MUCK CLASSIFICATION: RAW MATERIAL OR WASTE IN TUNNELLING OPERATION

Claudio OGGERI, *DIATI, Politecnico di Torino, Italy*
Taddeo Maria FENOGLIO, *DIATI, Politecnico di Torino, Italy*
Raffaele VINAI, *Queen's University, Belfast, Northern Ireland*

Abstract
Tunnel construction, structural diaphragms, debris from quarry exploitation require careful consideration of the spoil management, as this involves environmental, economic and legal requirements. In this paper a classification that considers the interaction between technical and geological factors in determining the features of the resulting muck is proposed. This gives indications about the required treatments as well as laboratory and field characterisation tests to be performed to assess muck recovery alternatives. While this reuse is an opportunity for excavations in good quality homogeneous grounds (e.g. granitic mass), it is critical for complex formation. It is therefore necessary to define a procedure that enables to assess the properties of natural ground and of the relative spoil or waste arising from the excavation or exploitation phases. This approach is presented in this paper for usual tunnelling cases, where the materials are resulting from the tunnel excavation carried out by drill and blasting and mechanised tunnelling. Physical parameters and technological features of the materials have to be assessed, according to their valorisation potential, for defining re-utilisation patterns. The methodology has proved to be effective in some cases tested by the Authors and the laboratory tests carried out on the materials allowed the suitability and treatment effectiveness for each muck recovery strategy to be defined.

Keywords: *tunnelling, TBM, soil conditioning, muck reuse, muck classification, spoil treatment.*

1. INTRODUCTION

Muck reuse is always an environmental benefit, since reduces both disposal in landfills and raw material extraction (Blengini et al., 2012), whatever the type of civil work concerned. In case of tunnel projects, since spoil has however to be removed from construction site, recovery is more convenient than the landfill disposal, mainly because of the following reasons:

- immediate availability and excellent
  ability to control the required characteristics in case of reuse within the production site (e.g. aggregates for construction, fillings, embankments, roads and ramps, local topographical re-shaping, etc.);
- possibility of on-site treatment of the excavated material, without buying equivalent materials processed elsewhere;
- regular or budgeted production throughout excavation (for big construction sites);
- not related to the changes in the price of raw materials (for long-lasting projects).

From the technical point of view, it's helpful to develop a classification scheme, with the aim of evaluate the appropriate reuse strategies and their efficiency, discerning the ways muck is produced and processed, as well as the evaluation of its mechanical characteristics and the eventual environmental impacts.

2. MUCK PRODUCTION

Muck can result essentially from three main operations:

- preliminary operations (surveys, adit excavation, overburden removal);
- tunnel excavation;
- demolition of reinforcements and consolidation works.

While surveys and adit excavation (i.e. shafts and raises) are of minor concern because of the small spoil quantities, overburden removal in tunnelling can result in considerable volumes but normally relates material with no particular interests for reuse (except the case of *cut and cover* excavation where spoil is removed and subsequently partially reused on-site). During a tunnel excavation, muck present a wide assortment of geotechnical (i.e. residual cohesion, friction resistance, hydraulic conductivity, consistency) and physical characteristics (grain size distribution, grain shape, bulk density, water content, abrasivity, viscosity) arising from the possible combinations between excavation techniques and ground types, as summarized in ***Table*** 1 and ***Figure 1*** (Oggeri et al., 2014).

Tunnel excavation can be performed by drill and blasting or by mechanised excavation. Drilling and blasting is adopted only in rock (hard to soft) and resulting muck has a wide range of grain size, from (MT1 and MT2). Mechanised excavation is usually divided in two sub-categories:

- mechanised excavation partialised (MT3÷MT6): suitable both in rock and soft rock (i.e. roadheaders, hammers) and soil (i.e. excavators, loaders);
- mechanised excavation full face with or without soil conditioning (MT7÷MT13): while in the past slurry shields or hydroshields were associated with the excavation in coarse and granular formations, whereas EPB shields were meant for fine cohesive materials, the technical development of full face excavation and the introduction of new excavation techniques (such as soil conditioning) allowed modern TBMs to tackle mixed ground conditions where alternation of granular soil, cohesive soil and even rock formation can be found. Thus, full face mechanised excavation could be presented under a global view according to the kind of geo-material that is to be excavated, in order to overcome the boundaries of the strict differentiation between Slurry shields and EPB shields, that could not keep into account the hybrid systems that are nowadays utilised.

