Performance-based Re-use of Tunnel Muck as Granular Material for Subgrade and Sub-base Formation in Road Construction

PERFORMANCE-BASED RE-USE OF TUNNEL MUCK AS GRANULAR MATERIALS FOR SUBGRADE AND SUBBASE FORMATION

P.P. Riviera (*), R. Bellopede, P. Marini and M. Bassani

(*) corresponding author

Pier Paolo Riviera
Department of Environmental, Land and Infrastructures Engineering
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0905612
Fax +39 011 0905614
pierpaolo.riviera@polito.it

Rossana Bellopede
Department of Environmental, Land and Infrastructures Engineering
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0907738
Fax +39 011 0907699
rossana.bellopede@polito.it

Paola Marini
Department of Environmental, Land and Infrastructures Engineering
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0907625
Fax +39 011 0907699
paola.marini@polito.it

Marco Bassani
Department of Environmental, Land and Infrastructures Engineering
Politecnico di Torino

Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0905635
Fax +39 011 0905614
marco.bassani@polito.it

Abstract

Large volumes of muck are produced in the Alpine Region and bordering areas as a result of new road and railway construction. Many other initiatives along European corridors will lead to further construction activity, with a consequent increase in environmental problems related to the use or disposal of muck. Therefore, there is a clear opportunity for the extensive re-use of muck due to the high demand for granular materials, the depletion of existing quarries, and the environmental constraints preventing or delaying the opening of new quarries.

In this scenario, a new approach to the re-use of muck is both necessary and timely. Although many typical defects deriving from its geological nature and/or from the extraction techniques employed may lead to its rejection as an aggregate, these same defects are of less importance in embankment, subgrade and subbase construction, and, indeed, in most cases they can be mitigated by granular or chemical stabilization.

The investigation described here embraces this new philosophy. Starting from the chemical physical characterization of seven different mucks derived from tunnelling activities on the Italian side of the Alps, the paper aims to explore the potential benefits deriving from their re use as a construction material. This activity has been undertaken in compliance with performance-based and performance related testing protocols. Notwithstanding the unfavourable geological origin of some of the considered materials, they all exhibited mechanical properties that would encourage their complete re-use in infrastructure construction projects.

Keywords: tunnel spoil, muck, tunnel boring machine, volumetric characteristics, mechanical properties, construction

1. Introduction

In Europe, the transportation infrastructure system is considered fundamental for the smooth operation of the internal market, the mobility of people and goods, and economic and social cohesion between European countries. In pursuit of this objective, the Trans-European Transportation Network (TEN-T) provides roadways, railways, and airports as defined by the European Union in the 1980's. In the twenty seven EU member countries 5,000,000 km of paved roads, of which 65,100 km are motorways, and 212,800 km of railway lines are included (European Commission, 2005). In Northern Italy, 200 km of new railway tunnels and 200 km of road tunnels of more than 2,000 m in length are planned (World's Longest Tunnel Page, 2012), together with new underground lines in the largest urban areas. From 2013 to 2015, the plan for the Italian railway system envisages approximately 2,500 km of new infrastructures (Rete Ferroviaria Italiana, 2012).

These new constructions will lead to the excavation of a great amount of granular materials, so the re-use of tunnel mucks, now considered a waste in accordance with new construction specifications, could make an important contribution to the sustainable, economic and technological development of European society.

A well-performing transportation network requires large volumes of natural resources such as soils and aggregates. The European Aggregates Association indicates that in 2010 the production of aggregates was of the order of 3,680 Mt, of which recycled aggregates accounted for 186 Mt (5%) and crushed rock accounting for 1,929 Mt (53%). In Italy there are no figures available for the percentage of recycled aggregates (European Aggregate Association, 2012). Despite the high level of activity associated with the provision of infrastructures and the considerable need for resources, the document on the impact assessment on European Transport Area (European Commission, 2011), attached great significance to the employment of environmental resources but paid very little attention to the employment of mineral raw materials (soils and rocks) and their recycling and re-use.

This paper promotes the consideration of tunnel muck as a stable and alternative source of surrogate and soils. For this purpose, seven tunnel mucks with different geological origins and produced by different excavation methods were considered. Although certain defects may lead to the rejection of some muck as aggregate, these same defects render the muck suitable for use in embankments, subgrades and pavement subbases which require large volumes of granular materials. Indeed, for these applications such deficiencies are of minor importance and do not compromise the in field performance of pavements.

2. Background and literature review

2.1. Re-use of tunnel mucks

The idea of an extensive re-use of tunnel excavated materials originated in the 1990s when growing environmental and sustainability problems associated with the supply of natural aggregates became one of the most important issues in civil construction (Kwan and Jardine, 1999; Gertsch et al., 2000). In recent years the problem has been exacerbated due to the construction of a number of very long tunnels which have generated significant quantities of muck to be disposed of, with an ensuing consumption of land, economic and environmental resources. This depletion of resources is certainly not sustainable in the long term. Nevertheless, in spite of the large scale impact of the problem, only a limited number of experimental investigations relating to the possibility of using muck as aggregate or soil surrogate have been disseminated in literature.

A number of these studies have focused on the effects of the excavation technique used on the properties of spoils. Grunner et al. (2003) underlined that the usages of excavated materials should be evaluated on the basis of the excavation driving method as this influences sweeping and the shape of mucks. They noted that the use of the Tunnel Boring Machine (TBM) led to a particle size which was suitable for aggregate, while the use of classical excavation methods implied that the characteristics of muck depend on the physical state of the original rock mass and on the blasting technology used.

Some attempts have been made to assess the possibility of reusing muck as concrete aggregate especially when the excavation process is carried out by means of the TBM. Using six different TBM mucks, Olbrecht and Studer (1998) obtained a highly-workable concrete characterized by a greater shrinkage and a lower elasticity modulus, approximately equal to 50% of that of conventional concretes. Thalmann-Suter (1999) also pointed out that the recycling of excavated debris begins with the choice of digging method and requires careful and continuous control of the muck produced to ascertain its quality with practice-friendly test methods.

The possible re-use of excavation materials has also been evaluated in Austria where 32x106 Mg per year of muck are produced. The research by Resch et al. (2009), supported by the Austrian Research Promotion Agency, highlighted that the re-use of muck depends mostly on the lithological properties of the excavated rock, the demand for mineral raw materials within a defined distance from the tunnel construction site, and the treatments which the tunnel mucks are subjected to after excavation.

In more recent years, some experience with the re-use of muck has been gained with the generation of large volumes thereof during the construction of new tunnels in the Alpine region. An investigation carried out at the Gotthard Base Tunnel (Lieb, 2009) analyzed spoil recycling for the production of high quality concretes and shotcretes. In this case, a specific testing plan was developed to assess the quality of both the raw material and the concrete mixes produced by evaluating workability time, mechanical properties and durability.

In the Danube Lobau tunnel experience (Schröfelbauer et al., 2009) it was observed that gravel and sands obtained from spoils can be used as aggregate for concrete production or as soil for embankments and subgrades. Silt and clay obtained from excavations can be used instead for embankment filling and backfilling (after suitable drying) depending on their plasticity.

Finally, Bourdin and Monin (2009) working on material extracted from the shafts of the Lyon-Turin high-speed railway, also remarked on all the different usages for excavated material. Depending on spoil characteristics, they identified three distinct quality classes for the production of concrete aggregates, of soil surrogates for embankments, and finally for disposal into deposit areas. They also noted that the extensive recycling of excavated debris could lead to significant benefits including a reduction in the area required for deposit, a reduction in the cost of aggregates and embankment materials, and above all lower CO_2 emissions.

As a result of the literature review, it can be noted that past experiences are centred on the evaluation of a unique source of muck in the construction of outstanding infrastructures. Moreover, most of the papers focus on the recycling of the most valuable part of mucks which is normally used solely in the production of cement mixtures, while limited attention is devoted to the total volume of excavated materials. Finally, the testing protocols considered in the experimental investigations are performance related tests that cannot lead to a re-use of muck based on a rationale approach.

