 2 for different mixes, together with their relevant uniaxial compressive strength at 28 days. The considered GWP values are, where possible, the actual ones from EPDs of commercial products otherwise they are derived from literature studies [12,13,14].

Table 2. Estimate of equivalent CO_2 produced by 1 m^3 of different two-component grouts calculated in the “cradle to gate” frame.

Products	kg CO_2e/kg	Reference mix (kg/m^3)	Snowy type1 P1 mix (kg/m^3) [1]	Snowy2.0 type2+ High performance mix (kg/m^3) [17]
Cement	0.8	295	149	243
Slag	0.1	-	149	365
Water	0	818	824	518
Bentonite	0.5	35	19	2.8
Filler	0.03	-	-	339
Retarder	0.9	5	4	11.3
Superplasticizer	1	-	-	3.6
Accelerant	0.7	87	90	176
total GWP (kg CO_2/m^3)		322	218	398
UCS at 28 days (MPa)		1.5	6	36

Even if ordinary Portland cement (OPC) has more clinker and therefore higher GWP than blended cements, in this comparison a single GPW value has been associated to the cement because the scope here is showing that the partial substitution of cement with alternative binders, obtained from the spoil of other productions (slag) or fillers, especially if they come from quarries close to the jobsite or from the excavated material itself, greatly reduces the carbon footprint of a grout while improving the performances. This also means that the same improvement would enable to produce a grout with typical requirements (1-3 MPa at 28 days), with equivalent emissions far lower than 300 kg CO_2/m^3. It is worth mentioning here that several suppliers are researching on and already providing alternative cement-free binders. The same substitutions also carry other advantages; in fact, reducing cement results in lower pH values induced in the surrounding groundwater, that, at 28 days, may go from about 12.5 to below 11 measured on the samples leching water, as from author’s experience and literature [15].

Two-component grouts requirements on quick setting and early strength nowadays are unachievable without the accelerator, which as a significant environmental impact not only in terms of embodied carbon, but also in terms of releases of chemical compounds in the groundwater and alkalinization. Furthermore, as far as known, to abandon the sodium silicate while maintaining a quick setting would entail the introduction of different alkaline compounds coming with safety and environmental issues as well. In this regard, further studies should be made to assess the compatibility of different mix designs with the environmental profile of the groundwater affecting the jobsite.

5. Final Remarks

The two-component backfilling grout properties proved to be decisive for the successful tunnel excavation and lining installation, particularly in delicate projects and contexts. In the last decade, customers, designers and contractors have been paying growing attention to the physical and mechanical properties of these materials, their durability and sustainability.

The considerable impetus in the development of infrastructure projects given by the European Recovery Fund, together with the increasing technical complexity of the projects – from the calculation models to the design to the realization – highlighted the need for specific studies and accurate investigations of the characteristics of these materials. In this scenario, it seems only reasonable to expect in the next few years a further and rapid evolution of these materials, which potential is still largely untapped. In parallel, the standardization of two-component grout testing should also proceed towards the sharing of methods and procedures.

This paper describes the main trends driving innovation in two-components backfilling grouts, presents useful insights regarding improved solutions and shares data concerning the evolution of the performance in terms of mechanical behaviour (i.e. stiffness, strength), durability and environmental impact.

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