Through hard rock, full face TBM excavation produces a more homogeneous muck in the form of regular chips (their dimension is related to the disks spacing and thrust) and powdered material (at disk-rock interface). The excavation in soft rock-hard soil adopting soil conditioning techniques leads to the production of a pulpy mud where cobbles and lumps of soils are surrounded by the fine soil fraction, that is lubricated by the conditioning agent. Eventually, the mechanised excavation in coarse soil returns a bulk material which can be assimilated to loose soil. In reference to reinforcements and consolidation works removal, the presence of materials of many different types (i.e. shotcrete, injected grout, fibreglass, steel fibres, resins, lubricants) makes muck separation quite complex and thus spoil recycle phases.

3. REUSE: RECOVERY STRATEGIES AND THEIR EFFICIENCY

It should be noted that tunnels excavation if often only a part of wider construction projects, involving ancillary works (such as roads, ramps and embankments construction, land reclamations, etc.) as well as a massive demand of raw materials (concrete/shotcrete aggregates, railroad ballast, etc.). very fine/powdered material to very coarse cobbles Therefore, the first destination for muck reuse is the construction site itself. The most common reuse strategies concerning the different types of spoil are summarized in ***Table 2***. Table is organised in a way where for each destination referred to various muck types, usual requested treatments are indicated, as the aim is to transform the bulk material in a raw material. From qualitative point of view, good quality muck can be reused as aggregates for construction and as raw material for industrial production; fair quality muck as material for road and embankments construction; low quality muck for land reclamation or as refilling material. In the following paragraphs a description of the different spoil destinations will be provided, as well as brief indications in relation to relevant properties required for the specific muck reuse strategies.

3.1. Aggregates for construction

Spoil reuse as aggregates has been studied by several Authors (Bellopede and Marini, 2011; Gertsch et al., 2000; Thalmann et al., 2003).

Concerning tunnel muck, within aggregates it is possible to distinguish:

- tout venant used for embankments, foundation and drainage layers;
- sand, gravel and crushed rocks used for concrete/shotcrete and asphalt;
- gravel and crushed rocks for railway ballast.

Relevant properties (physical, mechanical and chemical), in compliance with the essential requirements (89/106/CE), are:

- size, shape, specific gravity, roughness, void ratio, porosity;
- compressive strength and resistance to impact, fragmentation and crushing;
- resistance to polishing, abrasion and wear;
- chemical composition and presence of hazardous substances;
- volumetric stability;
- water absorption and solubility;
- durability to frost and alkali-aggregate reaction;
- cleanliness.

In general, aggregates with high percentages of clay, gypsum, talc and other soft materials should be avoided, as well as materials with fibrous or lamellar structure. It is also necessary to verify the presence of chlorides, sulphates, sulphides and other minerals which can affect solubility, alterability and reactivity to alkali (in particular for concrete or shotcrete production).

Table 1. Possible muck types (MT) (if natural or excess of contaminants occur, muck may need to be treated as a waste). (*) Features in presence of groundwater are reported in italic. (Oggeri et al., 2014)

Ground type / Excavation technique	**Rock**	**Soft rock / hard soil**	**Soil**	
			Coarse (granular)	**Fine (cohesive)**
Drill and Blast (D&B)	MT1: coarse to blocky fragments, angular shaped, presence of fines	MT2: wide grain size distribution, tabular elements, petrography variety, drainage could	N.A.	N.A.