2.2. Recycling and Construction Specifications

The common purpose in the management of large quantities of tunnel muck is their recycling in order to provide surrogate gravel for constructions. To obtain satisfactory mechanical properties in line with those exhibited normally by granular materials, tunnel muck should be first selected and then treated to improve size distribution and shape, breaking down flat and elongated particles into more polyhedral ones (Thalmann-Suter, 1997). This operation is necessary to obtain a more suitable material which can increase in value when its use passes from embankments, to subgrades, subbases, or better still to bituminous and/or cementitious mixtures used for pavements and constructions.

The European Directive 2008/98/EC (European Parliament and The Council of the European Union, 2008) considers tunnel mucks as waste material only, even when employed in other construction sites. Conversely, according to the recent European Communications on Prevention and Recycling of Waste (European Commission, 2011b), one of the main expected achievements of the European waste strategy is a reduction in the level of waste generated and, indeed, its use as a resource. With regard to material availability, the construction and industrial sectors are now facing a general depletion in the levels of traditional raw materials. The problems involve both the quantity of raw material produced as well as their quality and are caused by the exhaustion of good quality raw material quarries and the opening of quarries producing low to medium quality raw materials (Commission of the European Communities, 2005 and 2008). The need for treatments and higher transportation costs are playing a major role in the construction and industrial economy. From this point of view, the use of tunnel muck represents an important step towards the much heralded goal of sustainable development.

Two general markets exist for tunnel muck: the first one is very small and internal to the construction site of origin in which it is viewed as a construction material; the second one is the global “aggregate and soil market” which is external and larger but where the muck is deemed to be waste. Only small quantities of muck can be employed in the same site from which it has been excavated, so the second destination is prevalent. In this case, every national regulation attributes a specific sub classification to excavated rocks and soils. In Italy, for example, new norms are set to be introduced in which non hazardous excavated waste materials will be classified as by-products or secondary raw materials, facilitating their direct employment.

During tunnel excavation, only small quantities of excavated materials are of good quality, while the largest part is normally considered to be low quality and consequently employed in non structural applications or, more frequently, disposed of in landfill or dumping sites. As a consequence, good tunnel mucks have a negligible value. The idea of an extensive recycling of excavated materials dovetails with the consistently high demand for granular materials. Moreover, in many regions most of the quarries are close to exhaustion, while new quarries cannot be opened as a result of environmental constraints. Currently, in Northern Italy, up to 50% of granular materials employed in the formation of embankments and unbound granular layers of pavements derive from the recycling of construction and demolition waste.

In light of the abovementioned considerations, two main questions arise: is there the possibility to broaden the use of alternative granular materials, such as tunnel mucks, in the field of civil constructions? And secondly: does the attainment of this objection necessitate the adoption of different construction specifications?

Most of the difficulties encountered in the use of alternative materials centre on the type of specification stipulated in contracts (AASHTO Highway Subcommittee on Construction, 2003). Typically, “quality assurance” (QA) or “performance-related” (PR) specifications are used in the selection of road materials. In these two cases, material typology and acceptance limits are rigidly imposed in order to guarantee the use of specific materials, the selection of which depends exclusively on the judgment from an engineering point of view of test results on several representative samples. This approach is based on the idea that the quality of each single material can ensure the designated performance of the entire structure throughout its service life. In the case of PR specifications, only key parameters that demonstrate an empirical correlation with fundamental engineering properties are considered. Through the use of QA/PR specifications, the expected performances can be easily achieved by traditional materials.

On the other hand, “performance-based” (PB) specifications are rarely used in contracts (AASHTO Highway Subcommittee on Construction, 2003). They establish desired levels of fundamental engineering properties that must be reached to ensure the design life. Properties like resilient modulus and permanent deformation resistance are taken into account and used in mathematical models to calculate performance variables such as stress, strain, or distress levels under the prevailing traffic, environmental and structural conditions. As a result, the expected performance can be achieved by using any traditional, innovative or recycled materials. Therefore, the use of PB specifications does not preclude the use of any granular waste or by-products like tunnel muck.

3. Objectives and methodology

In 2007, with the target of exploring new possibilities in the realm of muck recycling, the Regione Piemonte financed the Remuck Project, which was developed by the Politecnico di Torino (2012) in cooperation with a number of private companies and public associations.

In the Remuck Project, seven tunnel mucks derived from the excavation of new tunnels in the Alps and from the construction of the new underground line in the city of Turin were considered (Table 1). In light of the different petrographical properties, excavation methodologies and treatment processes, the investigation sought to assess the effect of such factors on the properties of the derived material as an alternative source to surrogate traditional aggregate and soil.

After a first step which focused on the base characterization of mucks, the main stages of the investigation program included volumetric and mechanical tests carried out both in the laboratory and in full-scale tests. In particular, three different compaction methodologies were considered:

- the modified Proctor method, which entails a hammer impacting on squat cylindrical moulds;
- the gyratory method, which provides a simultaneous compressive and shear effort feed into thin cylindrical moulds;
- the rolling compaction method for the generation of full-scale layers.

The modified Proctor procedure is currently considered in QA/PR specifications for the derivation of fundamental parameters such as the optimal water content and the maximum dry density of soils. On the other hand, the gyratory compaction procedure was selected in order to better replicate the field compaction force, and hence to meet the requirements for the characterization of materials as per PB test protocols.

Table 1
Muck samples.

Code	Infrastructure	Sampling site	Excavation method	Treatments
S1	Turin underground, Marconi station	Turin, Italy	EPB	EM – CP
S2	Turin underground, Dante station	Turin, Italy	Cut & Cover	EM – CP
S3	Turin underground, Lingotto station	Turin, Italy	EPB	EM
S4	High Speed Rail Turin-Lyon	Clarea valley, Turin, Italy	Coring	CP
S5	Regional Road 229, Bocciol tunnel	Omegna, Verbania, Italy	Explosive	EM – CP
S6	Railway Verona-Innsbruck, Brennero tunnel	Aica, Bolzano, Italy	TBM	EM
S7	Hydroelectric plant tunnel, Torrent	La Thuile, Aosta, Italy	TBM	EM – CP

Remarks: EM: Excavated Material, CP: Crushed in mobile Plant.

The field operation was possible thanks to the availability of great quantities of just four mucks, which made it possible to evaluate the in-field density parameters for layers of 25 cm in height. In all cases, a heavy articulated vibratory roller was used. During the field operations, loose granular materials were taken from the deposits and used to reproduce laboratory samples. The samples obtained via the two compaction techniques mentioned above underwent mechanical tests.

Proctor samples were subjected to a CBR test, which is coherently included in QA/PR technical specifications, while gyratory samples were used in the evaluation of the resilient modulus through the dynamic triaxial test, which is conversely used in PB technical specifications and is assumed as the basis for the rational structural design of pavements. Similarly, Light Weight Drop (LWD) tests were performed on-site with the aim of assessing the bearing capacity of the granular full-scale layers through the estimation of the dynamic elastic modulus.

As a result of the extensive physical, volumetric and mechanical characterization of mucks, the analysis of test results in light of the acceptance limits pertaining to QA/PR and PB specifications is proposed in this paper. Furthermore, a comparison with reference limits derived from traditional materials led the authors to final conclusions about the recycling possibilities of the investigated mucks.

4. Materials

Table 1 contains the essential information on the seven mucks analyzed in this experimental investigation.

The first three materials, alluvial in nature, were collected from the new Turin underground line. The samples from Largo Marconi station (code S1) and Lingotto Station (code S3) were excavated by means of the Earth Pressure Balance (EPB) tunnel boring machine. This machine permits the excavation of tunnels in soft ground conditions where clay, silt, and sand are present. The front shield of the machine is filled with debris extracted by a screw conveyor. This screw compensates for the pressure difference between the bulkhead chamber and the atmospheric pressure. Foam injection renders the material more homogeneous, thus facilitating its excavation. The second alluvial sample (code S2) was taken at the Corso Dante station and excavated with the Cut and Cover method, in which a trench is excavated and roofed over with an overhead support system strong enough to bear the load of whatever is to be built above the tunnel.

