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Original
Marble sludge in two-component grout applications / Todaro, C., Carigi, A., Cardu, M., Peila, D.. - ELETTRONICO. - (2024), pp. 842-847. (ITA-AITES WORLD TUNNEL CONGRESS 2024 (WTC 2024) SHENZHEN, CHINA 19-25 April 2024) [10.1201/9781003495505-114].

Availability:
This version is available at: 11583/2988322 since: 2024-05-08T12:10:15Z

Publisher:
Taylor & Francis

Published
DOI:10.1201/9781003495505-114

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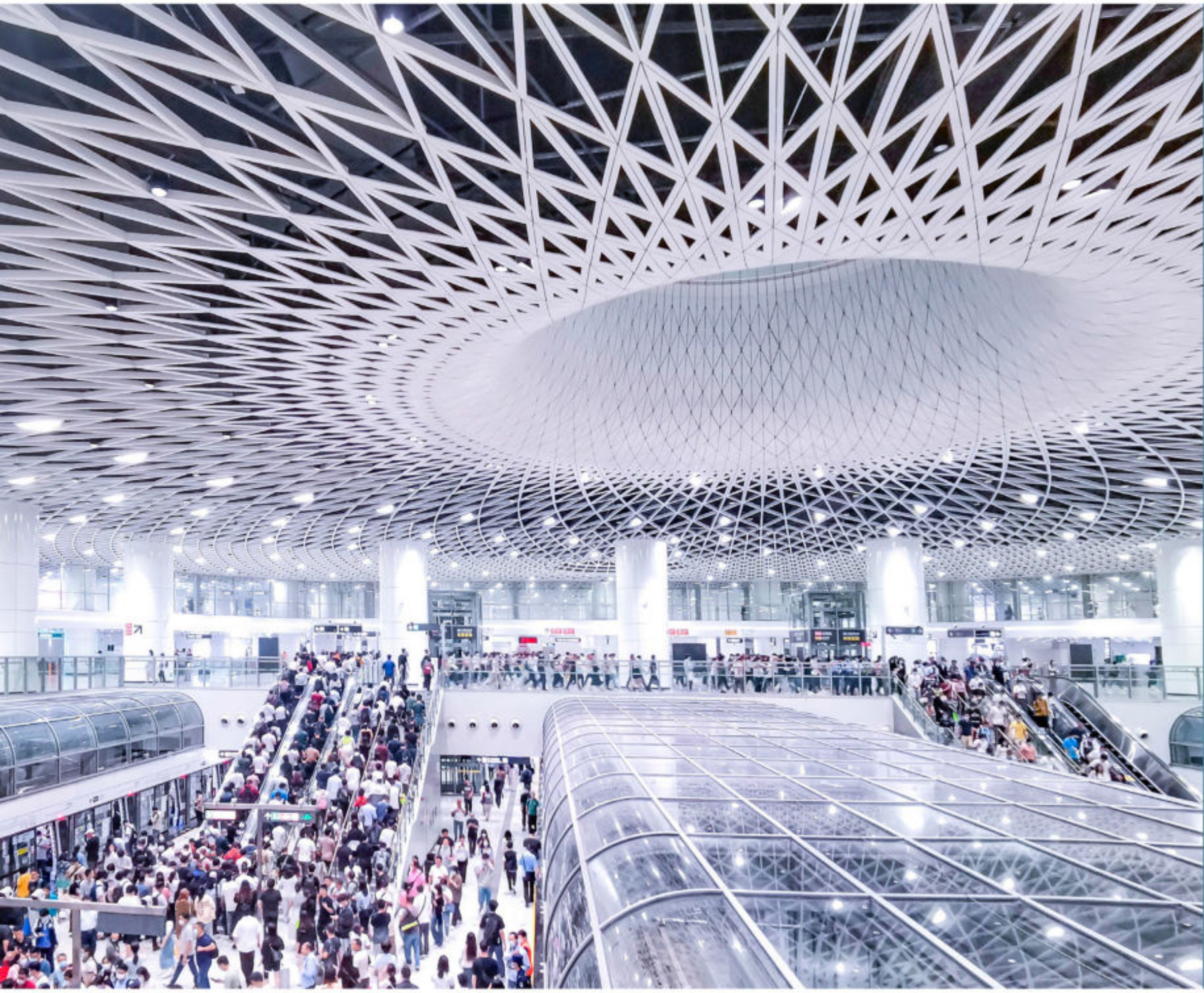
24 June 2026

