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ADVANTEX: Research of innovative tools to support the logistics of the use of excavation materials produced by the Lyon-Turin railway line for the best sustainability and circular economy of the process

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ABSTRACT: The Mont-Cenis Base Tunnel is the key work of the new Lyon-Turin railway line. The project envisages a total volume of 37.2 million tons of excavated material over a period of 10 years: a considerable part of the excavated material will be used for the tunnel lining (concrete or railway embankments) and for the embankments of the open-air sectors, while the remaining part will be transported by rail, conveyor belts, and heavy vehicles to the temporary and permanent storage sites. To maximize the circular economy and the efficiency of the materials logistic, TELT is working with the Politecnico di Torino (Department of Environment, Land, and Infrastructure Engineering, Department of Structural, Geotechnical and Building Engineering, and Department of Applied Science and Technology) and the Interdepartmental Laboratory SISCON - Safety of Infrastructures and Constructions, to study innovative solutions for the characterization and reuse of the excavated materials. Given that the materials are substantially undifferentiated during the excavation and that the geological classification requires long and complex additional verification activities, which can negatively affect the process, a significant sample of materials excavated at the survey tunnel of La Maddalena (place where the base tunnel will be excavated) were analyzed. The objective of this first phase is the search for new technologies and new processes for the early characterization of the excavated material in order to determine its intended use, designing green concretes (defining its sustainability and mechanical characteristics for structural use, through synthetic parameters, including durability analysis) and backfilling, seeking innovative tools for optimal logistics, in order to “industrialize” the identification process and optimal technologies for automatic process control and traceability, in order to give strength and speed to all activities. The subject of this work is the results of the early characterization experimentation process with the application of artificial intelligence and possible innovative circular solutions.

1 INTRODUCTION

The choice of the excavation technique, as known, affects the size distribution of the muck: for the purpose of reusing the material, knowing the best excavation technique can help to evaluate the type of possible reuse. The rock mass’s geological and geotechnical parameters affect the excavation technique and the possible uses of the muck. The technique selected, being the rock characteristics the same, influences the particle size distribution, shape indices, and material’s physical-mechanical properties.

The excavation process, when using TBMs for rock excavation, is significantly affected by the geometry of the tools, which is defined by their diameter and edge profile (Ozdemir, 1992). In

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particular, the increase in diameter leads to an increase in the thrust and linear speed of the tools (Rostami and Chang, 2017). The excavation process basically involves the formation of chips between adjacent cracks created by the cooperation among the tools. Many theories agree on the formation of an almost pulverized zone in the immediate contact between the tool and the rock ("pressure bulb"), generated by the high concentration of stresses. This zone provides the transfer of stresses in the medium (Rostami and Ozdemir, 1993), which cause the formation and propagation of tensile stresses in the rock mass, whereby the cracks propagate until the tensile strains at their ends fall below the tensile strength of the rock (Bilgin et al., 2014). For chip formation to occur, the cracks generated by a cutting path must coincide with those developed by the adjacent cut, or by a free surface. A scheme of the phenomenon is shown in Figure 1. The efficiency of the cutting process depends primarily on the properties of the rock mass, but also on the cutting geometry, i.e., the spacing between the tools and their penetration into the medium. With the same rock and tool penetration, there is an optimal spacing that allows providing the maximum efficiency of the cutting process; this condition involves the minimum consumption of specific excavation energy, defined as the energy spent to excavate a unit volume of rock.

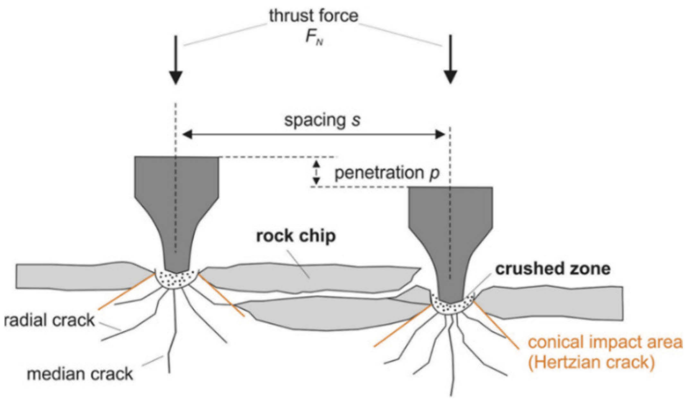


Figure 1. Schematic representation of the indentation and chip formation process during rock excavation using disc tools (Rostami, 1997).