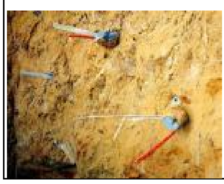
	due to over-comminution, well draining. Sometimes abrasivity issues. **No meaningful interference.*	be a concern also for hauling. **Muddy behaviour, adhesion issues*		
Mechanised excavation Partialised *(not applicable in water bearing formations)* 	MT3: generally wide grain distribution in coarse fraction, angular shape, sometimes abrasivity issues,	MT4: heterogeneous shaped and wide grain sizes, heterogeneous mineralogy and consistency, bulking attitude.	MT5: natural grain size distribution, rounded shaped elements, possibly cobbles and boulders, abrasivity.	MT6: medium to fine grain size, easy to handle, bulking attitude, lump appearance.
Mechanised excavation Full face 	MT7: narrow grain size distribution, possible presence of blocks, chip-shaped fragments, occurrence of fines also relevant, abrasivity. **Technique suitable only for low water flow rates. In wet conditions, difficulties in handling operations.*	MT8: irregular shaped fragments, wide grain size distribution, petrography heterogeneity, **Muddy consistency, low drainage capability,*	MT9: similar to MT5, generally rounded shaped elements, good drainage. **Granular behaviour*	MT10: narrow grain size distribution closed around silt and clay with presence of sand, homogeneous mineralogy, plastic behaviour, or muddy due to natural moisture. **Technique suitable only for low water contents.*
Mechanised excavation and soil conditioning  © Herrenknecht	N.A.	MT11: heterogeneous grain sizes, mineralogy and consistency (from wet to flowing behaviour), lubricated, possible adhesive behaviour, low drainage capability under additive effects. Presence of surfactants, polymers, traces of grease.	MT12: similar to MT9 but increased flowing behaviour, higher water content, time-dependent drainage capability. Presence of surfactants, polymers, filler added, traces of grease, possibly bentonite.	MT13: similar to MT10, often muddy to sticky, presence of surfactants and polymers, traces of grease, very low drainage capability.
Grouting or reinforcing of the ground in the above listed methods 	MT14: similar to MT1, presence of shotcrete, synthetic lubricants, steel fibres, fibreglass, injection grout.	MT15: depending on actual cases MT2, MT4, MT8 presence of shotcrete, synthetic lubricants, steel fibres, fibreglass, injection grout.	MT16: depending on actual cases MT5, MT9, presence of grouts, possibly fibreglass, shotcrete and fibres.	MT17: depending on actual cases MT6, MT10, presence of grouts, possibly fibreglass, resin elements, sometimes shotcrete.

Figure 1. *Examples of tunnel spoil types. (a) Granitic rock, Drilling and Blasting in large-section road tunnel (Omegna Tunnel, Italy); (b) Granitic rock, full face TBM in small-section exploratory drift (Aica-Mules Tunnel, Italy); (c) Soft rock-hard soil, full face excavation and soil conditioning for large-section highway tunnel (Sparvo Tunnel, Italy); (d) Coarse soil, mechanised excavation for railway tunnel (Turin Railway "Passante", Italy). (Oggeri et al., 2014)*

Table 2*. Possible muck destinations (different than waste disposal) (Oggeri et al., 2014)*

	Aggregates for constructions	**Road works / embankments**	**Raw material for industry**	**Environmental or land reclamation**	**Backfilling**
MT1	Yes *[a, b, d]	Yes *[a, b, d]	Yes *[b, d]	Possible	Possible
MT2	N. S.	Yes *[a, b, d]	N. S.	Yes	Yes
MT3	Yes *[b, d]	Yes *[b, d]	Possible *[b, d]	Possible	Possible
MT4	N. S.	Yes *[b, d]	N. S.	Possible	Yes
MT5	Yes *[b, d]	Yes *[b]	Yes *[b, d]	Possible	Possible
MT6	N. S.	N. S.	N. S.	Yes	Yes
MT7	Yes *[a, b, d]	Yes *[a, b, d]	N. S.	Possible	Possible
MT8	N. S.	Yes *[a, b, c, d, f]	N. S.	Yes *[a]	Yes *[a]
MT9	Possible *[a, b, d]	Yes *[a, b]	N. S.	Yes *[a]	Yes *[a]
MT10	N. S.	Possible *[a, b, c, f]	N. S.	Yes *[a, f]	Yes *[a, f]
MT11	N. S.	Possible *[a, b, c, d, e, f], **	N. S.	Yes *[a, f], **	Yes *[a, f], **
MT12	Possible *[a, b, d], **	Possible *[a, b, c, f], **	N. S.	Yes *[a, f], **	Yes *[a, f], **
MT13	N. S.	N. S.	N. S.	Possible *[a, f], **	Possible *[a, f], **
MT14	Possible *[a, b, d, e, g], **	Possible *[a, b, g], **	N. S.	Possible *[a, g], **	Possible *[a, g], **
MT15	N. S.	N. S.	N. S.	N. S.	Possible *[a, f, g], **
MT16	N. S.	Possible *[a, b, f, g], **	N. S.	Possible *[a, f, g], **	Possible *[a, f, g], **
MT17	N. S.	N. S.	N. S.	N. S.	Possible *[a, f, g], **

