Geotechnical Characterization and Applications of Riyadh Metro Tunnel Boring Machine Excavated Material (TBMEM)

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Abstract. The Riyadh city is witnessing one of the most significant infrastructure projects in its history. The 22.5 billion dollars and 180 km in total length Riyadh Metro project will be constructed using different tunnelling methods: 10 m diameter tunnel boring machine (TBM), cut and cover, and new Austrian tunnelling method (NATM). About 35 km will be constructed using 10 m diameter TBMs, which will produce approximately 2.8 million cubic meters of TBM excavated material (TBMEM). Transferring such an amount of material will cause a severe impact on the environment and traffic as it required many trucks to transport the material to a remote site. The comprehensive geotechnical characterization profile of the material was prepared in order to understand the performance of the material and identify the areas in which the material can be utilized. In addition, this paper will explore the potential of using TBMEM after being treated and mix with clean sand to enhance its geotechnical characteristics. Several potential areas to utilize the TBMEM will be presented. Furthermore, the project will investigate the applicability of TBMEM to be used as backfill material and to what extent the treatment should go to achieve a mixture that meets the standard requirements.

1. Introduction

The effects of megaprojects on the environment are significant in different ways. For example, it requires an enormous quantity of concrete, which will lead to the release of greenhouses gases in the air during the production of the cement. Furthermore, these effects also include damages to the trees, forest, water, and animal habitats. Therefore, it is essential to take some measures to reduce these adverse effects.

The annual need for granular materials in Europe is around three billion tones, which has led to the utilization of TBM excavated material for structural concrete [1]. As a result, several studies, mainly in European countries, investigate the properties of the TBMEM. Accordingly, the tunnel excavations are a vital renewable aggregate source for construction purposes[2]. Olbrecht and Studer [3] used TBM aggregate in concrete, and it was found a relatively low modulus of elasticity compared to the ordinary concretes. Their concrete was produced using six different types of granular materials, retrieved by the TBM.
Moreover, Tokgöz [4] and Gertsch et al. [5] studied the uses of aggregate produced from the TBM hard rock and found that that is likely beneficial as sand filling materials, and for the road pavements and concretes applications. The primary justification for this positive effect is that the excavated material, for such type of applications, needs a minimum treatment. Oggeri and Ronco [6] have also studied utilizing TBM muck and stated the significance of the categorization of the TBM material in processing stations. The processing stations would provide the classification and crushing of the components (including the muck, rock, and the additives used during the excavation process).

Additionally, Tokgöz [4] investigated the application of eight different rocks obtained from TBM excavated material as rock covering in water tanks and the corresponding facilities. The study showed the possible use of the TBM muck as covering material. Riviera et al. [1] investigated the feasible usage of seven various TBM mucks for construction applications such as sub-base and subgrade for road constructions. This approach was based on the physical and chemical characterization of the unprocessed material and its measure regarding the standard construction requirements. It was stated that the examined materials had displayed a proper mechanical behavior that motivates their wide-ranging utilization for civil engineering applications. The available research on TBM-material-based concrete includes not only conventional but also fiber-reinforced-concrete. Voit and Zimmermann [7] experimentally studied the mechanical properties of plain and fiber reinforced concrete formed by an aggregate obtained from tunnel projects using various types of cement. These investigators have demonstrated that concrete with excellent mechanical characteristics is obtainable by incorporating the aggregate from the tunnel quarry. Furthermore, the relatively low dosage (30 kg/m3) of steel fibers have remarkably increased the compressive strength (from about 40 MPa to 60 MPa) of the concrete utilizing tunnel muck materials. In contrast, the PP fibers have a marginal effect on the compressive strength of concrete made of tunnel-material-base aggregate.

The project produced about 2.8 million cubic meters of the tunnel boring machine excavated material (TBMEM) and requires about 250,000 transporting truck trips to move these materials to remote locations. This paper investigated the geotechnical properties of the tunnel boring machine excavated material (TBMEM) for the Riyadh Metro project and proposed some applications to reduce the environmental impact of transporting the material and reduce greenhouse gas emissions.