Tunnelling for a Better Life



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WTC 2024
ITA-AITES
Shenzhen, China

CRC Press
Taylor & Francis Group

TUNNELLING FOR A BETTER LIFE

Tunnelling for a Better Life contains the contributions presented at the ITA-AITES World Tunnel Congress 2024, which was held from 19-25 April 2024 in Shenzhen, China. As urbanization accelerates, the pivotal role of tunnels and underground spaces in fostering environmental sustainability and improving quality of life becomes ever more pronounced. These underground structures serve as sustainable solutions to the challenges posed by rapid urban growth. By seamlessly integrating into urban landscapes, they alleviate congestion, reduce pollution, and enhance overall mobility, thus contributing to a greener and more sustainable urban environment. Moreover, tunnels and underground works provide vital support for various urban functions, such as accommodating economic activities, providing safe shelters during emergencies or disasters, and facilitating efficient utility management. They address immediate urban needs and lay the foundation for a better and more resilient future.

By focusing on the latest trends in tunnelling and underground engineering, and looking ahead to the era of low-carbon and intelligent technology, the papers in this book illustrate the transformative potential of tunnels and underground works in shaping a better life for present and future generations. The contributions cover a comprehensive range of topics on tunnel engineering, showcasing the latest advancements, insights, and innovations across the following areas:

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4. Ground Stability and Consolidation
5. Support and Lining
6. Conventional Tunnelling
7. Mechanized Tunnelling (TBM, shield)
8. Immersed Tunnels
9. Waterproofing and Drainage
10. Instrumentation and Monitoring/Testing and Inspection
11. Digital and Information Technology
12. Machine Learning
13. Underground Caverns/Underground Space Use
14. Operational Safety, Maintenance and Repair
15. Contractual Practices and Risk Management

Tunnelling for a Better Life is a must-read for professionals, engineers, owners, and other stakeholders worldwide in tunnelling and underground engineering.

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PROCEEDINGS OF THE ITA-AITES WORLD TUNNEL CONGRESS 2024 (WTC 2024),
19–25 APRIL 2024, SHENZHEN, CHINA

Tunnelling for a Better Life

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CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

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First published 2024
by CRC Press/Balkema
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by CRC Press/Balkema
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

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Typeset by Integra Software Services Pvt. Ltd., Pondicherry, India

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British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-1-032-80042-4 (hbk)
ISBN: 978-1-032-80113-1 (pbk)
ISBN: 978-1-003-49550-5 (ebk)
DOI: 10.1201/9781003495505

Tunnelling for a Better Life – Yan, Celestino, Thewes & Eberhardt (Eds)
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Preface

The World Tunnel Congress 2024 and the 50th ITA-AITES General Assembly are held in Shenzhen, China, from 19–25 April, 2024. The China Civil Engineering Society (CCES) is honoured to host this prestigious and significant event which is not only a milestone in the history of the ITA, marking its 50th anniversary but also a testament to the enduring commitment and collaboration within the international tunnelling community.

With the visionary theme of "Tunnelling for a Better Life," WTC2024 is set to spotlight the pivotal role of tunnelling and underground works in creating sustainable, efficient, and resilient environments. This theme is a call to the global community to leverage the latest in innovation and technology, addressing the era's most pressing challenges, including climate change, urbanization, and the quest for low-carbon, intelligent infrastructure solutions.