Key: N.S. Not Suitable; (*) Treatment or plant needed on site; (**) Compulsory environmental compatibility verification prior to treatments. a. Desiccation; b. Sieving; c. Dewatering (cycloning, filtering); d. Crushing; e. pH chemical stabilisation; f. Binder addition (CaO or cement); g. Special treatments.

3.2. Road works/embankments

This muck reuse strategy is the most common and the most efficient (in economic and logistic terms), since in large excavation work sites it is always necessary to realize roads, ramps and embankments (***Figure 2***) to support internal and external transportation system (Riviera et al., 2014).

***Figure 2**. Embankments and ramps in road construction project in central Italy (Oggeri, 2012)*

Usually, cohesive and high-stiffness materials are adopted for road-vehicles interface (superstructure), whereas non-cohesive and low stiffness materials are suitable for foundation layers. Materials used for base layers or road paving (with or without the addition of binding agents) must maintain a suitable bearing capacity and regularity during the service life. In order to be properly compacted, spoil particles must be well-graded, with sharp-edges elements, a small amount of fines and low plasticity. To assess the ability of the material to a specific use within the road construction, the following laboratory tests have to be performed:

- grain size distribution and consistency indices (Atterberg's limits);
- natural moisture content, consistency;
- proctor compaction (maximum dry density and optimum moisture content);
- bearing capacity (CBR, plate loading, penetrometer);
- content of soluble salts, sulphides, sulphates, chlorides and measurements of pH and electrical resistivity (for muck destined to reinforced embankments).

  Furthermore, on-site tests are needed to determine paving layers thickness and compaction issues.

3.3. Raw material for industry

Despite it doesn't represent the main reuse strategy, there are many industrial processes that may involve materials from excavations. Some authors (Resch et al., 2009) cite as a possible future development recycling at the industrial level, taking into account that this type of reuse is hardly conceivable for the material resulting from tunnelling. Required characteristics are specific for the single industry process, so in this paper we are limited to a non-exhaustive list. Clayey muck could be destined to brick industry, while limestone and dolomite could take part in processes relating chemical, glass, paper and steel industry. Siliceous materials could be suitable for glass, ceramic, steel, refractory and abrasive materials industry, whereas micas as material for paint industry. Feldspars from granitic rocks are destined to ceramic industry. Rock powder is sometimes adopted as improvement for agricultural land.

3.4. Land reclamation and backfilling

Generally, the choice of materials to be used for land reclamation and backfilling is subjected to site-specific demands, since no specific regulatory guidance are concerned due to the wide range of reuse opportunity (exhausted quarry fillings, pond fillings, underground cemented fillings, landfills covers, artificial islands, etc.). From environmental point of view, it is necessary that muck would not adversely affect hydro-geological conditions and it has to be physically and chemically compatible with planned remediation activities. References to local and general environmental regulations are of primary importance to define concentration limits of pollutants in water and soils. Since fillings usually interacts with water (i.e. groundwater or rainwater) the parameter of major concern is the eventual content of contaminants which can dissolve in water. Concerning landfills, spoil can be used for slopes reshaping, banks construction and as filling material for the covers. If clay is present, it can be adopted for the disposal of impermeable layers, with or without bentonite addition.