Greater tools' penetration allows a greater spacing to achieve the optimal chips process (Ozdemir, 1992). For these reasons, a dimensionless parameter is used to define the optimal cutting geometry: the ratio of the spacing between the tools and the penetration (s/p). The optimal s/p ratio is typically between 10 and 20 (Rostami, 2008; Rostami and Chang, 2017), and depends on the type of rock to be excavated.

According to Bilgin et al. (2014), the factors influencing the performance of a TBM can be divided into three main groups: mechanical factors (related to the machine), geological-geomechanical factors (related to the rock material), and operational factors. While the mechanical factors are often constant during excavation (having provided proper machine maintenance), geological-geomechanical factors are typically those that most influence the performance of the TBM during excavation, their variability being sometimes very considerable, especially for very long tunnels, when it is not uncommon for the characteristics of the rock mass observed during excavation to be significantly different from those foreseen in the design phase. Regarding the operational factors, the choices that define the operating level of the machine (i.e., thrust, rotational speed, torque, and power) can vary during excavation, affecting the net and overall performance of the TBM. The particle size obtained is a good indicator of excavation efficiency and can provide information on rock-breaking mechanisms.

In homogeneous rock masses, the size of the fragments is fundamentally governed by the spacing and penetration of the tools (Gertsch et al., 2000). In fractured masses, the structural characteristics of the rock are particularly important, as evidenced by Farrokh and Rostami (2008). For these reasons, to better understand the efficiency of the system by evaluating the size of the debris, the particle size distribution of the muck must be compared with the parameters of the TBM and the properties of the rock mass. It is necessary to conduct detailed analyses using a large number of samples taken at various stages of excavation.

An early prediction of rock petrographic characteristics could be useful not only for the machine parameters' efficiency in terms of timesaving and cost but also to obtain a muck with optimal characteristics for recovery as concrete.

TBM excavation produces a muck with a wide range of particle size distribution, also in function of the properties of the excavated rock: from coarse fragments to powders smaller than 2 mm. The production of particles finer than 2 mm is high, and its recovery has not been studied in literature with respect to the recovery of the coarser fraction (Bellopede et al. 2011; Voit et al. 2020; Bellopede et Marini 2011; Petitat et al. 2015). This paper aims at a sustainable goal for the reuse of muck from TBM excavation: this kind of approach can be successful if all the necessary requirements are met according to the planned reuse: the tests and investigations carried out to evaluate the characteristics of the muck for the purpose of its reuse are described; moreover, the circular economy, as well as environmental factors, are important concerns, and the need for re-mucking can address them. The concrete required in the various phases during the construction of the tunnels represents a significant value in terms of cost: for this reason, the reuse of muck is mainly aimed, in addition to other possible purposes, at the production of several types of concrete.

However, it is of primary importance to assess the petrographic and chemical composition of the muck to be sure that any dangerous mineral as gypsum and sulfur/sulfates in general as well as amorphous silica, salts, and carbonaceous materials (Collepardi, 2013), could affect the future concrete. The chemical/mineralogical composition of the muck has been investigated by means of X-ray powder diffraction (XRD), portable Raman and petrographic microscope.

2 MATERIALS CHARACTERIZATION

2.1 *Traditional methodologies*

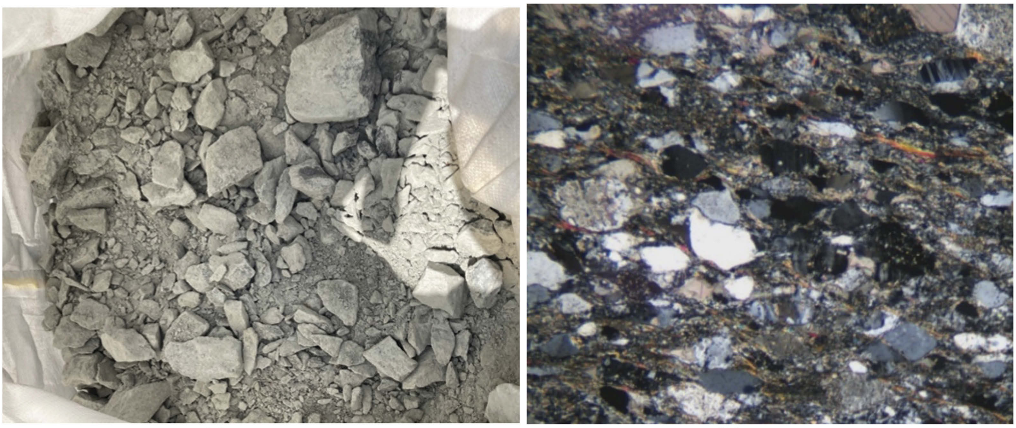
The materials characterization was performed by means of traditional methods which have the goal to validate innovative digital methods linked to early on-site recognition. The analysis performed are petrographic analysis, and particle size distribution.

