Characterization and assessment of crushed limestone powder and its environmental applications

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Abstract. The subway (metro) and tunnel excavation works are of high demand in today’s large and urban cities. The use of tunnel boring machines resulted in huge quantities of crushed rock powder and generally treated as waste. This work is aimed at the characterization and assessment of Riyadh limestone powder and its possible use as a construction material. The environmental application of this powder as an additive to clay sand liners proved to be useful and efficient. Advanced testing indicated that this material can occupy part of the voids and help in reducing the high expansive nature of the liners and yet maintain a satisfactory hydraulic conductivity. Geotechnical characterization as well as SEM testing was performed. Soil water characteristic curves were established for selected mixtures. The introduction of this material was found environmentally friendly and can reduce the demand for bentonite and highly expansive additives.

1. Introduction

Tunnel boring machines are extensively used in today’s subsurface urban construction. Huge waste material is produced as a result of removing the content of the tunnel material. The general waste material associated with the conventional excavation works using hydraulic machines and drilling hammers did not attract any attention to reuse it for other purposes. This material is mostly classified as waste and recommended for disposal. This work is aimed at the characterization and assessment of Riyadh limestone powder and its possible use as an environmental protection construction material. The environmental application of this powder as an additive to clay sand liners is expected to be useful and efficient.

In a large city like Riyadh, Saudi Arabia, heaps and extended stockpiles of cuttings or soil waste material (spoil) material produced by advancing TBM equipment can be utilized in different construction applications. (Kwan and Jardine, 1999) stated that several million tons of TBM soil waste material (spoil) material are produced worldwide every year. This paper is concerned with the fine particles and cuttings resulting from coring using TBM machines. Other large-sized excavated materials in the form of rock fragments can be utilized in other construction usages like concrete production or as road paving materials. The tunnel boring industry is expanding and giant tunnel
boring machines are now produced in many countries in Europe, USA Japan, and other Asian countries.

In Riyadh city, Saudi Arabia a major subway (metro) project involving tunneling and underground facility is in progress. Fig.1 shows the main lines proposed as the first stage of the project.

![Fig.1. Proposed Riyadh Metro (Subway) Lines.](image)

Tunnel boring machines of various brands were used by different contracted entities. The style of the cutting tools of each machine plays a significant role in the shape and size of cuttings produced. Fig. 2 shows typical inserts and blades attached to the disc of the machine.

![Fig. 2. Configuration of disc reinforcements as suggested or used in Riyadh metro (subway).](image)

The characteristics of the cuttings and soil waste material (spoils) produced by tunnel boring machines need to be assessed and evaluated for use as an aggregate specification in the construction industry (Gertsch et al, (2000). Many countries prohibit the direct reuse of excavated materials unless assessed and checked against specific regulatory requirements of their use (Seidler, 2018). Seidler called for analyzing the elemental and mineral properties of excavation materials as a first step for implementing their possible reuse. Grain size and shape analysis are important identifiers before deciding on further investigations. The project schedule of tunnel construction may not be flexible to accommodate time for assessment or testing but sorting based on size may be possibly accommodated. It is normally all excavated materials from tunnels are stockpiled and heaped in a nearby locality if not immediately transported to the disposal destination.

This publication is focussed on the use of excavated material in environmental applications. Dafalla and Almahbashi (2014) suggested treating highly plastic bentonite with other materials of low plasticity in regions subjected to severe weather changes and variable rainfall. Alnuaim et al (2019) introduced the crushed limestone powder as an additive to liners including highly expansive bentonite.
2. Materials and testing methods

The excavated materials were transported to the laboratories of King Saud University from stockpiled heaps of a nearby tunnel. The material is of variable texture and sizes. It is sorted in the lab by simple screening using sieves of selected openings. General groups are classified as fines, extra fines, coarse and rock fragments. These groups were chosen based on the intended future use of the soil waste material (spoil).

Out of the fine and extra fine material further screening was conducted using sieve number 40 to perform plasticity tests.

2.1. Sieve Analysis of Natural Excavated Material

The excavated materials brought to the laboratory were tested for the grain size distribution following the ASTM D6913 requirements. This test method presents particle sizes in soils in which material coarser than 75 µm is obtained by using a set of sieves of well-known openings, while the particle sizes passing sieve 75 µm is obtained by a sedimentation process.