3.5. Case historie

Besides muck type, the effectiveness of the different reuse strategies (thus their efficiency) depends upon:

- specific construction site demands;
- muck amount and type;
- chemical, physical and mechanical characteristics (and relative uncertainty);
- availability and cost of alternative raw materials;
- legal and economical incentives for recycling.

One of the most successful recovery example is the Gotthard Base Tunnel, a 57 km tunnel through the granite and gneiss of the Swiss Alps, where only 1% of the total 13,3 Mm3 was disposed as waste; the other 99% has been reused as aggregates for concrete (20%, after on-site process) or adopted – and sold to third parties – as material for embankments construction (20%) and for land remediation (60%) (Ritter et al., 2013; Del Col and Lanfranchi, 2011). During the excavation of the Turin Railway "Passante", the 2,4 Mm^3 spoil (coarse-blocky alluvial soils) was reused as aggregates (31%) and for embankments construction (16%) (Oggeri and Vinai, 2012). For the Turin-Lyon Base Tunnel (Modane ramp), up to 79% of the 14Mm^3

quartzite muck was reused as aggregate for concrete lining segments casting (Parisi and Burdin, 2011). Otherwise, during the excavation of one of the recent lines of Istanbul Metro, a part of the total amount of $12Mm^3$ muck has been destined to the construction of reservoir for water storage, drainage layers, embankments and refilling (Tokgöz, 2012). Moreover, Gertsch et al. (2000) provides numerous other reuse examples. Other indications arise from CIRIA's stuff research (Construction Industry Research and Information Association), which undertook a survey by questionnaire of the clients, designers and contractors about UK practice in reuse of excavated materials generated by construction operations (J.C.T. Kwan et al., 1999). Muck volumes ranged between 1.400 and 3.000.000 m^3. On a total of 32 examined projects, 21 reused excavated material on-site, whereas 12 found an external destination. The most common reuse strategies were land reclamations and embankments construction, because of their flexibility in management practice, but also a considerable amount of material has been recovered as aggregates for the realisation of drainage layers. It has to be noted that in most of the works in which muck has been successfully recovered, the reuse strategies were planned since the early stage of the project.

4. CLASSIFICATION

Classification process can be defined as the tool used to combine relevant material characteristics in order to obtain practical indications for a suitable muck reuse strategy. While other classifications are possible, based on petrography, mineralogy, grain size distribution or other geotechnical data, the proposed system concerns the actual features of the tunnel spoils, considering their possible behaviour on a phenomenological approach, determining site-specific parameters concerning the chosen muck recovery strategy (***Table 3***). Some specific details regard the listed parameters. On the topic of deformability and strength, the scale effect is relevant and it involves different test procedures and devices, as well as the eventual anisotropy. Compaction and grain size distribution can be varied during the treatment process, so the range of related mechanical parameters can be conveniently adapted. Durability requires careful petrographic determinations and, if the case, proper selection during treatment process. Contaminants in leachate and/or dust and fines have to be evaluated considering the interferences with environment during the by-product lifetime.

5. TREATMENT TECHNIQUES AND PLANTS

Muck can sometimes be suitable as excavated (eventually washed and screened), but more often needs treatments and additions to be reused. Depending on the excavation methods, treatments can begin at the excavation face or just outside the tunnel (***Figure 3***). In fact, if the excavation material results in non-homogeneous particles with a wide range of grain size (i.e. drill and blasting or mechanised excavation partialised) a primary screening and crushing may facilitate material loading, hauling and dumping, limiting outsize blocks. Otherwise, muck from TBMs is normally suitable to be handled with conveyor belt system or wagons with no need for treatments at the tunnel face (except primary visual identification of lithotypes that has to be compared with geological surveys). Hereinafter main on-site treatments and their implications will be examined.