The petrographic characterization made through a petrographic microscope identified the rock as a mica-schist macroscopically compact, with a gray color and schistose texture highlighted by the alternation of quartz beds and micaceous beds with minor albite crystals. In thin section can be detected: quartz (about 50%) in individuals with an irregular outline with average dimensions ranging from 0.05 to 2 mm with some crystals about 4 mm, in levels oriented parallel to the schistosity; white mica (about 40%) in lamellae reaching even 1 mm in length; albite for around less than 10% in crystals with dimensions similar to the quartz crystals (0.05 to 2 mm) with which they are associated; accessory minerals: titanite, apatite, opaque, zircon.

Figure 2a shows the analyzed muck obtained by TBM excavation and Figure 2b shows microscope analysis in thin sections.

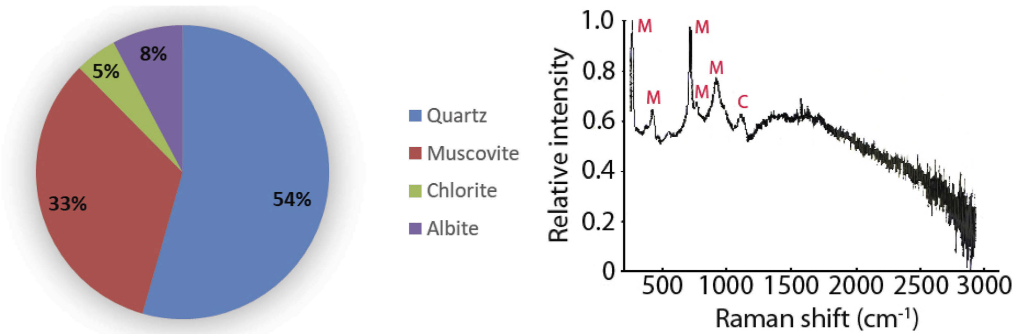
The petrographic analysis performed by means of XRD, Rigaku SmartLab SE, verified the composition. The results obtained by means of Quantitative XRD Analysis obtained by Rietveld refinement are shown in Figure 3a. The aggregates were then analyzed by means of Raman spectroscopy with a Thermo Scientific TruScan GP portable instrument with a laser diode that emits a 250 mW beam at 785 nm in the Raman range from 250 cm^{-1} to 2875 cm^{-1}. The aggregates were analyzed as such and after washing. Several areas were investigated on the same aggregate, based on the distinct colors. Figure 3b shows a Raman spectrum of a bright area on a washed aggregate. The Ruff database was used for Raman peaks indexation (Ruff 2022). These results confirmed the previous ones from XRD measurements. No harmful compound for concrete manufacturing was found (gypsum and sulfur/sulfates in general, amorphous silica, salts, and carbonaceous materials). Particle size distribution was performed according to UNI EN 933 Part 1 on the muck fraction below 2 mm. The results are shown in Figure 5 (sample1, sample2, sample3).

In order to perform a granulometric analysis, to obtain a representative sample for sieving, it would be advisable to take the sample directly from the conveyor belt, as suggested by Bruland (1998).



(a) (b)

Figure 2. Material deriving from TBM excavation (a) and thin section of material deriving from tunnel excavation. Scale 200 μm; magnification 5X (b).



(a) (b)

Figure 3. Results of quantification analysis by means of XRPD using Rietveld method (a) and Raman spectrum of a bright area on an excavated aggregate (M=muscovite, C=calcite) (b).