2. TBM material for this study

Riyadh Metro Project is an express rail infrastructure, which is currently the largest under construction transportation system worldwide. In the expecting future, this project would be an essential pillar in the Riyadh public transportation system, and therefore notably enhancing the quality of life of its populations [8, 9]. As shown in Figure 1, the total length of Riyadh metro (RM) is divided into six standard gauge lines (with a total length of about 176.3 km). It worth noting that the TBM material of the present study is based on Riyadh Metro Line-5 (Figure 1, has an overall length of about 12.5 km). Additionally, the tunneling works of the Riyadh Metro are performed by seven TBMs of 10 m diameter (90-120 m length) and weight of 700 tones with a production rate of 100 m/week. The entire geology of Riyadh (Ar-Riyadh) quadrangle is underlain by Phanerzoic sedimentary rocks of the western edge of the “Arabian Platform,” which rest on the Proterozoic basement (Precambrian rocks) of Arabian Shield (Figure 2). The Phanerzoic sequence is overlain by Late Tertiary to Quaternary deposits [10]. The geological units present in the study area (Line 5), can be subdivided into three groups: Jurassic deposits, Cretaceous deposits, and Quaternary deposits.
Figure 1. (a) standard lines of Riyadh Metro, (b) alignment of line 5

Figure 2. Map of Saudi Arabia geology [10]
2.1. The sampling of the materials

The samples were retrieved directly from the muck pit, as shown in Figure 3. The TBMEM was stored and sealed in a plastic barrel (see Figure 4). A total of five barrels were collected with a total weight of about 200 kg. As soon as the sample was reached the King Saud University’s soil lab, the moisture content of the sample was measured using ASTM D2216 [11]. It found that the initial moisture content of the material equal to 14%. Part of the retrieved samples were dried and prepared to conduct different characterizations tests, which will be presented in the next section. The oversized pieces (e.g., pebble, cobble, and boulder) was crushed to smaller sizes, which was utilized in the experimental program.

Figure 3. Muck pit of Riyad metro Line 5.

Figure 4. The TBM material: a) wet and b) dry.
3. Experimental program

Different tests were conducted in order to determine the geotechnical properties of the TBMEM, which include the grain size distribution, Atterberg limits, compaction test, direct shear and permeability test. The results of these tests will help to identify the ideal way to utilize TBMEM in different aspects of civil construction projects.

3.1. Grain size distribution

The sieve analysis tests were conducted according to the ASTM D422 [12]. The TBMEM composed of about 26.2% fine material passing sieve #200. In order to reduce the fine material content, the TBMEM was mixed with typical concrete sand (CS) by 40%; as a result, the particles finer than sieve #200 % was reduced to 14.7%. Moreover, to understand the effect of compaction effort during the construction on the soil particle distribution, sieve analysis tests were performed after conducted the compaction test, which will be presented in this paper (section 3.3). It was found that the fine material passing sieve #200 increased from 14.7% to 29.8%. This increase in the fine content may have a negative effect on the performance of the TBMEM once it becomes saturated as the pore water pressure may increase during loading.

Figure 5. The grain size distribution.

3.2. Atterberg limits

The Atterberg limits for the TBMEM was performed based on ASTM D4038 [13]. It was found that the liquid limit, plastic limit and plasticity index are 20.05%, 16.93% and 3.12, respectively. These results can help during the classification of the materials.
3.3. Compaction

Different compaction tests were performed according to the ASTM D698 [14] and ASTM D1557 [15] for standard Proctor test and modified Proctor test, respectively. For the TBMEM, the dry unit weight and optimum moisture content are 19.28 kN/m³ and 11.2%, respectively, using the standard Proctor test. These values changed when the modified Proctor test was performed to become 20.05 kN/m³ and 8.8% for the dry unit weight and optimum moisture content, respectively. From the compaction test results, the maximum dry unit weight was increased as compaction effort increases when using the modified Proctor test.