Fig. 3. The grain size distribution of a natural soil waste material (spoil) crushed limestone material.

2.2. Sieve Analysis of Sorted Excavated Material

ASTM D6913 test method is utilized including the particle sizes passing sieve 75 µm by a sedimentation process for the natural crushed sample only.

Fig. 4. The grain size distributions of sorted natural soil waste material (spoil) crushed limestone material.
2.3. Plasticity tests for excavated natural material

These test methods are provided in ASTM D 4318 and used together with gradation to enable characterization and classification as per the ASTM D 2487.

2.4. Modified Proctor for natural excavated soil.

This test method is used to determine the relationship between molding water content and dry unit weight of materials to obtain a compaction curve. For the modified type of test the natural excavated soil was compacted in a 152.4mm diameter mold using a 44.48 N hammer dropped from a height of 457.2 mm as given in ASTM D 1557.

![Fig. 5. The modified proctor of a natural soil waste material (spoil) crushed limestone material.](image)

2.5. Falling head permeability test for natural excavated soil passing sieve 4.

Falling head permeability cell was used to study the rate at which water can pass through the soil. This method is more suitable for fine-grained soils and clay-like or silty soils. The procedure as in ASTM D 2434 was followed for material passing sieve number 4 ($\gamma_d \text{ max} = 20.3 \text{ kN/m}^3$).

| Test no. | h1 cm | h2 cm | t min | Temp. ºC | $H_T/\eta_{20}$ | $k_T$ cm/s | $K_{20}$ cm/s |
|----------|-------|-------|-------|----------|----------------|------------|-------------|
| 1        | 170   | 141.4 |      | 1500     | 23             | 0.9311     | 2.639 E-07  | 2.457 E-07  |
| 2        | 170   | 144   | 1420  | 23       | 0.9311         | 2.512 E-07 | 2.339 E-07  |
| 3        | 170   | 144.6 | 1415  | 23       | 0.9311         | 2.457 E-07 | 2.289 E-07  |
| 4        | 180.5 | 136   | 2720  | 23       | 0.9311         | 2.236 E-07 | 2.082 E-07  |
| 5        | 180.5 | 157   | 1355  | 23       | 0.9311         | 2.212 E-07 | 2.060 E-07  |
| 6        | 180.5 | 155.2 | 1455  | 23       | 0.9311         | 2.230 E-07 | 2.077 E-07  |
| 7        | 180.5 | 156.7 | 1335  | 23       | 0.9311         | 2.276 E-07 | 2.119 E-07  |
| 8        | 180.5 | 154.8 | 1465  | 23       | 0.9311         | 2.253 E-07 | 2.098 E-07  |
| 9        | 180.5 | 155   | 1410  | 23       | 0.9311         | 2.321 E-07 | 2.161 E-07  |
| 10       | 180.5 | 159.5 | 1230  | 23       | 0.9311         | 2.161 E-07 | 2.012 E-07  |
| 11       | 180.5 | 116.5 | 4320  | 23       | 0.9311         | 2.178 E-07 | 2.028 E-07  |

$K_{20}$ average = 2.156 E-07
2.6. Extra fine particles

The TBM spoil or soil waste material is a crushed powder of limestone sieved through # 200 (75 micro mm size). The specific gravity is 2.714 a little higher than that measured for the fine sand. The plasticity index of the crushed powder is very low and reported as 3. The optimum moisture content is reported as 16 at a maximum dry density of 17.6 kN/m³. The TBM soil waste material (spoil) is a crushed powder of limestone sieved through # 200 (75 micro mm size). Table 2 presents the characterization test results for the TBM soil.

| Test                              | Value   |
|-----------------------------------|---------|
| Specific Gravity                  | 2.714   |
| Liquid Limit, (%)                 | 21      |
| Plastic Limit, (%)                | 18      |
| Shrinkage Limit (%)               | 18      |
| Plasticity Index (%)              | 3       |
| Compaction characteristics        |         |
| Optimum moisture content (%)      | 16.50   |
| Maximum dry unit weight (KN/m³)   | 1.76    |

