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Sustainability in construction works: Reuse of sludge from tunnel boring in lime mortars

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ABSTRACT

This study is based on reuse of sludge from tunnel boring for the manufacture of mortars with calcium hydroxide and their possible application in construction. Three samples have been tested with different percentages of sludge from tunnel boring obtaining high consistency. This percentage was used to produce two types of mortars, one with limestone-type aggregates and the other with siliceous-type material, which were then subjected to compression and flexural tests.

The analysis shows that the use of these sludge, with calcium hydroxide and siliceous-type aggregates, helps to improve the mortars' properties and increase their flexural strength to values above 4 MPa, which could be reused as a coating for underground work and road construction as long as its complies with the standard.

1. Introduction

Currently, the sludge from tunnel boring is considered as waste material which is disposed of in landfills, causing environmental problems and additional costs to the companies. Therefore, the option of reusing this material has been considered, provided it is improved, for use in construction (Bergaya and Lagaly, 2006; Castro-Fresno et al., 2011a, 2011b).

It has been studied the behavior of lime mortar with sludge from tunnel boring (clays), aggregates, and siliceous limestone. For this purpose, samples were made with different proportions of materials, which were subjected to curing periods of 28 days, and then tested in the laboratory to analyze their performance and demonstrate their suitability for application in tunnels and other public works (ditches, gutters, coatings, etc.).

In 1988, the company Putzmeister carried out an innovative project that consisted in the application of excavated material as filler in the empty space between the outer surface of the tunnel ring sections and the adjacent rock in the Channel Tunnel (Yang et al., 2013).

The work on the Extension of the Madrid Underground was finished in 2003. It included several excavations in which cement grout was injected to fill the gap outside the tunnel shell, reaching pressures of 4 MPa. In addition, the surrounding buildings were protected with jet-grouting so the advancement of the tunnel boring machine would not produce changes in their structures (Herrera-Álvarez and Rodríguez-Rodríguez, 2003).

Later, it was developed a system for the Barcelona subway, which filled the tunnel gap with materials fed through several injection points creating shields (Mertens et al., 2004).

The idea proved successfully because it was founded that if the perforation equipment was used in combination with an adequate plasticity of the mix, the filling of the gap in shield earth pressure balance (EPB) would be almost 100% (Castro-Fresno et al., 2011a, 2011b).

In 2007, radar techniques were used to measure the discontinuities that existed in the filling mortar located in the tunnel gap of Line 4 of the Shanghai Subway. The results demonstrated that if this material had suitable proportions, it would be able to withstand very high loads. In addition, it was concluded that the electrical permittivity was related to the curing time of the mortar filling (Xie et al., 2007; Aggelakopoulou et al., 2011).

Today, in places such as Hong Kong, numerous excavations are being carried out in which the gap filling method is used with lime mortars and excavated material. Yang et al. (2013) have demonstrated that the lime mortar led to lower CO_2 emissions, meaning that this material less detrimental to the environment.

2. Materials and methods

2.1. Characterization of sludge from tunnel boring

For the manufacture of the lime mortars, the following materials were used: calcium hydroxide, sludge proceeding from tunnel boring,

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Table 1
Geotechnical characterization of the sludge proceeding from tunnel boring.

Test	Standard	S_1	S_2
LL (%)	ASTM D4318	34.71	47.74
PL (%)		25.68	23.32
PI (%)		9.03	24.42

limestone sand, silica sand, and various additives. Two types of sludges proceeding from tunnel boring were previously characterized through granulometric analysis, pH, conductivity, and plasticity tests as well as chemical and mineralogical tests X-ray diffraction (XRD), scanning electron microscopy (SEM), and X-ray fluorescence (XRF), to guarantee acceptable properties in the manufacture of mortars (Vidal & Volzone, 2009; Amin Eisazadeh et al., 2012).

2.2. Mortar manufacture

The manufacturing process was performed according to the standard ASTM: C270-14a. The equipment necessary for such purposes were a planetary kneading and mixing machine, a calibrated precision balance with 0.1 g of accuracy, an electronic timer to control the mixing time, normalized molds for normalized sample manufacturing, a compartment with relative humidity of 95% or more and a temperature of 20 °C for sample curing, and a mold and vibrating table to determine the mortar consistency.