The S4 material was derived from the crushing of micascist cores collected during the exploration phase in the Clarea Valley for the new High Speed Railway line from Turin to Lyon, which forms part of the TEN-6 axis. Only part of the cores taken from the depth of the future tunnel were taken and used to form the S4 sample. The S5 and S6 samples were both grey granite: the first was excavated by means of the Explosive method along the Bocciol tunnel belonging to the new section of the Regional Road 229 in Piedmont, while the second was extracted from the pilot drift in Aica (Alto Adige) of the Brennero base tunnel which is part of the new High Speed Railway line from Verona to Innsbruck along the TEN-1 axis. In this latter case, a Tunnel Boring Machine (TBM) was employed; with this technique disc cutters on the front shield create compressive stress fractures in the rock, causing it to chip away. Finally, the S7 is a calcareous schist excavated by means of a TBM from the Torrent-La Thuille hydroelectric plant tunnel.

The seven mucks were processed in a mobile plant. As a result, the mucks were divided into freshly excavated material (EM), and crushed muck in the mobile plant (CP) as indicated in Table 1.

The mobile plant (Figure 1) has a production rate of 280 Mg/h and a maximum input dimension of 600 mm for the material to be treated. It is composed of a vibrating screen placed above a jaw crusher and a magnetic separator, which is positioned on a conveyer belt on which the output material is transported. The material exiting from the crusher can be regulated to a minimum size of 30 mm. As a consequence, the plant offers one end product only.

Fig. 1. Mobile crushing plant used for the treatment of excavated materials.

4.1. Petrographic and geotechnical classification

The petrographic description and the geotechnical classification of the mucks are reported in Table 2, while the particle size distribution is illustrated in Figure 2.

The particle size distribution was performed using the wet sieving method for the granular fraction larger than 75 µm and the air jet sieving method for fractions finer than 75 µm in accordance with EN 933 1 (1999) and EN 933-10 (2009) respectively. As indicated in EN ISO 14688-2 (2004), two separate parameters have been used to define the shape of the grading curve: the uniformity coefficient C_U:

$$C_u = d_{60}/d_{10} \qquad \text{(eq.1)}$$

and the coefficient of curvature C_C:

$$C_c = (d_{30})^2/(d_{10}\cdot d_{60}) \qquad \text{(eq.2)}$$

where d_{10}, d_{30} and d_{60} denote the particle sizes corresponding to the ordinates 10%, 30% and 60% by mass of the percentage of material passing through the sieve.

The three alluvial samples (S1, S2, and S3) presented the typical petrographical composition, albeit with some minor variations between sites, of Turin deposits, a composition which is quite well appreciated in the aggregate market for concrete production. The three samples contained a high percentage of rounded fragments of hard rock. Of the three alluvial mucks, S1 contains the highest percentage of fine grains.

Sample S4 is composed of mica schist from the Ambin Unity in the Alps and was obtained from the crushing of core probes: hence the reason why grading curve and geotechnical classifications are not present in Table 2 and Figure 2. The first sample of the two grey granites (S5) shows a certain degree of weathering mainly due to the high presence of saussurrite in the feldspars; the second one (S6) is more compact and characterized by mechanical strength. Saussurrite is a common, greenish mineral aggregate, produced in part by the alteration of feldspar, consisting chiefly of epidote and zoisite. Finally, sample S7 is a calcschist with a low percentage of mica and, consequently, low schistosity.

Table 2
Petrographical description and geotechnical classification of mucks.

Code	Petrographical description	AASHTO classification	CEN classification	C_U	C_C	Shape of grading curve
Standard	EN 932-3	M 145-91	EN ISO 14688-2			
S1	Alluvial rock composed of quartz (30%), calceschist (20%), green stones (30%), granites, limestone, sandstones (20%), fines (10-15%)	A1-a	saGr	314	2.4	Multi-graded
S2	Alluvial rocks composed of quartz (25%), calceschist (25%), green stones (18%), cemented rocks (20%), micaschist (10%) on the grains size 20-30 mm, fines (<10%)	A1-b	saGr	93	0.8	Gap-graded
S3	Alluvial rock composed of quartz and green stones	A1-a	saGr	147	0.8	Gap-graded
S4	Mica schist	N/A	N/A	N/A	N/A	N/A
S5	Granite composed of potassium feldspar (35%), quartz (40%), plagioclase (10%), biotite passing to chlorite (10-15%), and other materials including zircon with pleochroic halo, pyrite and white mica.	A1-a	saGr	44	0.7	Gap-graded
S6	Granite	A1-a	saGr	146	1.3	Multi-graded
S7	Calcareous schist composed of carbonates (65%), quartz (25%), white mica (5%), and opaque (5%)	A1-b	sasiGr	454	0.9	Gap-graded

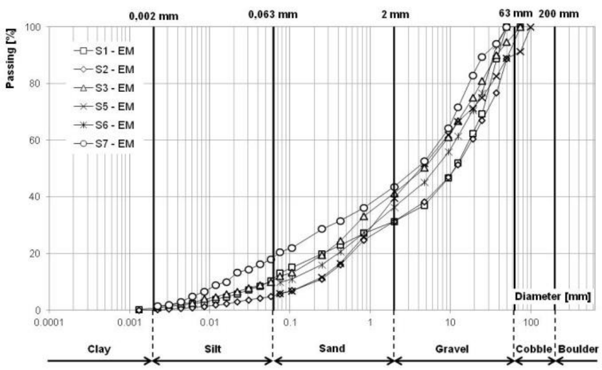


Fig. 2. Gradation curves of the excavated mucks.

4.2. Physical characterization

Table 3 reports all the results obtained from physical tests on particles (density, shape, flakiness, fragmentation and wear resistance) in accordance with current QA/PR European standards included in the European Committee for Standardization list. Table 3 includes data derived from laboratory tests performed on freshly excavated material (EM) and on crushed muck (CP). Furthermore, it states the category to which each material belongs as per EN 13242 (2008), which is used to classify aggregates for unbound and hydraulically bound materials for use in civil engineering works and road construction.

The particle density (EN 1097-6, 2000) of the investigated mucks assumed values in the typical range for granular materials commonly used in road construction (around 2.70 Mg/m^3). The granite samples (S5 and S6) were characterized by lower values, while the alluvial and schist mucks were characterized by higher density values.

Shape and flakiness indexes have been evaluated in accordance with EN 933-3 (2003) and EN 933-4 (2008) respectively. The shape index represents the ratio between the mass of non-cubical particles and the total mass of particles tested, while the flakiness index is the ratio of the total dry mass of elongated particles passing through specific bar sieves to the weight of the full sample expressed in percentage terms (the test consists of two standardized sieving operations; firstly, particles are separated into various size fractions; secondly, each fraction is then sieved using bar sieves).

The two tests provide useful indications with respect to the parameters relating to the compaction attitude of granular materials. In order to attain significant strength and stiffness levels, high percentages of flat and elongated particles are undesirable as they influence the shear resistance of granular materials during the compaction process leading to weaker granular layers under traffic loads. Normally, they must be discarded or limited to a specific percentage. Figure 3 shows that muck index values can vary and depend on their mineralogy, the excavation method used and the milling process applied. However, it must be emphasised that the crushing processes led to a significant improvement in these characteristics as clearly indicated by the arrows that link the EM data to the corresponding CP ones. In fact, all the arrows indicate a decrease in the SI and FI indexes which is particularly evident in the case of mucks such as S2 and S7 characterized by high values for both indexes.

The soundness of coarse granular materials was tested through the determination of the fragmentation resistance by means of the Los Angeles test, and of the wear resistance according to the Micro Deval test. These fundamental tests permit the evaluation of the mechanical degradation of aggregates during handling, construction and in-service time. Please note that some data could not be included in Table 3 for several reasons. For S4 muck, only the density test could be performed on particles derived from its crushing in the mobile crusher. In other cases, the Los Angeles and Micro Deval tests were not performed due to difficulties encountered in the formation of the test samples caused by limited quantities of granular classes as required by the new EN norms.