Table 3. Typical physical properties of bentonite

| Property                     | Value |
|------------------------------|-------|
| Specific gravity, GS         | 2.6-2.7|
| Liquid limit, LL (%)         | 480   |
| Plastic limit, PL (%)        | 50    |
| Plasticity index, PI (%)     | 430   |

Table 4. Typical chemical composition of OCMA grade bentonite

| FeO₃%  | K₂O%  | Na₂O% | Al₂O₃% | MgO%  | SiO₂%  | TiO₂% | CaO% |
|--------|-------|-------|--------|-------|--------|-------|------|
| 2.9    | 0.1   | 1.9   | 17.0   | 4.6   | 55.2   | < 0.1 | 0.9  |

Source: Ore-Arabian Gulf region-OCMA Grade
2.7 Soil water characteristic Curves

The soil-water characteristic curves (SWCC) were constructed for a mixture of compacted crushed limestone powder and commercial bentonite as additives to sand. The crushed limestone and bentonite together form 15% clay content of the total weight of the liner material.

The pressure plate method or as called (axis translation technique) is performed for a wide range of suction pressures. Fig. 6 presents the SWCC of the mixtures using crushed limestone powder, commercial bentonite, bentonite with one-third crushed limestone and bentonite with two-thirds crushed limestone. The test was performed following the standard procedure described in ASTM D6836-02 (ASTM, 2008). The SWCC plot is presented as suction versus water content.

\[
w(\Psi) = w_s \left[ 1 - \frac{\ln \left( 1 + \frac{\Psi}{h_r} \right)}{\ln \left( 1 + \frac{10^{d} \Psi}{h_r} \right)} \right] \left[ \frac{1}{\ln \left\{ \exp(1) + \left( \frac{\Psi}{a} \right)^{n} \right\}} \right] \quad [1]
\]

Where:
\( \Psi \) = soil suction,
\( w \) = gravimetric water content,
\( w_s \) = saturated gravimetric water content,
\( w_r \) = residual gravimetric water content,
\( a \) = suction related to the inflection point on the curve,
\( n \) = soil parameter related to slope at the inflection point,
\( m \) = soil parameter related to the residual water content, and
\( h_r \) = suction related to the gravimetric residual water content.

2.8 Scanning Electron Microscope

The scanning electron microscope was used to view the fabric features of mixtures at magnifications of 40, 100, and 200. This technique can provide better visibility of the fabric formed by the components of the liner. SEM process required dried-specimens because of the expansion-shrinkage nature of the bentonite materials. Liquid nitrogen was used in freeze-drying. Bentonite sand mixture with 15% bentonite was viewed and compared to samples with one-third and two-thirds replacement of bentonite. SEM tests were conducted using Joel apparatus (Model JSM-7600F) with a high resolution of 3.0 nm, and operated at 5kV-10kV.
3. Test results and discussion

Extensive characterization tests conducted on the soil waste material (spoil) from a selected tunnel in Riyadh indicated that the material can be used for different purposes. The scope of this study is limited for possible usage as environmental protection and environmental-related activities. The general recommendation of governmental authorities is to dump all soil waste material in depressions or landfill sites. This study encourages screening and sorting the material into four categories including extra-fine material, fine material, coarse materials, and rock fragments. The boundaries between these groups are at present wide and not yet well defined. The suggested environmental usage is as follows:

1-Extra fine material (EXF-LM) which can be defined as materials passing sieve number 200 can be utilized in the design of impervious or low permeability sand clay liners. This material can act as inert fill to reduce the need for bentonite material.
2. Fine material (F-LM) which can be defined as material passing sieve number 40. This material is unlikely to satisfy the hydraulic conductivity requirements but can be used as an extra layer below or above a recommended liner layer.

3. Coarse material (C-LM) is defined as all waste material retained on sieve number 40. It can be used in thin layers to densify low density dumped material. It can help in transferring compaction effort in an even way and enable quick compaction.

4. Rock fragments (RF) are pieces that cannot be classified as soils. It can be subdivided further into small fragments and large fragments. Pieces of size in the order of 10 cm to 20 cm are small fragments and can be used in Gabions while large fragments can be utilized in shore protection.