2.3. Laboratory tests

2.3.1. Fresh mortar consistency

The consistency of mortar was determined according to the standard ASTM C 305-14, filling a tapered mold with fresh mortar on the vibrating table. After 15 repetitions, two perpendicular diagonals were measured, obtaining the final mortar plasticity.

2.3.2. Flexural strength test of hardened mortar

The fresh mortar was placed in a standard triple 4 × 4 × 16 cm mold for each compartment. Subsequently, the board dropped about 60 times before proceeding with the second layer, which was compacted in the same way. Once the second layer was compacted, the molds were removed from the compaction equipment and finished with a spatula, leaving them level with to the surface (Horpibulsuk et al., 2012).

Before performing the flexural strength test, the samples were conserved without any movement or vibration, as this could change their resistance value. After a curing time (7, 14, and 28 days), tests were carried out according to the standard ASTM C 348-14. After the test, each of the two parts obtained was used for a compression test (Habert et al., 2009):

$$Rf = 1.5\left(\frac{F \cdot l}{b \cdot d^2}\right)\Bigg| \tag{1}$$

where F: maximum load applied (N); l: distance between the axes of the support roller (mm); b: sample width (mm); d: sample thickness (mm).

2.3.3. Compression test on hardened test

Each of the two parts obtained was compression tested according to the standard ASTM: C348-14, in which a load of 1500 KN was applied using a press at a loading velocity of 0.80 kg/s (Horpibulsuk et al., 2012). In this case, the compression strength was calculated using the expression:

$$R_c = \frac{F_{max}}{S_{Trans}} \tag{2}$$

Where F_{max}: maximum load supported by the sample (MPa); S_{trans}: sample transversal section (mm^2).

3. Results and discussion

3.1. Sludge characterization

3.1.1. Granulometric analysis of the sludge from tunnel boring

The mortar should not contain coarse particles which impede a specific flow velocity, so it was sieved to ensure there were no oversize particles which exceeded 5 mm. The test was then carried out according to the standard ASTM: C144-11.

3.1.2. Laboratory tests

The results obtained in the sludge geotechnical characterization tests are summarized in Table 1. These tests were very important before manufacturing each mix, it is necessary to identify the properties and the material content.

After determining the Atterberg limits and plasticity index of each type of sludge, the material was classified (Fig. 1). According to the "Plasticity Chart of Casagrande," it was determined that sample 1, an inorganic mud low plasticity (ML) and falling below the line A, and its liquid limit is lower than 50. Furthermore, sample 2 was classified as an inorganic clay with low plasticity (CL) since plasticity index exceeds "line A" and plasticity index is greater than 20.

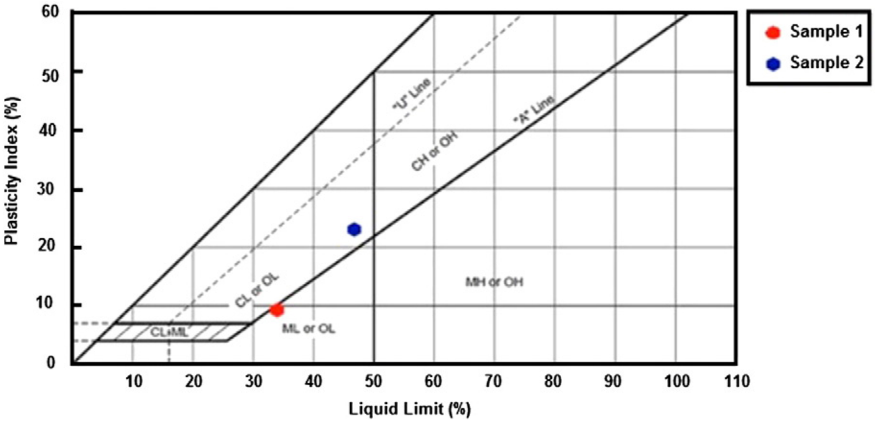

Fig. 1. Casagrande plasticity chart.