The proceedings encompass a wide array of critical topics in tunnelling and underground space, reflecting the latest trends, insights, and innovations. WTC2024 has received more than 1,000 abstracts and 540 full papers from authors of 46 different countries. After the peer review by the Scientific Committee which was composed of 145 experts from 39 countries, 486 papers from 40 countries were accepted for publication in the WTC2024 Proceedings. From integrating low-carbon technologies to applying intelligent systems in the design, construction, and management of tunnelling and underground works, the contributions within these pages showcase a forward-looking approach to tackling the complexities of modern urban development. The sustainable solutions presented within the proceedings illuminate a path toward resilient, low-carbon, and eco-friendly practices, reflecting our commitment to minimizing environmental impact and underscoring our dedication to efficiency and progress in the intelligent and digital era. The WTC2024 proceedings will inspire and guide our community toward realizing the potential of underground spaces to create a better, more sustainable life for present and future generations.

As we gather in Shenzhen, a city renowned for its dynamic innovation and rapid growth, we are reminded of the power of collaboration and the importance of knowledge exchange in advancing our field. The WTC2024 serves as a platform for experts, practitioners, and stakeholders from across the globe to come together, share insights, and forge partnerships that will drive the future of tunnelling and underground space development.

On behalf of the organizing committee and the CCES, we express our deepest gratitude to all participants, contributors, and sponsors who have made this event possible. As we celebrate the 50th ITA-AITES anniversary, WTC2024 in Shenzhen will provide invaluable opportunities for the international tunnelling community to explore the depths beneath our cities and the heights of our aspirations for a sustainable future and a better life.

Yi Jun
Chair of the WTC2024 Organizing Committee
President of the China Civil Engineering Society (CCES)
Shenzhen, April 2024

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Acknowledgements

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The Editors wish to extend their gratitude to all the members of the Scientific Committee for their unwavering dedication and invaluable contributions.

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Marble sludge in two-component grout applications

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ABSTRACT: The two-component grout is currently the most used backfilling technology in shield tunnelling applications. The technology is widely used all around the world thanks to its versatility. In fact, by properly calibrating dosages and types of raw ingredients, the technical specifications proper of a certain construction site can be easily satisfied. In this work, an innovative two-component grout mix design is introduced, in which a marble sludge is added to component A of the two-component grout system as a new ingredient. The marble sludge, obtained during the cutting process of ornamental stones in marble quarries is commonly considered a waste, an environmental problem that must be correctly managed. The idea of the authors was, hence, to use the marble sludge as an ingredient in the two-component grout, by physically blocking it in the gelling reaction and making it permanently part of the backfilling material, confined between the bored medium and the lining extrados.

In this paper, a laboratory test campaign on the potential use of marble sludge in the two-component grout technology is reported. A standard two-component grout and the innovative one have been compared according to standardized testing protocols. Outcomes highlight that the innovative grout has similar properties compared to the standard one and that the addition of marble sludge does not worsen the grout's properties.

Keywords: two-component grout, backfilling, marble sludge, waste reduction

1 INTRODUCTION

At present times, the two-component grout is the most used backfilling technology in mechanised tunnelling, using shielded machines.

During the tunnel excavation and the machine advancement, a gap is continuously created from the difference in diameter between the head of the machine and the lining extrados. This gap is inevitable since this geometrical peculiarity is essential and allows for the assemblage of the segments in linings under the protection of the shield, as well as avoiding potential machine block due to convergence of the excavated medium.

This gap, commonly called annulus, has an order of magnitude of centimetres and is schematically shown in Figure 1.

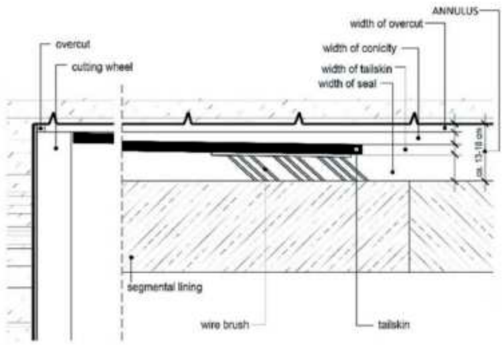

Figure 1. Annulus. Modified from thewes and budach (2009).

Different technologies can be used for the complete filling of the annulus (Grasso et al., 2023) but two-component grout is undoubtedly the most popular all around the world, due to its aptitude for preventing and controlling surface settlements (Fargnoli et al., 2013). This feature is guaranteed by an almost instantaneous gelation of the grout: the material after the gelation starts immediately to improve its mechanical and elastic properties (Oggeri et al., 2021; Todaro and Pace, 2022).