3 DIGITAL INNOVATIVE METHODOLOGIES

In order to address the problems related to the traditional sieving and the early petrographic recognition, a digital methodology by means of photogrammetric techniques, LiDAR sensor (Light Detection and Ranging) and hyperspectral images was developed to evaluate the particle size distribution, an estimation of volume and a petrographic recognition of the muck. The proposed methodology starts from data acquisition with the different sensors and is then divided into 1. direct use of RGB images for the granulometric characterization through MATLAB instance segmentation (MIS, he and al, 2017).); 2.use of hyperspectral images to create a reference library (ground truth from laboratory rocks) of hyperspectral signatures. These hyperspectral images, divided into smaller hypercubes, are then used for the CNN training, and led to the petrographic characterization.

To simulate a conveyor belt, a specific structure was built (Figure 4), equipped with various sensors and able to move on wheels along the linear strip on which the excavated material was positioned. In particular, the structure presented: 1. 2 hyperspectral imaging cameras for the material recognition (Senop Rikola with spectral range in visible and NIR region from 500 to 900 nm, Specim FX17 with spectral range in NIR region from 900 to 1700 nm); 2. n.3 RGB compact digital cameras (SONY RX0 II) for the reconstruction of the 3D point clouds, 3. n. 8 halogen spotlights able to homogeneously cover the entire light spectrum from 400 nm to over 800 nm; 4. millimeter calibration bar to define the acquisition position. These acquisitions were conducted every 0.1 cm for the Specim and every 5 cm for the RGB cameras and the RIKOLA. In Figure 5, the results were compared with the traditional one, denoting a limited (10%) underestimation of the processed curves that can be explained by the presence of hidden grains not located on the surface and by the difficult processing of the finer part.

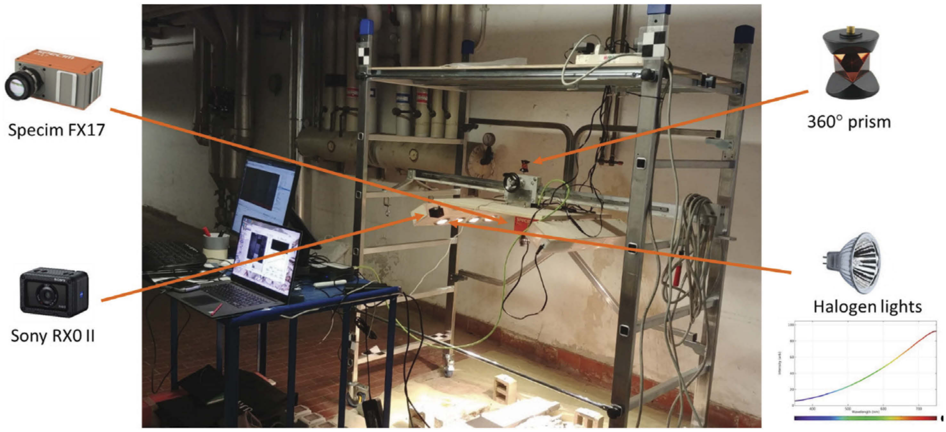


Figure 4. Scaffolding equipped with the sensors.

For petrographic recognition, the neural network presented in (He et al, 2017) has been used through Deep Learning techniques, based on the hypercubes of size 1x1xN (pixel/pixel/bands), N equal to 198 for the case study.