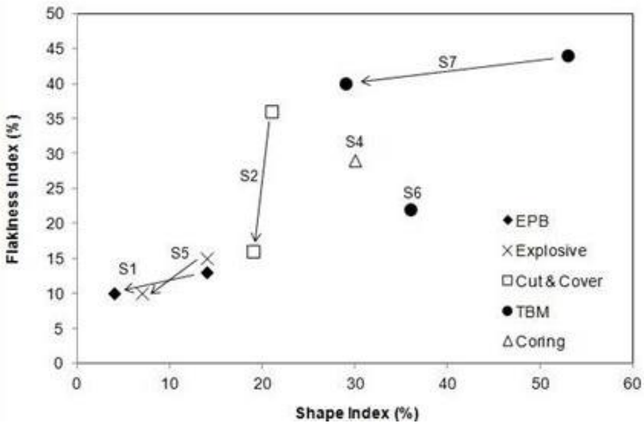


Fig. 3. Shape and flakiness indexes of mucks (the arrows indicate the variation of indexes following the crushing process).

Table 3
Physical and mechanical properties of freshly excavated (EM) and crushed (CP) materials and classification according to EN 13242.

Test		Particle density	Shape index		Flakiness index		Los Angeles		Micro-Deval	
Standard		EN 1097-6	EN 933-4		EN 933-3		EN 1097 - 2		EN 1097 - 1	
Code	Treatment	(Mg/m^3)	(%)	Cat.	(%)	Cat.	(%)	Cat.	(%)	Cat.
S1	EM	2.75	14	SI_{20}	13	FI_{20}	22	LA_{25}	11	$M_{DE}20$
	CP		4	SI_{20}	10	FI_{20}	24	LA_{25}	12	$M_{DE}20$
S2	EM	2.75	21	SI_{40}	36	FI_{50}	28	LA_{30}	19	$M_{DE}20$
	CP		19	SI_{20}	16	FI_{20}	28	LA_{30}	18	$M_{DE}20$
S3	EM	2.71	N/A	-	N/A	-	N/A	-	N/A	-
S4	CP	2.79	30	SI_{40}	29	FI_{35}	N/A	-	N/A	-
S5	EM	2.65	14	SI_{20}	15	FI_{20}	N/A	-	N/A	-
	CP		7	SI_{20}	10	FI_{20}	38	LA_{40}	23	$M_{DE}25$
S6	EM	2.69	36	SI_{40}	22	FI_{35}	24	LA_{25}	N/A	-
S7	EM	2.74	53	SI_{55}	44	FI_{50}	N/A	-	9	$M_{DE}20$
	CP		29	SI_{40}	40	FI_{50}	27	LA_{30}	N/A	-

In general terms, the data reported in Table 3 and Figure 3 confirm that the investigated mucks can be employed in the formation of unbound granular layers of the road structure, and that the milling process has a significant, positive effect on the shape and elongation parameters without altering the mechanical properties of particles.

Regarding samples S1 and S2, which are very similar, alluvial materials excavated from along the new Turin underground line in two locations located 1200 m apart, further investigations regarding the fines content were performed in order to better determine the influence of the excavation method (EPB for S1 and Cut and Cover for S2). In particular, in the case of sample S1 derived from excavation with EPB, a foaming biodegradable agent was used in order to reduce friction, stress and strain on tools, and to reduce blocking due to kneading of the material.

The sand equivalent (SE) test (EN 933-8, 2000) and the methylene blue (MB) test (EN 933-9, 2009) were conducted on the granular fractions finer than 2 mm in order to assess the presence of dangerous organic clay in the two materials. A SE test value lower than 30 indicates a significant amount of fines (clay and silt), while a MB test value lower than 10 highlights the presence of a negligible amount of noxious clay.

Sample S1 exhibited a SE value equal to 36, and a MB value equal to 1.9; while the S2 sample exhibited a SE value equal to 96, and a MB value equal to 0.5. Part of the difference was certainly caused by the different excavation methods that resulted in a higher amount of fine grains in the S1 muck compared to S2, a finding which can be mainly attributed to the presence of silt. Both mucks showed a very low clay content which, however, does not compromise their use in embankments, subgrades and subbases.

5. Testing methods

5.1. Sample preparation and volumetric characterization

Referring to Figure 4, the laboratory samples were compacted by following two procedures. In the case of the Proctor method, only filtering with the 19 mm sieve was considered using moulds with a diameter of 152.4 mm and a height of 116.4 mm as per AASHTO T180 (2010).

The optimal moisture content (w_{opt}) and the maximum dry density values ($\gamma_{d,max}$) were evaluated at 2.68 MJ/m^3 of compaction energy corresponding to 56 blows of the compaction hammer on each of the five layers with a weight equal to 4540 g falling from a height of 0.457 m. The maximum dry density was used as a target value for the production of samples at the gyratory shear compactor (GSC). Even though such a compaction technique is normally used for the production of bituminous mixture samples in accordance with AASHTO T312 (2009), the authors included it in the experimental program thanks to its ability to transfer shear stress to laboratory samples in the same manner that rollers operate on full scale layers.

The samples compacted at the GSC were produced by applying and maintaining a vertical pressure of 600 kPa on the top of the mould, which gyrates at a rate of 30 gyration/min with a tilting angle of 1.25°. Three moisture contents corresponding to the optimal one (w_{opt}) and two variations of 2% around the optimum (w_{opt} – 2%, w_{opt} + 2%) were considered for the production of the specimens. The total quantities of dry granular material and water were calculated in advance so as to obtain the target Proctor dry density and moisture content for samples of 200 mm in height and 100 mm in diameter.

The samples were produced fixing the height as a mode of operation which is alternative for GSC to the number of gyrations mode; hence, the number of gyrations at the target height was always variable. To facilitate equal distribution of the compaction energy in the sample, the loose material was divided into four parts, with each part then being compacted separately in the mould adding one part over the former one.

The degree of compaction (C_g) was evaluated at a generic number of gyrations for each layer using the following formula:

$$C_g = 100 \cdot \frac{\gamma_d \cdot h_f}{\gamma_g \cdot h_g} \qquad \text{(eq.3)}$$

where γ_g is the particle density of the grains (EN 1097-6, 2008), and h_g and h_f represent the height of the sample measured at the generic number of gyrations (n_g) and at the end of the compaction process (n_{gf}) respectively. It is worth noting that the degree of compaction indicated in eq. 3 is the complement to one hundred of the void content expressed in percentage terms of the dry granular material.

Four compaction curves associated with each sample were obtained considering the dependency of the degree of compaction (C_g) to the number of gyrations (n_g). In all cases the following equation was found to be the best regression function:

$$C_g = C_1 + k_g \cdot \log(n_g) \qquad \text{(eq.4)}$$

where the regression parameters k_g and C_1 represent the workability and the initial degree of compaction at the first gyration ($n_g = 1$) respectively.

Field operations on full-scale layers of the investigated mucks were performed in order to assess the workability of such materials in the field. Compaction parameters like workability (k_p) and the initial compaction degree (C_1) cannot be derived with sufficient accuracy after each roller pass (n_p). As a consequence, the compaction assessment was made by comparing the field dry density to the laboratory maximum density from the Proctor test (Figure 4). In-field dry density was evaluated by performing the sand cone test subsequent to the completion of the compaction process consisting of a specified number of roller passes (n_{pf}).