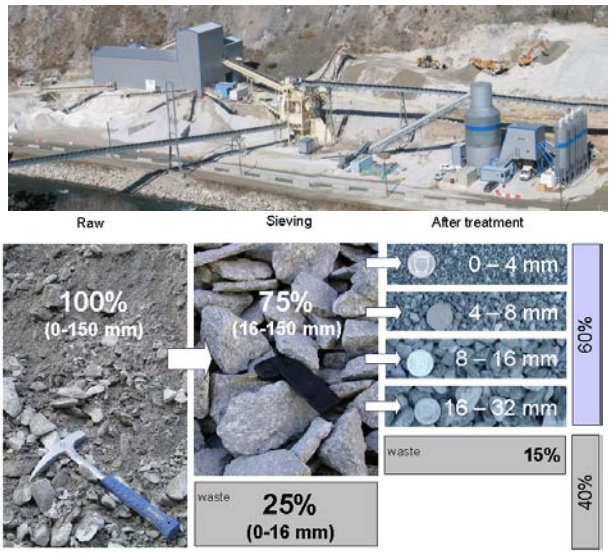


Figure 3. *Treatment plant in Modane drift (France) and process for aggregates from muck in Bodio (Switzerland)*

Table 3. *Mechanical and physical properties concerned for the most common muck destinations mentioned in* ***Table 2***. *(Oggeri et al., 2014)*

Parameter	Aggregates for constructions	Road works / embankments	Raw material for industry	Environmental or land reclamation	Backfilling
Deformability (modulus; coefficient of consolidation; compressibility indices; bearing capacity)	X	XXX	O	XX	XX

Strength (uniaxial compressive strength; shear strength; angle of friction; cohesion	XX	XXX	XX	XX	X
Spoil particles structure (voids ratio; compaction; unit weight)	X	XXX	X	XX	XX
Durability (resistance to wear, to fragmentation and frost; alkali aggregate reaction)	XXX	XX	XXX	X	X
Leaching properties	XX	XX	XX	XXX	XX
Ore grade and stone value	XX	X	XXX	O	O
Particle size distribution and morphology (presence of fines; petrography; shape of elements)	XXX	XXX	X	X	X
Water interactions (water content; consistency indices; hydraulic conductivity)	XX	XXX	X	XX	XX

Key: XXX Relevant; XX Important; X Minor concern; O Not applicable

5.1. Comminution

For *comminution* is meant the process according to which the material is reduced into smaller particles by means of mechanical energy. According to the final size of the grains, the following processes can be distinguished:

- crushing: between 1m and 10^{-3} m;
- grinding: below 10^{-5} m;
- micronisation: up to 10^{-6}m.

The choice of suitable machines can be based on the type of material to be treated. Typical machines used for crushing are crushers (jaw, rotating and impact) and mills (hammers and bars); with regard to grinding, main technologies consist in bars and balls mills. For the micronisation, microniser mills are commonly adopted. The aims of comminution, concerning especially muck reuse purposes, are:

- allow the separation between mineral species and barren materials;
- reduce particle size into homogeneous commercial groups (e.g. cobble, gravel, sand);
- prepare the material for the eventual subsequent industrial operations.

5.2. Sieving

Can be defined as the process leading to the classification of materials of different shapes and sizes through the transfer of these on perforated grids that, depending on the size of the openings, separate materials passing through and retained. In reference to spoil recovery, this process is used for:

- classify products for subsequent processing operations that should relate material with well-defined particle size;
- separate finer or coarser fragments;
- classify crushed material into commercial sizes.

Sieving is normally adopted for separations larger than one millimetre by means of screeners (static, vibrating or rotating) and grids; below this measure the process not guarantee enough efficiency and it therefore passes to the dewatering process, which will be discussed in the following paragraph. The choice of screening decks (i.e. grids, perforated metal plates, fabrics, nets) depends on the following factors:

- particles size and shape;
- material abrasiveness;
- efficiency required by the process.

5.3. Dewatering (cycloning and filtering)

Dewatering is a classification process in which fine particles are separated because of their different relative velocity while within a fluid. Depending on whether the fluid is a liquid (typically water) or a gas (usually air) are distinguished respectively hydro-classifiers and pneumatic separators. Dewatering has the following purposes:

- classify grains with uniform unit weight but different size and shape (volumetric classification);
- classify grains with the same volume but different unit weight (gravimetric classification);
- classify grains with different shape and unit weight that settle with the same velocity.