The technology is based on two liquid components: the component A and the component B. The first is a cement-based material made up of cement, water,

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DOI: 10.1201/9781003495505-114

bentonite and retarding/fluidifying agent, while the second is commonly a solution of sodium silicate. Recently, new ingredients have been experimentally introduced to component A production such as, for example, fly ash, blast furnace slag, and industrial solid waste (André et al., 2022; Schulte-Schrepping and Breitenbücher, 2019; Song et al., 2020, Song et al., 2022).

These last studies were the starting point for this research, meaning that the idea to re-use something considered industrial waste was followed. In detail, the new ingredient selected to produce the component A has been the marble sludge, typical waste coming from the cutting process of ornamental stones. The choice was dictated by the nature of the marble sludge, composed mainly of calcium carbonate ($CaCO_3$) and directly available with a grain size distribution suitable for the proposed application. This material is produced in large amounts in marble quarries (Cobo-Ceacero et al., 2019): On average, for each cubic metre of marble exploited, 50-95 L of marble sludge is obtained. This material must be correctly managed, and the cost for its disposal significantly impacts the marble quarry business.

In this work, a preliminary test campaign is presented concerning the use of marble sludge powder as a raw ingredient for the production of component A. In the following paragraphs, the term “marble sludge” refers more specifically to the powder of marble, naturally produced during the cutting operation performed in a dry way (no water or other lubricants added).

Starting from a mix design typically used in construction sites for the two-component grout production, two different dosages of marble sludge have been tested to produce the grout. To verify the feasibility of using this new ingredient in the two-component grout technology, the component A properties, the reaction of gelation, and the hardened grout have been tested according to a standardised testing protocol (Todaro et al., 2019). The results of the grout prepared with the marble sludge have been compared to those of the reference mix.

2 THE ISSUE OF THE MARBLE SLUDGE

Considering the ornamental stone processing chain, the cutting operations are important since blocks of huge dimensions (m^3 of order of magnitude) are split into easily transportable slabs, suitable for further processing (Figure 2, left). Taking into account the Italian scenario, marble quarries are by far the most common, yet other types of ornamental stone quarries are also present on the national territory. For the reason of “abundance”, authors have selected marble sludge as an experimental ingredient in this study (Figure 2, right).

Figure 2. Chain cutting machine used for splitting the marble blocks in slabs (on the left) and the marble sludge obtained during this cutting operation (on the right).

Considering only the Carrara marble basin, hundreds of thousands of tons of marble sludge are produced every year due to the huge production of blocks (about 900,000 tons/year) of one of the finest marbles in the world. This big production inevitably leads to big amounts of produced marble sludge. Additionally, the environmental problem associated with marble sludge disposal is challenging, especially in the area where quarries operate.

From this scenario, the authors’ idea has been conceived, while considering the new big tunnel projects that are going to start in the next years in Italy according to the National Recovery and Resilience Plan funding: use the marble sludge in the backfilling phase in shielded mechanised tunnelling.

If, from one side, the environmental positive impact of “trapping” the marble sludge in a grout is practical, the calibration of the two-component grout mix design for using the marble sludge as an ingredient is a complex phase from the other side, considering the sensitive balance between compounds. The two mix designs presented have been calibrated not only to maximize the dosage of marble sludge but also to try to improve the mechanical performances of the obtained grout.

3 MATERIALS AND METHODS

The test campaign has been organised in two different parts: the first aimed to assess the properties of component A only and the gel time, while the second aimed to test the mechanical performance of the gelled grout at a short curing time. The short curing time is intended for no more than 3 hours after the casting. The procedure for preparing component A, for the sample casting and the used mix designs are reported in the following.

3.1 *Used materials*

To produce the two-component grout, Portland Cement type CEM I 52.5 R (CEN, 2011) was used. The accelerator, retarding/fluidifying agents, and bentonite were provided by Mapei company. The marble sludge was instead provided by the “Rock cutting laboratory”, part of the “Geomechanics and Geotecnology laboratory” of the Politecnico di Torino.