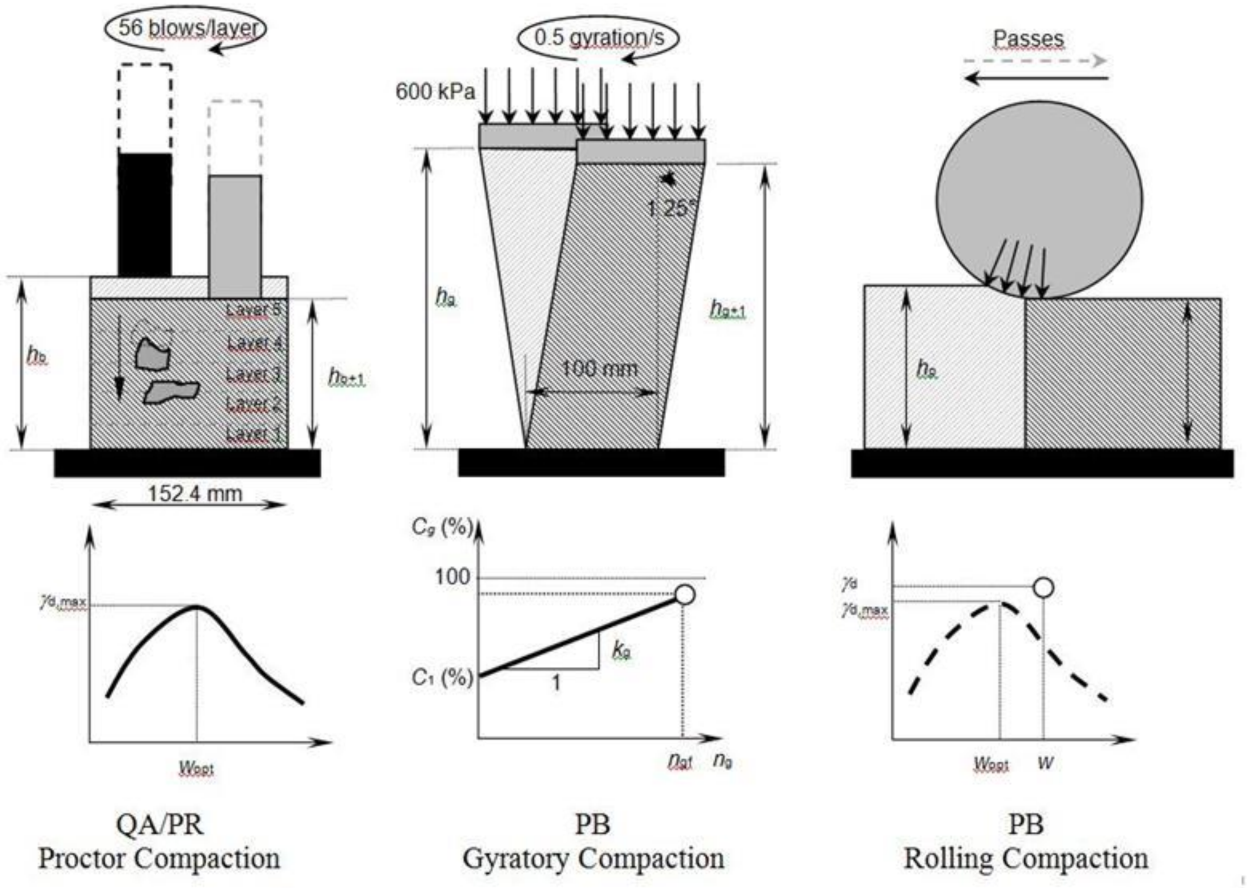


Fig. 4. Proctor, gyratory and in-field roller compaction methodologies and typical results.

5.2. Mechanical characterization

As per the schema hitherto described, the mechanical tests, adhering to QA/PR and PB specifications, were conducted to assess the bearing capacity of mucks. In the case of the QA/PR approach, California Bearing Ratio (CBR) tests were performed in adherence with AASHTO T-193 (2010) on specimens compacted with the Proctor procedure. For the PB approach, tests performed included resilient modulus tests (AASHTO T-307, 2007) on laboratory specimens, and dynamic Light Weight Drop tests (TP BF-StB section B 8.3, 2003) for the derivation of the dynamic modulus on in-field layers.

The CBR is an index of bearing capacity that is traditionally used for the evaluation of natural soils and granular materials employed in the formation of embankments, subgrades and subbase layers. The index represents the highest percentage ratio between the force (P_1) necessary to penetrate to two specific depths (h, equal to 2.5 and 5 mm) in a confined specimen of compacted granular material, and the force necessary to repeat the same procedure with the reference Californian limestone crushed rock, characterized by a CBR equal to 100% (Figure 5). During the test, the stress and strain state is unknown and the performance can only be adjudged in relative terms.

The resilient modulus test is a dynamic triaxial test (Figure 5) where an impulsive pressure (σ_1) is applied to the upper surface of a cylindrical laboratory specimen. The resilient modulus represents the ratio between the maximum deviatoric stress ($\sigma_{1,max} - \sigma_3$) recorded at each load application, and the maximum recovered vertical strain ($\varepsilon_{z,max}$). Two testing protocols are available in AASHTO T-307 (2007) for subgrade and subbase materials respectively. In this investigation the first was adopted to test the EM samples, whereas the second was used to test the CP samples. In both cases, only particles passing through the 20 mm sieve were used for the formation of test samples.

The Light Weight Drop (LWD) test is a plate loading test that is used to estimate the dynamic modulus (E_d) of subgrades and subbases. It consists of a falling weight that impacts on a rigid plate, 0.3 m in diameter, and an accelerometer that records the maximum deflection of the layer on impact. The estimate of the dynamic modulus (E_{df}) is made referring to the equivalent half space system through the application of the following formula:

$$E_{df} = \pi \cdot \frac{\sigma_{1,max} \cdot r \cdot \left(1 - \nu^2\right)}{2 \cdot \Delta h_{max}} \qquad \text{(eq.5)}$$

where $\sigma_{1,max}$ is the maximum pressure applied by the falling weight on the rigid plate, r is the radius of the plate, ν is the assumed Poisson Ratio, and Δh_{max} is the maximum deflection of the plate as measured by the accelerometer.

When used in the case of a two- layer system like the one in Figure 5, the modulus of the upper layer (E_d) can be calculated by considering the Biroulia-Ivanov equation:

$$E_{df} = \frac{E_{hs}}{1 - \frac{2}{\pi}\left(1 - \frac{1}{n^{3,5}}\right)\arctan\left(\frac{\pi \cdot h_1}{4a} \cdot n\right)} \qquad \text{(eq.6)}$$

in which E_{hs} is the dynamic modulus of the lower half-space, h_1 is the thickness of the upper layer, and finally $n = (E_{hs} / E_d)^{2.5}$.

During the LWD test performed in-situ, a peak value of the testing force equal to 7.1 kN was applied, which corresponds to a peak stress of 100 kPa ($\sigma_{1,max}$). Each layer was tested at three different points; the dynamic modulus at each point was calculated, following three pre-conditioning loading applications, through the recording of deflection (Δh_{max}) of three further load applications. The average of the three testing point values was considered as representative of the entire layer.