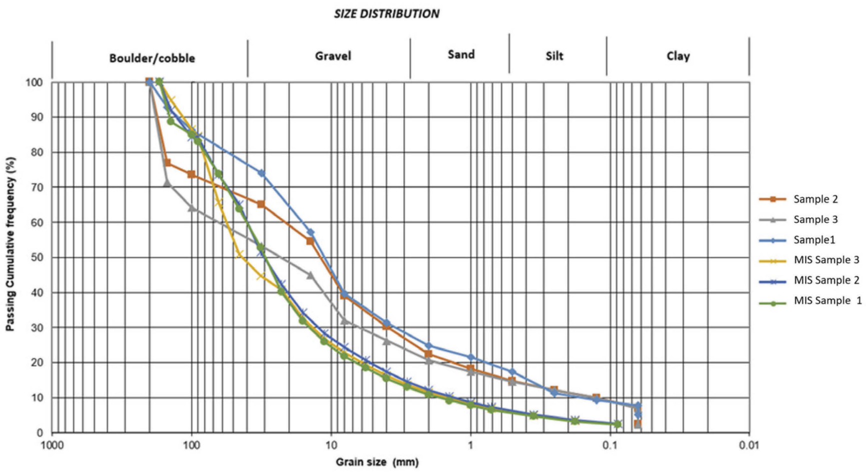
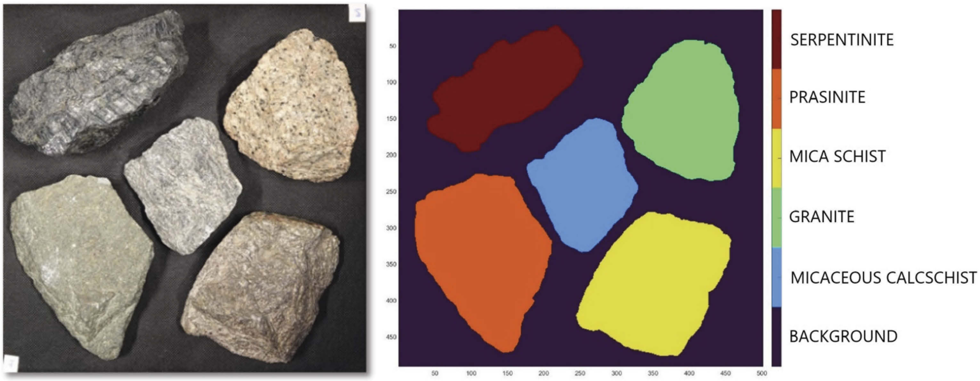


Figure 5. Comparison of grain size curves: traditional (Sample) and digital (MIS sample) methodologies.



(a) (b)

Figure 6. The laboratory sample (a) and the result of petrographic recognition.

Due to the homogeneity of the sample aggregates of TBM excavation at La Maddalena, the digital petrographic characterization has been tested using a dry laboratory sample (Figure 6a) and the results have been shown in Figure 6b. These preliminary results show that the classification has a high accuracy (at least 74% of accuracy for micaceous calc-schist, 95% for others): the rocks are correctly recognized, in micaceous calcschist, granite, mica schist, prasinite, and serpentinite, respectively, most of their hypercubes are associated to the correct ones.

4 FUTURE DEVELOPMENT FOR MUCK RECOVERY

4.1 *Green concrete design*

An eco-design approach of concrete structures should be based on the selection of concrete components, with low carbon footprint, and on the minimization of the concrete mass. In other words, the following strategies can be applied to obtain green concrete (Habert and Roussel 2009): 1. *Material performance strategy*, which is based on the reduction of the total amount of concrete, and thus of the volume of structures. Obviously, the mechanical performances, such as the compressive strength, need to be increased with respect to the traditional concrete under the same loading demand; 2. *Material substitution strategy*, which consists of substituting some of the concrete components with recycled or waste materials, having a low carbon footprint.

The success of these two strategies is therefore based on the measure of the mechanical index (MI) and of the ecological index (EI) of the final concrete mixtures. Both the values of MI and EI can be reported within the diagram depicted in Figure 7. In this diagram, MI_{inf} is the lower bound value of mechanical performances (e.g., the compressive strength of concrete), whereas the upper bound value of ecological impact is represented by EI_{sup}. (e.g., the equivalent CO_2 of an LCA). Both these bounds can be either prescribed by code rules or imposed by tender requirements. Accordingly, four different zones can be detected within the non-dimensional diagram (Figure 7).

Concerning the concrete of a tunnel lining, it is practically impossible to apply the performance strategy. Indeed, the increment of strength does not lead to a remarkable reduction of the volume of concrete used to cast the lining, because building codes impose a minimum thickness (for instance to resist compression and shear actions as specified by Fantilli et al. (2019)).