Another compaction test was performed for the mixture of TBMEM and CS to study the effect of reducing the fine content on the maximum dry unit weight. The mixture contains 56% TBMEM and 44% CS. It was found that the mixture has a slight increase in maximum dry unit weight by about 5%.

3.4. Direct Shear

The direct shear tests were conducted according to the ASTM D3080 [16]. The shearing rate was set to 0.3 mm/min. The angle of internal friction for the TBMEM for compacted soil (0.95 maximum dry unit weight) is 44°. Furthermore, by mixing the TBMEM with 44% CS, the angle of internal friction for the compacted mixture (0.95 maximum dry unit weight) becomes 45°; this increase is negligible.

3.5. Hydraulic Conductivity

The purpose of determining the hydraulic conductivity is to identify the applicability of using the TBMEM as filling, landfill liner, or filtering materials. The tests were carried out according to the ASTM D5084 [17]. For the TBMEM, the hydraulic conductivity determined by the falling head method is $9.8 \times 10^{-7}$ cm/s. These results passed on preparing the sample passing sieve # 4 and were compacted to 0.95 of the maximum dry unit weight. Once the coarse materials were increased in TBMEM, and the material passing sieve ¾ inch (19.05 mm) was used, the hydraulic conductivity increased to become $2 \times 10^{-3}$ cm/s.

An additional set of hydraulic conductivity tests were conducted using the mixture contains 56% TBMEM and 44% CS. It was found that the hydraulic conductivity using material passing sieve # 4 and with a unit weight equal to 0.95 of the maximum dry unit weight is equivalent to $6 \times 10^{-5}$ cm/s. After the compaction test, the sample was used to estimate the hydraulic conductivity, and it was decreased to $5 \times 10^{-7}$ cm/s compared to $6 \times 10^{-5}$ cm/s before the compaction test. This increase can be attributed to the increase in fine content after the compaction effort.

4. Proposed Application for TBMEM

Based on the experimental program, several applications of the uses of the TBMEM can be suggested. It worth mentioning that some applications require some preparations for the raw TBMEM. For all the applications, the TBMEM needs to dry out as the initial moisture content is very high, 14%. The proposed applications are listed below:

1. Using the TBMEM as a subbase for road construction or in the asphalt mix design: this will require some processing to meet the requirement for this use, which is typically A-1-a, according to the AASHTO for the subbase and the pavement mix design according to Marshall mix design method, Superpave method or local authorities specifications. It is essential to evaluate the capability of the TBMEM particles withstand the stress from the traffic load, which can be evaluated based on the California Bearing Ratio (CBR) [18] and Los Angeles abrasion test [19].
2. Utilizing the TBMEM as non-structure elements reinforcement concrete projects. For this type of use, the material should be prepared to meet the specifications of the ASTM C33/C33M [20]. This process can be conducted on the site by using mobile crusher equipment. Currently, some works are being undertaken by the author to assess the workability for the use of these materials in the concrete mix design.

3. Employing the TBMEM as backfilling materials. As presented before, the shear strength for the compacted material is high; however, the fine content for the raw material is high, and the hydraulic conductivity is low. This will result in pore dissipation of the excess pore water pressure, which may cause some issues.

4. Landfill liner is a potential use for the TBMEM; however, this will require additional crushing for the sample to increase the material passing sieve# 200 and to add some fine material such as bentonite.

5. Conclusions

In this study, the geotechnical properties of the tunnel boring machine excavated materials (TBMEM). These properties include the grain size distribution, Atterberg limits, compaction test, direct shear and permeability test. Furthermore, some applications were proposed to utilize TBMEM, such as subbase for road construction, in the asphalt mix design, as non-structure elements reinforcement concrete projects, as backfilling materials, or landfill liner.

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