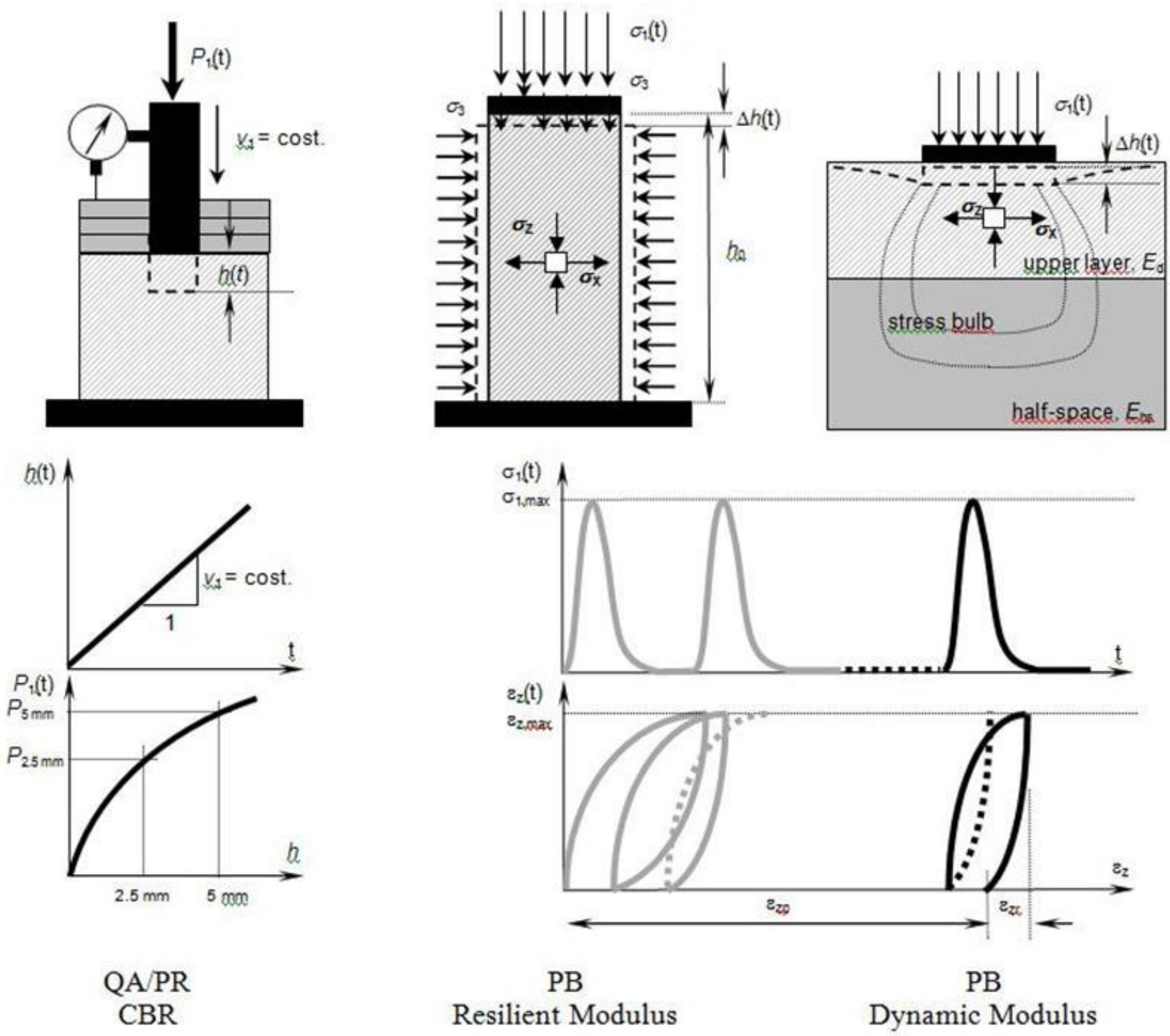


Fig. 5. CBR, resilient modulus and dynamic deflectometer tests and results.

It should be highlighted that the stress-strain conditions under the test plate are not representative of those occurring under real traffic conditions, where the pressure applied by trucks is 6-8 times greater in the contact area between tires and pavements. As a result, the stress bulb generated under the test plate is relatively shallow with its depth only marginally exceeding its diameter.

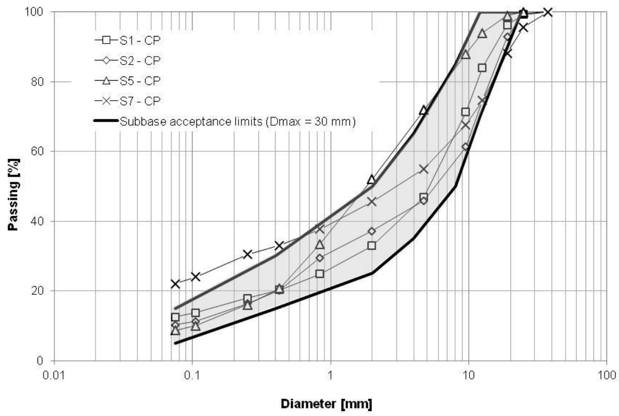
6. Results analysis

6.1. Classification, grading and particle shape

On examination of the tables and figures presented in Section 4, the test results on granular materials obtained from mucks show all of them to be potentially suitable materials for the formation of embankments, subgrades and subbases. In fact, the data reported in Table 2 show that the excavated materials are classified as sandy gravel and belong to the A1 class of the AASHTO classification systems (AASHTO M 145 2008). Their grading levels vary from multi-graded to gap-graded curves and they exhibit a wide range of values for the uniformity coefficient (C_u) variable, even though the coefficient of curvature (C_c), which represents the second moment of the grain size distribution curve, reveals well graded materials as evidenced by the fact that all values are included within the two reference limits, equal to 1 and 3.

Figure 6 reports the grading curves of the materials crushed in the portable milling machine and the two limits for subbases. Such limits are reported in the technical specifications of the Ministero delle Infrastrutture e dei Trasporti (2001) which consider two types of UGM, the difference between which is in the maximum diameter (D_{max}). Table 1 indicates that five CP materials are largely in compliance with the specifications, with the exception of two materials:

- S7 presents an excessive quantity of fine grains (d < 0.075 mm) with respect to D_{max} = 30 mm;
- S4 shows a lower content of sand when compared to the D_{max} = 70 mm lower limit.



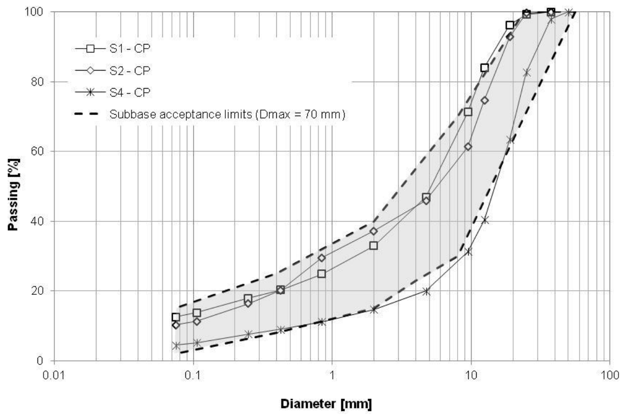


Fig. 6. Gradation curves of the mucks following the treatment process.

The excessive quantity (of fine grains) in S7 is partly due to the high initial fine content in the (EM) material generated by the TBM, while in the case of S4 it should be remembered that the CP materials derive from the crushing of cylindrical cores. In this latter case, higher quantities of fine grains are expected following traditional excavation.

6.2. Volumetric analysis of compacted materials

Table 4 synthesized the volumetric results obtained on compacted materials referring to methods and test procedures shown in Figure 4.

Despite the origins and types of selected mucks, all the materials require a restricted water content to ensure sufficient workability (between 4.05 and 6.50%), with a small variation when crushed materials are considered in place of the EM ones. Dry density is in line with the typical values presented in literature, with variations that depend on grading and particle density (Table 3). In Table 4, in addition to the parameters presented and discussed in Paragraph 5.1, in the case of

Proctor compaction the ratio between the uniformity coefficient of the granular material derived through the sieve analysis before ($C_{u,in}$) and after compaction ($C_{u,fin}$) has been included. Such a parameter is related to the sensitivities to compaction forces that lead to a grading variation especially in the case of tender and weak mucks, as in the case of the spoiled gray granite (S5) which demonstrates the widest range in values from 1.56 (CP) to 1.91 (EM). Such behaviour is also confirmed by the high Los Angeles and the Micro-Deval values reported in Table 3.

In the columns referring to the in-field compaction, the ratio between the field and laboratory dry density ($\gamma_d/\gamma_{d,max}$) has been added to attest to the soundness of field compactions operated by rollers and, at the same time, the attitude of the granular materials to be rolled in full scale layers. During compaction, the water content was less than the optimal value measured in the Proctor study, thus confirming that mucks may be used effectively and worked even when the water content is not well controlled.