Main equipment for dewatering process consists in classifiers (static, mechanical and centrifugal), cyclones and filter presses. These equipments are crucial especially when dealing with slurry shield and EPB muck which has been admixed respectively with bentonite (or clay) and surfactants and additives (polymers). In fact conditioning agents create with soil a pulpy mud which retains water much more than natural soils, so sedimentation process is not enough to separate soil particles and water: it is necessary a dewatering plant with cyclones and filter presses in order to achieve a suitable separation percentage. Plants dedicated to slurry machines or diaphragm wall rigs specifically working on the separation of clayey minerals. Slurry shield TBMs require wide spaces for sedimentation process because of the large muck production; otherwise during diaphragm excavation, dewatering operations are concentrated in standard and modular plants which can process materials also in reduced spaces (***Figure 4***).

Figure 4*. Compact slurry treatment plant (dewatering, fines separation and partial bentonite recycle)installed for Turin Railway "Passante" works (Oggeri, 2009).*

5.4. Washing and desiccation

Washing is commonly adopted as a practice to reduce powder and to eliminate fines, as well as a way to reduce the content of pollutants and unwanted substances (oils, greases, polymers, foams, blasting residues, etc.). In particular, the use as aggregates requires a complete removal of additives, as technical requirements set for a clean material to be mixed for concrete preparation; the aggregate does not produce other leachate when in contact with the water of the concrete mixture. While for rocks the presence of water is of minor concern, moisture content influence many soils properties. With concern to muck performance, water content affect workability (consistency, fluidity, compaction, etc.) and mechanical characteristics (deformability, compressive strength, apparent cohesion, etc.). In addition to washing, water takes part in many excavation processes, especially while excavating with TBMs. In fact while tunnelling with TBMs EPB, material in the excavation chamber is treated with foaming agents and water, in order to obtain a muddy (pulpy) consistency, which is a benefit in terms of excavation process but a disadvantage as regards the possibility to reuse the spoil as excavated. Thus, for suitable TBMs muck recovery, a desiccation is required in order to:

- reduce the moisture content to a favourable level, obtaining a material physically and mechanically suitable for the predicted reuse strategy (i.e. limiting pulpy behaviour and allowing compaction);
- facilitate conditioning agents degradation, achieving environmental compatibility.

Requested time for foam and polymers degradation (when possible) while disposed in small piles (in direct contact with air) can vary about between two weeks and 2 months or more.

5.5. Compaction

Compaction is a key-practice while reusing spoil for road construction purposes with the following main objectives:

- reduce material deformability, limiting settlements due to static or dynamic loads;
- improve mechanical characteristics (i.e. stiffness, shear strength, etc.);
- reduce water influence, as a consequence of void ratio reduction.

In-situ compaction (static or dynamic) can be performed, according to material types, by means of:

- padded drum compactors (for fine-grained soils);
- vibrating roller compactors (for granular soils);
- pneumatic tired compactors (polyvalent, depending on tires pressure);
- static roller compactors (for previously compacted layers).

On-site required values for dry density are usually expressed as a percentage of those obtained in laboratory tests (i.e. Proctor and modified Proctor compaction).

5.6. Stabilization treatments

Stabilization treatments are widely adopted in road works and consist in the addition of binders (lime or cement) or a certain amount of a particular grain size fraction. The purpose of these treatments is to improve soil physical-mechanical characteristics, allowing to achieve the required performance and reducing the supply of materials external to the site, thus reducing economic and environmental costs. Two types of stabilization, suitable for muck improvement, can be distinguished:

- mechanical stabilization, which occurs through mechanical operations such as mixing, moistening and compaction;
- chemical stabilization, admixing spoil with lime, cement or bitumen.