Therefore, the only way to tailor green concrete for tunnel lining is to apply the material substitution strategy. Namely, with respect to traditional concrete (having fixed values of MI_{inf} and EI_{sup}) the virgin components of the mixtures can be substituted by waste materials. In the concrete

- Zone 1: Low mechanical performances– Low ecological performances.
- Zone 2: High mechanical performances– Low ecological performances.
- Zone 3: High mechanical performances– High ecological performances.
- Zone 4: Low mechanical performances– High ecological performances

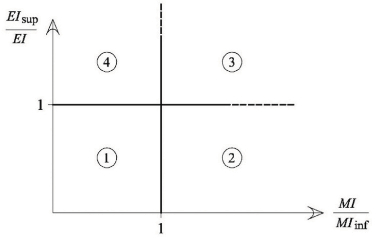


Figure 7. The non-dimensional diagram for assessing the eco-mechanical performances of concrete (Fantilli and Chiaia 2013).

of tunnel lining, some fractions of the aggregate can be substituted by the muck, maintaining the type and the amount of the other components (i.e., water, cement, additives) unchanged (Voit et al. 2020). Nevertheless, the new concrete is likely to fall within zone 4 of the non-dimensional diagram depicted in Figure 7. This is because the substitution tends to decrease EI with respect to EI_{sup}, but, contemporarily, MI becomes lower than MI_{sup} (see for instance the case of recycled concrete aggregate (Wang et al. 2021). In such a situation, to maintain the $MI > MI_{inf}$, recycled steel fibers can be added to the mixture containing the muck (Qina and Kaewunruenb 2022), because fiber-reinforced concrete behaves better than traditional plain concrete. The combination of these two recycled materials is herein proposed to make the concrete of the Lyon-Turin railway lining greener than the traditional solution.

4.2 *Backfilling*

The backfill materials as flowable fill, controller density fill, flowable mortar and plastic soil cement are self-leveling cementitious materials mainly used as fillers as an alternative to traditional granular materials (American Concrete Institute Committee 229R, 1994). The technical documents ACI 229R-13, is a guideline, which describes the requirements that this type of materials must possess in terms of resistance, permeability, constituent materials and their dosage ranges according to the objectives to be achieved; how it is transported and the pouring. The backfill materials must satisfy specific properties that allow them to distinguish it from other filling materials. These properties are flowability, time of hardening, pumping, not increasing resistance over time, high density, permeability, excavability. It is used as a fill instead of traditional compacting soils. Due to its characteristics of high fluidity and self-compaction, it is ideal for use in tight and inaccessible areas where it is difficult to place and compress the material.

The main actual applications are sewage trenches, bridge shoulders, containment walls, road foundations, underground tanks, piping laying beds, and thermal insulation with high-air-based cement mortar. Generally, contains water, Portland cement, fly ash, fine aggregates or coarse aggregates and additives. Some mixtures consist only of water, Portland cement and fly ash to avoid segregation.

Recent studies on recovery of sludge deriving from cutting of silicate materials in CLSM (Control low strength materials) and FBT (Fluid thermal backfill) (Choorackal et al. 2020, Zichella et al. 2020), demonstrate that the presence of quartz content and eventually of heavy metals, due to cutting tools wears, in the aggregate and filler fraction, considerably improves the thermal conductivity with the same mechanical characteristics of a standard granular material.

The ongoing research involves using material deriving from the tunnel excavation with particle size distribution smaller than 2 mm as filler and with material deriving from demolition and construction waste of dimensions from 0 to 16 mm as aggregate, in addition to cement and superplasticizer additive type Dynamon SP1.

This type of reuse was designed to reduce and/or eliminate the production of waste by reusing the muck in the same excavation site, in accordance with the concepts of circular economy and end of waste.

5 CONCLUSION

The particle size distribution of the fragments produced by the TBM excavation, in addition to conditioning the possible reuse of the material, can provide important indications both on the performance of the machine and on the characteristics of the rock mass. However, on-site determination of particle size distribution is not easy to implement in terms of time and cost. It is known that the grain size distribution of the muck obtained from the excavation depends on the characteristics of the rock mass and on the operating parameters of the machine, but in this case attention was paid to the purpose of reducing the production of waste, by reusing the excavated material.

Concerning the chemical-petrographic and dimensional properties of the muck, laboratory tests were carried out to validate, through standardized methodologies, the unconventional analysis done by means of portable instruments and digital techniques.

The proposed digital methodology based on photogrammetric techniques, LiDAR sensor (Light Detection and Ranging), and hyperspectral images allows evaluating of the particle size distribution with an underestimation of the particles of about 10% and to extract the petrographic characterization on dry excavated aggregates with high accuracy.

By combining the proposed digital methodology of classifying the excavated materials and concrete technology, the so-called material substitution strategy can be applied to tailor sustainable cement-based composites. In particular, the reuse of both gravel and finest fractions of muck was assessed and promising results were obtained, to reduce the production of waste.

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