Although the data does not reveal a clear tendency when simply associated with the physical parameters included in Tables 2 and 3, self-compaction and workability are correlated as clearly indicated in Figure 7. Data evolve following a squared parabola: low workability is exhibited by the excavated samples of S5, S6, and S7 mucks, while higher values are shown by crushed samples. In the case of samples S5 and S7, the crushing process increases the workability although different degrees of self compaction occurred. The maximum value of workability is evident in those mucks derived from the excavation of alluvial sandy gravel, so it cannot be excluded that the rounded surface of most of the constituent grains contributed to such a result.

On the other hand, self-compaction (C_1) is mostly influenced by the particle size distribution and by the shape and surface texture of particles. In the case of S7 EM and CP samples this is due to the high content of very fine particles that completely fill the space between the coarse grains (the mass percentage of particles finer than 75 μm is equal to 20.6% for EM, 22.0% for CP), while in the case of the S6-EM muck this is a consequence of its regular continuous grading curve that favours the initial packing of grains.

Table 4
Compaction, workability and optimum water content values resulting from laboratory and in-field compaction studies.

Code	Treatment	Proctor (impulsive) compaction				In-field roller compaction			Gyratory compaction	
		$\gamma_{d.max}$	$w_{opt.C}$	$C_{U,fin}/C_{U,in}$	ΔC_U	γ_d	$\gamma_d/\gamma_{d.max}$	w	C_1	k
		g/cm^3	%	–	%	g/cm^3	%	%	%	-
S1	EM	2.233	4.85	0.75	- 25.0	-	-	-	-	-
	CP	2.236	5.15	1.23	+ 23.3	-	-	-	68.3	8.06
S2	EM	2.146	6.50	1.18	+ 17.8	-	-	-	-	-
	CP	2.180	6.00	0.91	- 9.2	-	-	-	67.0	8.50
S3	EM	2.231	4.05	-	+ 75.3	2.125	95.2	4.20	72.5	6.88
S4	CP	-	-	-	-	2.073	-	4.46	-	-
S5	EM	2.048	6.38	1.91	+ 90.9	2.014	98.3	2.14	64.7	7.16
	CP	2.108	6.40	1.56	+ 55.6	-	-	-	65.9	8.03
S6	EM	2.204	4.66	1.01	+ 0.6	2.169	98.4	2.53	69.7	6.34
S7	EM	-	-	-	-	-	-	-	69.4	6.51
	CP	2.245	4.80	0.88	- 11.9	-	-	-	68.5	7.43

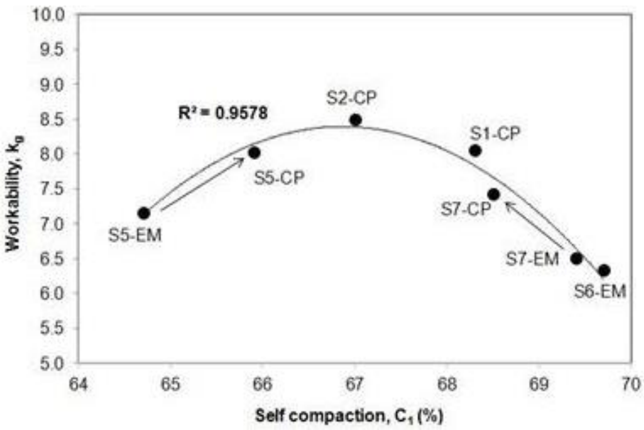


Fig. 7. Relationship between self compaction (C_1) and workability (k_g) parameters derived from gyratory compaction and reported in eq.4.

6.3. Mechanical analysis

In Table 5 the results of the CBR test, adhering to the QA/PR approach, are reported. It should be stressed that the high values measured confirm that the CBR test is sensitive to local conditions in the sample, so tough particles derived from the crushing of rock lead to very high CBR values. All results present values greater than 80%, which is considered to be the lower limit for crushed rock. Considering the data for S1 and S2 mucks, the crushing performed in the mobile plant produced great benefits in the samples of alluvial origin, while in the case of muck S5 a reduction in the CBR index was observed. The optimal water content for this test is, generally speaking, approximate to the corresponding one derived from the Proctor test (Table 4).

In Table 5 the average ratio ΔCBR/Δw is also reported which illustrates the sensitivity of the investigated materials to water content variation from the optimal value. These values were calculated by considering the CBR data derived from tests in which the water content varied by ±2% from the optimal value ($w_{opt.CBR}$), so the results were specific for a variation in water content above ($w > w_{opt.CBR}$) or below ($w < w_{opt.CBR}$) the optimal value. A minimum of three CBR tests were performed on each muck sample.

The results highlight the very high sensitivity to water content variation, subverting the inference derived from the Proctor compaction study. In fact, for a variation of only 1% in water content, the CBR of materials like S6 and S7 became too low, reaching values that are under the acceptance limit for subgrades and subbases.

In the case of the resilient modulus test, the investigated materials fall within the typical domains for reference materials. In contrast to the CBR test, repeated triaxial load tests involve the entire volume of the sample, and therefore the toughness of particles has limited influence while the surface interaction occurring at the points of contact between grains plays a major role.

Table 5
Mechanical properties derived from laboratory CBR tests.

Code	Treatment	CBR	$w_{opt.CBR}$	(ΔCBR/Δw) for $w < w_{opt.CBR}$	(ΔCBR/Δw) for $w > w_{opt.CBR}$
		%	%	-	-
S1	EM	154.6	5.34	60.3	61.9
	CP	184.4	4.37	66.1	82.0
S2	EM	105.6	6.83	29.9	34.6
	CP	176.4	5.97	27.7	91.0
S3	EM	149.9	3.82	18.1	59.6
S5	EM	212.1	6.97	19.0	46.4
	CP	166.3	6.41	23.6	-
S6	EM	210.3	4.78	77.1	134.8
S7	CP	201.0	4.10	178.7	62.0

As previously mentioned, in this experimental investigation the subgrade protocol of AASHTO T-307 (2007) was considered for the characterization of EM samples, while the subbase one was used for the CP samples. The synthesis of results derived from experimental data is given in Table 6, where the two parameters k_1 and k_2 were obtained via regression analysis through the Hick-Monismith (1971) equation:

$$M_R = p_a \cdot k_1 \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \quad \text{(eq.7)}$$

where θ is the bulk stress equal to $\sigma_1 + 2\sigma_3$ for the triaxial conditions, and p_a is the unit reference pressure of 1 kPa used to make the stresses non-dimensional. As originally indicated by Hicks and Monismith, the resilient response is influenced by bulk density, gradation and fines content, particle roughness and angularity, and degree of saturation (which in turn depends on the residual voids content after compaction and on water content). In particular, when granular materials are compared, high quality materials have larger k_1 values and smaller k_2 values (Rada and Witczak, 1981).

In Table 6, crushed samples of S1 and S2 alluvial mucks presented similar values and trends when water content varied from dry to wet conditions. In contrast, the third alluvial material (S3) was more sensitive to water content variation, with higher values of both parameters in correlation with damp conditions. Granular materials derived from the mucks show values similar to the alluvial ones; S5 muck exhibits a stable behaviour independently of the water content, while S6 shows lower moduli. Finally, the crushed sample of S7 muck shows a higher resilient behaviour than the original excavated material, in particular for dry and damp conditions.

Through the use of eq.7 a very good coefficient of determination (R^2) was found and is reported in Table 6. The six graphs of Figure 8 report the comparisons between the regression curves and the typical limits of granular subbase materials for three moisture conditions (dry, damp and wet), that were associated respectively with the $w_{opt.c}$ - 2%, $w_{opt.}$ and $w_{opt.}$ + 2% for both excavated (EM) and crushed (CP) materials. Without referring to specific cases, it can be observed that the resilient behaviour of the materials considered is in line with literature data (Huang, 2004). In the case of low water content ($w_{opt.c}$ - 2%) and EM samples, the materials derived from the crushing of rocks have a lower performance than those derived from alluvial deposits (S3). Materials with optimal or high water contents exhibited resilient moduli values within the ranges reported in literature (Huang, 2004).