The choice of the stabilization type refers primarily to grain size distribution and consistency indices. However, one of the most common stabilization techniques is lime addition; effects of lime stabilization can be divided in short and long term effects. Concerning short-term effects, it is possible to observed:

- variation of the natural moisture content, with the improvement of compaction features (optimum water content moves towards higher moisture content and Proctor compaction curve flattens);
- changes in grain size distribution, with better fines distribution due to flocculation;

- changes in consistency indices, with reduction of plastic behaviour field;
- mechanical characteristics improvement with greater bearing capacity.

Relating long-term effects, are expected:

- improvement of compressive strength;
- improvement of shear strength (i.e. greater cohesion);
- improvement of stiffness;
- greater resistance to frost and water actions.

5.7. Special treatments

In particular cases, related to the specific reuse strategy or industrial requirements, special treatments have to be considered. For instance, in particular land reclamation processes or in road works, a pH chemical stabilization of the muck should be needed. Otherwise, if muck contain unwanted metals particles, a magnetic separation plant may be installed onsite.

6. ENVIRONMENTAL ASPECTS

The muck reuse is subjected to some restraints in terms of environmental compatibility, thus chemical analyses are relevant for a correct classification of the muck and its reuse, as a reference on the natural ground characteristics. As noxious and pollutants can be present both in ground and in the water (leachate), a comparative analysis on both natural and excavated materials is recommended in order to investigate the concentration of contaminants, following general or local environmental regulations. Additives adopted during excavation have generally a certain biodegradation attitude, mainly because of time, oxidative reactions, bacterial actions and muck remoulding (Jing, 2006). This natural degradation, emphasised by washing or desiccating the excavated material, has to be monitored by analyses repeated over a certain period of time which could show a reduction of marker concentration below the mandatory threshold limits. With concern to TBMs muck, additives for soil conditioning (surfactant agents, polymers, bentonite slurry, tail sealing greases, anti-abrasion chemicals, etc.) show different behaviours. While a relatively quick chemical degradation of surfactants agents is expected (2-4 months), incertitude car arise with concern of polymers and greases (these latter can only partially degrade), determining however high concentration of contaminants. Also mortars and bentonite do not undergo biodegradation processes, but they produce leachates. Focusing on stabilized muck, lime addition increases the pH value due to alkaline properties of CaO (in fact, lime is sometimes adopted to neutralize acid components of industrial emissions); this could affect soil properties making lime-stabilized spoil not suitable as a filling for agricultural purposes.

7. CONCLUSIONS

Spoil reuse as by-product has proved to be an environmental benefit (i.e. reduction of waste disposal and raw material extraction), as well as a technological advantage during tunnelling projects (i.e. immediate availability, ability to control the required characteristics, possibility of on-site improvement treatments, budgeted production) while associated to a phenomenological characterization. Muck classification is an helpful tool to discriminate waste and raw material, with concern to both geological (i.e. ground types) and technological (i.e. excavation techniques) site-specific aspects. The choice of reuse strategy arise from a compromise between the technical characteristics of the natural material, complexity of required treatments, actual utilization and specific demands for raw materials. In reference to muck quality, common reuse opportunity for tunnelling spoil are (i) refilling and land reclamation (low quality muck), (ii) road works and embankments construction (fair quality muck) and (iii) aggregates for construction and raw materials for industry (good quality muck). Scheduling muck classification since the early stages of tunnelling projects leads to high efficiency spoil management practices: 99% of muck has been reused during the Gotthard Base Tunnel excavation (20% aggregates, 20% embankments, 60% refilling); 79% for Lyon-Turin Base Tunnel (aggregates); 47% for Turin Railway “Passante” project (31% aggregates, 17% embankments). While technical characteristics of muck appear fair, improvement processes are required. With concern to tunnelling, common spoil treatments consist in mechanical processes (comminution, sieving, dewatering) and chemical stabilization (by means of binder addition such lime, cement or bitumen). Environmental compatibility must be assessed monitoring chemical characteristics of muck both during excavation (presence of conditioning agents, greases, oils, etc.) and after the eventual treatment processes, adopting simple solution to reduce contaminants content (such washing and desiccation).

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