3.2 *Component a production and sample casting*

The component A production was carried out by using a laboratory stirrer, according to the procedure described in Todaro et al. (2019) and hereinafter shortly summarised in Table 1.

Table 1. Mixing procedure.

Phases	Impeller rotation speed (rpm)	Duration (min)
Start – only water	800	/
Bentonite mixing phase	2000	7
Marble sludge mixing phase	2000	if the marble sludge is added, the mixing time should be calibrated for obtaining a suitable mix
Cement mixing phase	2000	3
Mix of retarder/ fluidifying agent – End	2000	2

The mix designs used are reported in Table 2. Those where the marble sludge is used are “1M” and “2M”, while “R” is the reference mix design. Dosages are expressed in kg/m^3.

Table 2. Mix designs.

Ingredient	1M	2M	R
Cement	230	230	230
Bentonite	30	30	30
Marble sludge	50	100	/
Water	834	816	853
Retarding/fluidifying agent	3.5	3.5	3.5
Accelerator	81	81	81

When component A was obtained, the sample casting was performed manually. The metered amount of components A and B were prepared in two different tanks, followed by quickly pouring component A inside the tank holding the component B, and later pouring all the grout into the empty tank, which led to the final step of emptying the grout (still liquid) into the sample moulds.

Used samples have dimensions in compliance with CEN (2016) (40*40*160 mm).

3.3 *Performed test*

The characterisation of component A, the reaction between components A and B, and the hardened grout at short curing time have been studied in accordance with the well-established, detailed procedure reported in Todaro et al. (2019). Briefly, the characterisation of component A was assessed by measuring the unit weight and the flow time on the fresh component A (i.e. within 10 minutes after the production) while the bleeding was assessed after 1, 3, and 24 hours after the component A production. The gelation of the grout obtained by turbulently mixing component A and component B has been assessed by measuring the gel time. Finally, the hardened grout has been characterised by assessing the surface compression strength (SCS) after 1 and 3 hours of curing.

3.3.1 *Unit weight*

The unit weight was assessed by using a mud balance (Figure 3), according to the standard ASTM D4380 (2020).

Figure 3. Mud balance used for the unit weight assessment. (Todaro et al., 2023).

3.3.2 *Flow time*

The flow time was assessed by using the Marsh funnel (Figure 4), in line with UNI 11152-13 (2005). This test provides indications on the viscosity of the tested material. The outcome of the test is the time spent by 1 L of mortar to flow through the funnel. The higher the viscosity of the mortar, the higher the flow time.

Figure 4. Marsh funnel used for the flow time assessment (Todaro et al., 2023).

3.3.3 *Bleeding*

The bleeding test allows the evaluation of the physical stability of component A. The test has been carried out according to UNI 11152-11 (2005). A standardised cylinder is filled with 1 L of component A, to which particles of cement tend to settle on the bottom of the cylinder due to the gravity force,, leaving a layer of water on the top of the surface. After a certain time, the volume of the segregated water is measured (V_w), and by computing the ratio on the whole volume of 1 L (V_t), the bleeding index is computed, expressed as a percentage according to equation (1):

$$Bleeding = \frac{V_w}{V_t}(\%) \tag{1}$$

Figure 5. Bleeding assessment. (Todaro et al., 2023).

3.3.4 *Gel time*

The gel time has been assessed by following the experimental procedure proposed by Todaro et al. (2019) and used also by André et al. (2022). Once the quantities of components A and B are metered and prepared according to the mix design, component A is poured into component B; after that the whole material is quickly poured again in the empty tank and so on with subsequent series of pouring. The time recorded started when the first contact between components A and B occurred, and ended when the grout is not able to flow.

3.3.5 *Surface compression strength (SCS)*

The surface compression strength (SCS) has been assessed according to the procedure proposed by Todaro et al. (2020). A dynamometer was equipped with a flat circular bit having a surface of 177.9 mm^2 (A in equation 2) (Figure 6).

The test consists of the penetration of the bit orthogonally on the cast surface of the grout (previously cast in moulds with the shape in compliance to CEN (2016) and cured for 1 or 3 hours in a sealed environment) till a penetration of 5 mm is reached. The maximum force (F in equation 2) reached during the test is recorded. SCS is consequently computed according to equation (2) where F is expressed in N.