Field data derived from the LWD test have been plotted in the same graph of Figure 8. Considering the water content data reported in Table 4, the tests on S3 and S4 were performed on damp layers while the tests on S5 and S6 were performed on dry layers. In the graphs, the values have been associated with a bulk stress equal to 83.6 kPa which is the average value in the stress bulb limited to a depth of 0.4 m (Figure 4). With the exception of the layers composed of S5-EM and S6-EM mucks which were affected by a low water content (dry condition in Figure 8), in the other two cases characterized by damp conditions (S3-EM and S4-CP), the dynamic modulus is coherent with the stiffness values derived from resilient modulus tests.

Table 6
Hicks-Monismith regression parameters.

Humidity		Dry ($w_{opt.c}$-2%)			Damp ($w_{opt.c}$)			Wet ($w_{opt.c}$+2%)		
Symbol		k_1	k_2	R^2	k_1	k_2	R^2	k_1	k_2	R^2
Code	Treatment	MPa	-	-	MPa	-	-	MPa	-	-
S1	CP	358	0.64	0.991	323	0.69	0.994	269	0.57	0.988
S2	CP	335	0.60	0.989	362	0.64	0.991	326	0.66	0.993
S3	EM	359	0.28	0.983	575	0.65	0.996	227	0.28	0.983
S5	EM	339	0.61	0.995	-	-	-	294	0.72	0.998
	CP	291	0.68	0.994	291	0.75	0.996	290	0.70	0.994
S6	EM	239	0.27	0.982	-	-	-	323	0.52	0.993
S7	EM	292	0.50	0.992	178	0.30	0.983	371	0.65	0.996
	CP	475	0.56	0.987	456	0.65	0.992	399	0.66	0.993

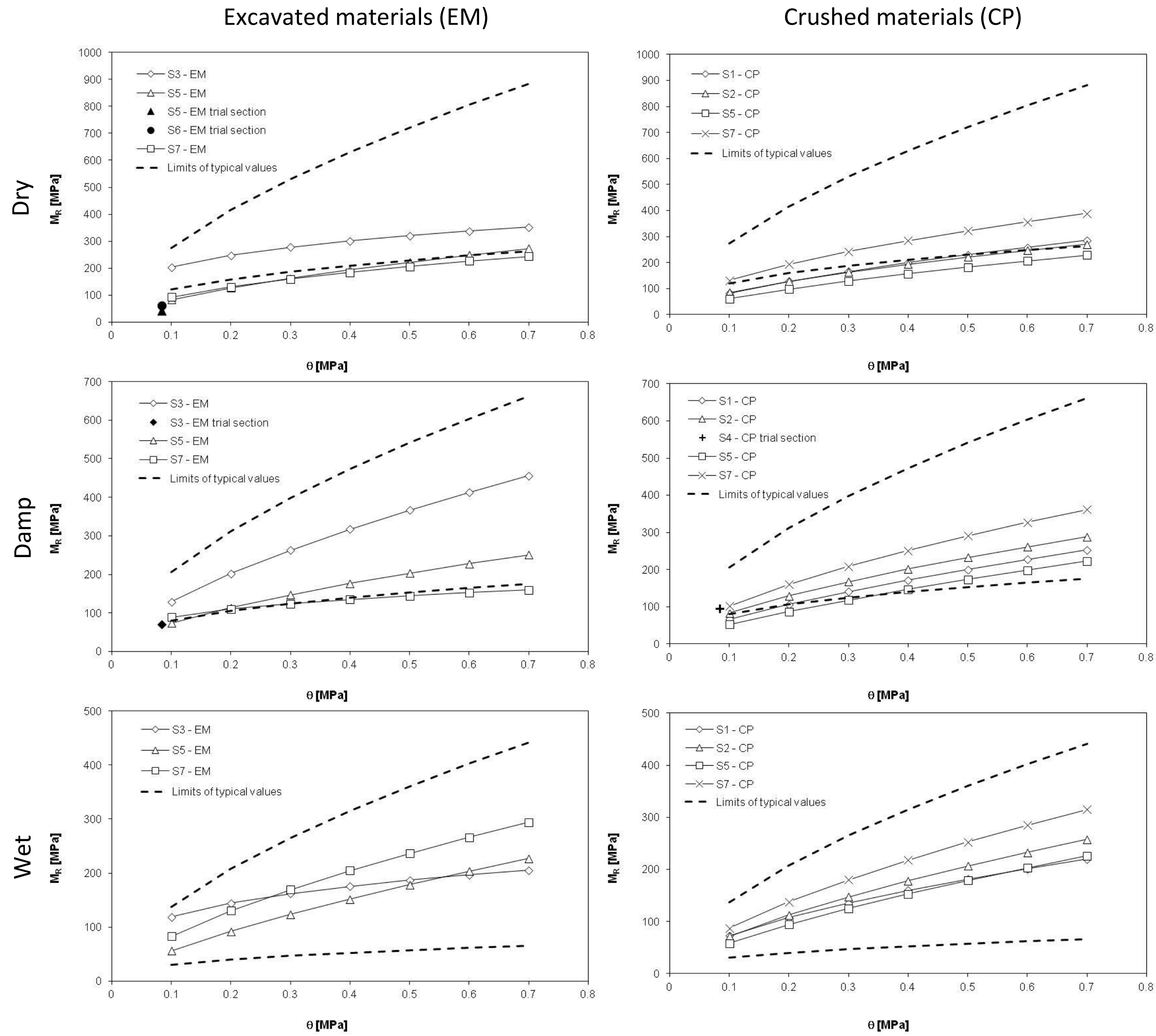


Fig. 8. Resilient modulus and dynamic modulus comparisons: experimental data and typical ranges for granular subbase materials.

7. Discussion and conclusions

The excavation of tunnels is an important issue for the Alpine Region and neighbouring areas, and one that is expected to have an even greater environmental impact in the near future due to new initiatives on very long railway tunnels and other new transportation infrastructures. A major aspect of the management of the significant volumes of mucks generated will be the endeavour to find possibilities for their effective use as a resource rather than their disposal as waste material.

The paper set out to make a contribution, in the form of practical solutions, to this issue. In the course of an extensive research program, the paper assessed the effect(s) of the excavation methodology (EPB, TBM, Cut & Cover, Explosive) and the treatment process (EM/CP) on the volumetric and mechanical performances of several mucks that were collected as representative samples from some of the main infrastructures under construction on the Italian side of the Alps. The experimental program was organized by referring to empirical (or performance related) and rational (or performance based) testing criteria and the results compared to traditional unbound granular materials and soils that are currently in use.

The work focused on the laboratory characterization of seven mucks that were fragmented using a full scale plant. Furthermore, thanks to their availability in large quantities, four mucks were employed in the formation of full scale layers.

The excavation methodology certainly affects the grading of tunnel muck. Table 2 confirms that the material excavated by means of a mechanized shield like EPB and TBM are characterized by high values of the uniformity coefficient (CU). Looking at Table 3, the effect of mechanized excavation is notable for hard, compact rocks such as the granite S6 and the calcareous schist S7 that have high shape and flakiness index values. In contrast, in the case of alluvial mucks S1 and S3, the effect of the excavation method used is negligible.

Regarding the treatment process, the mobile jaw crusher causes a beneficial decrease in the shape and flakiness indexes, particularly in the case of schistose rocks such as S7. At the same time, the mechanical resistance of mucks, which was measured by means of Los Angeles and Micro-Deval, remained unchanged (Table 3). Furthermore, Figure 6 highlights how the change in shape occurring after the grinding process led to a significant improvement in terms of workability during the compaction process.

Although some defects revealed by qualification tests may lead to the rejection of some mucks for the production of aggregate for high performance composite materials (i.e., concrete or bituminous mixtures), all the mucks appear to be suitable for employment in embankments, subgrades and/or pavement subbases. In fact, with the proviso that they are first subjected to a milling process, these typical deficiencies of rock spoils can be largely alleviated when used in the above applications. The results of this investigation demonstrate that standard specifications should not be considered an impediment to change, and that performance based tests allow the use of non-traditional materials and practices. When rational approaches are adopted, materials regarded as waste may be usefully employed in road constructions.

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