The onsite sorting process can be performed using screens of suitable openings. Extra fine material needs to be sorted in laboratories or using grinders. The characterization is required for each rock of similar classification and appearance. The works conducted here refer to the limestone of Riyadh, Saudi Arabia. The geology of Riyadh city indicates three types of limestone formation which include Arab formation, Jubaila formation, and Sulay formation.

The grain size distribution test conducted on natural recovered soil waste material showed a well-graded material with fine portions of more than 25% as an extra-fine material (EXF-LM) and more than 50% for a general fine material (FLM). Figure 3 indicates the general gradation curve. Figure 4 presents the grain size analysis for sorted samples with material passing sieve number 4 and material passing sieve 3/4” (19 mm). The liquid limit obtained for the natural crushed limestone was 21 and the plastic limit was 18. Very low plasticity is measured with a plasticity index of 3 or less.

The maximum dry density \( \gamma_{d,max} \) was reported as 20.82 kN/m\(^3\) at an optimum moisture content of 7%. This was found different for extra fine powder passing sieve number 200. The maximum dry density was reported as 17.60 kN/m\(^3\) at an optimum moisture content of 16.5.

Eleven (11) measurements of permeability tests were conducted on natural crushed limestone soil. Although the final computed value did not satisfy the requirements of the standard liner hydraulic conductivity (<10\(^{-7}\) m/sec) but was found very close to the acceptable value. This is mainly dependent on the quantity of material passing sieve number 200. The nature of the tunnel boring machine cutting tools also contributes to the fines content. Table 1 presents a falling head permeability test carried out as part of this study.

Table 2 presents the properties and characteristics of the extra fine soil waste material produced by sieving through a 75-micron opening sieve.

Table 3 and Table 4 present the typical physical and chemical properties of bentonite used in the liner along with the crushed limestone powder.

The variation of gravimetric moisture content with matric suction of the extra fine crushed limestone with other samples including mixtures of bentonite and sand is shown in Fig. 6. The trend of all curves is converging towards low moisture content at high suction levels. The benefit of adding crushed limestone is reducing the plasticity of the liner mixture and providing spacers within the voids. The inert added crushed limestone will maintain a satisfactory permeability and reduces unwanted shrinkage or swelling.

SEM selected micrographs shown in Figure 7 for liners containing 15% bentonite and two other liners with bentonite partly replaced with crushed limestone. The voids occupied by the crushed limestone are not moisture sensitive and less bentonite is sufficient to close unoccupied voids. This study
highlights environmental benefits for Ar Riyadh Development Authority (2018) to be considered during the project execution.

4. Conclusion
The crushed limestone powder obtained from tunnel boring machines can be utilized as an environmentally friendly material and not be disposed of as waste. It is recommended to run sorting and screening and perform characterization tests to decide on its possible usage for a specific purpose. This study encourages screening and sorting the material into four categories including extra-fine material, fine material, coarse materials, and rock fragments.

1-Extra fine material (EXF-LM) which can act as inert fill to reduce the need for bentonite material.
2-Fine material (F-LM) which can be can be used as an extra layer below or above a recommended liner layer.
3-Coarse material (C-LM) that can be used in thin layers to densify low density dumped material. and help in transferring compaction effort in an even way and enable quick compaction.
4-Rock fragments (RF) material which can be subdivided into small fragments and large fragments. Pieces of size in the order of 10 cm to 20 cm to be used in Gabions and large fragments to be utilized in shore protection.

This study recommends characterization tests to be conducted on all types of sorted crushed limestone material. This needs to include routine and advanced testing relevant to the intended use of the material.

The inert added crushed limestone will maintain a satisfactory permeability and reduces unwanted shrinkage or swelling. SEM selected micrographs for liners containing 15% bentonite, two other liners with bentonite partly replaced with crushed limestone indicated the homogeneity of the mixture, and the fabric produced. The voids occupied by the crushed limestone are not moisture sensitive and lesser bentonite is sufficient to close unoccupied voids.

Acknowledgments
The authors wish to acknowledge the assistance of the technical staff of King Saud University laboratories for support while conducting different tests. The authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this study through the Research Chair Program of King Saud University.

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