Figure 6. Dynamometer used for the surface compression strength assessment during the test. Todaro et al. (2020).

$$SCS = \frac{F}{A} \tag{2}$$

According to the reference standard, tests have been performed without demould samples. At least 6 tests were carried out for each assessment performed after 1 hour, while between 3 and 6 determinations were performed for testing after 3 hours of curing. The reason for a higher number of assessments at 1 hour of curing is related to the higher dispersion observed.

4 RESULTS

The obtained outcomes are summarised in Table 3.

Table 3. Used mix designs.

Mix design	1M	2M	S
Unit weight (kg/L)	1.20	1.27	1.17
Flow time (s)	36.0	38.0	34.5
Gel time (s)	7	4	8
SCS 1h (MPa)	0.38	0.45	0.41
SCS 3h (MPa)	1.65	1.71	1.62
Bleeding 1h (%)	0.3	0.0	/
Bleeding 3h (%)	0.68	0.00	1.04
Bleeding 24h (%)	3.10	2.40	2.09

5 DISCUSSION

Taking into account the unit weight, an increment of values is recognised for 1M and 2M compared to R. The higher weight for a fixed volume of the considered component A is due to the replacement of a certain amount of water with the marble sludge. However, values of 1.2-1.3 kg/L are typically accepted in construction sites, therefore it can be stated that compliance has been respected.

On the other hand, a significant reduction in gel time was observed. If for 1M the reduction is only of 1 s (a time lapse consistent with the test error), the gel time of 2M is half of those of R. The value of 4 s is very short, hardly applicable in standard practices, and not commonly acceptable in construction sites. Probably, the gelation between components A and B is affected by the presence of the marble sludge that plays an active role as a further booster of the reaction.

Considering the flow time, a slow increase has been observed (about 4 % and 10 %, respectively for 1M and 2M) compared to the flow time of the mix R, but then again, these values are accepted in common practice.

Optimal results have been obtained for the bleeding test, despite the presence of the marble sludge and consequently the tendency of these particles to segregate (similarly to the concrete ones), bleeding values are lower than 1% after 3 hours and abundantly lower than 8% (the threshold commonly fixed for construction sites) after 1 day.

As for the strengths at short curing time, 2M seems to be more performant than R: values greater than about 10 % and 6 % compared to the reference mix design have been obtained for a curing time of 1 hour and 3 hours respectively. Differently, 1M exhibits similar results compared to R (for 1 hour of curing, the strength was lower than that of the reference mix).

6 CONCLUSIONS

This work describes a preliminary test campaign where marble sludge, a material considered as waste in the ornamental stone supply chain, is reused in a tunnelling application. The preliminary nature of the work is related to the used mix designs; in fact, starting from a real two-component grout mix, no variations on dosages of raw ingredients have been applied: only the water has been replaced by the marble sludge in a quantity dictated by the sludge dosages and the respective unit weights. This choice was dictated by the need to check the potential impact of the new ingredient on the two-component grout technology by monitoring the reference parameters and their "fluctuations" in presence of the new ingredient.

Despite this limitation, the results highlighted the concrete possibility of giving the marble sludge a noble use as an ingredient in the two-component grout technology, as backfilling in tunnelling applications. No breach has been actually identified, granted that the gel time could extend by increasing the dosage of the retarding/fluidifying agent. It is also important to note that an increment of the retarding/fluidifying agent could allow the increase of the marble sludge dosage that, according to the presented results, could turn into higher strength performances. In conclusion, the preliminary outcomes reported in this study highlight that the innovative grout has similar properties to the standard one and that adding marble sludge does not worsen the grout's properties.

Results presented in this paper should be considered as a first step of the research since further analyses on mechanical and elastic performance at long curing time should be carried out before transferring the technology to a pilot construction site.

The research is currently on-going.

ACKNOWLEDGMENTS

The authors want to thank Utt Mapei for chemical ingredients and Buzzi Unicem for cement.

FUNDING

This publication is part of the project NODES which has received funding from the MUR - M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

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