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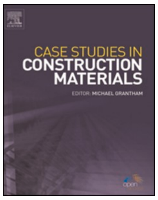

Reuse of EPB mucking for concrete production: A laboratory test campaign

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ABSTRACT

This paper presents a comparative test campaign between concrete produced with clean aggregate and aggregate treated with surfactants. The latter condition simulates the effect of earth pressure balance (EPB)-tunnel boring machine (TBM) on aggregates during the excavation and their successive reuse for concrete production. Uniaxial compressive strength, the dynamic elastic moduli, and the specific weight were measured and compared. The results show that the presence of surfactants, introduced in the mix by the aggregates, reduces significantly the compressive strength (up to 41 %), the elastic moduli (up to 25 %), and the specific weight (up to 7 %).

1. Introduction

As a result of the large amount of civil infrastructure and transportation needed, tunnel construction is becoming more and more important worldwide [25,26,43]. At the same time, the use of full-face mechanised machines is increasing. Among the mechanised machines, the earth pressure balance-tunnel boring machines (EPB-TBM) are the most frequently used due to the large number of advantages they offer [14,19,32,35,42].

These machines require the excavated soil to have specific properties [6,9,16,31,37] that are usually obtained with the addition of chemical products (conditioning agents), among which foam is the most frequently used [8,10,20,22,27,33,41].

Subsequently to the excavation, this material is primarily used for embankments and fillings [5,10,18,36,39] after the surfactants decay in time, thus guaranteeing acceptable environmental management [15,32].

Frequently, the excavated soil, or a part of its components, has properties that can make it suitable as aggregate for concrete, that is, in a more “noble” application. There are several studies of the reuse of TBM muck for civil purposes [1,17] but few for EPB-conditioned soil as aggregate for concrete production are limited [29]. However, many studies have examined the use of surfactants in foamed concrete production [23,34], but in those cases, the types and amounts of surfactants were specifically designed.

Conversely, when tunnelling with EPB-TBM, the quantity of conditioning agents (foam) is driven by the soil properties and the excavation needs. For this reason, the amount of surfactant cannot be designed in relation to the way it affects the behaviour of concrete. Before the reuse, the aggregates (sand and gravel) must be washed, but the level of effort to completely remove the surfactant agent is unknown.

This research seeks to understand if, and with what magnitude, the presence of residual amounts of surfactants in aggregates could affect the mechanical properties of concrete. This research is based on a comparison approach: The concrete produced with clean aggregates was compared to that produced with aggregates that were treated with surfactants for a proper excavation with an EPB-

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TBM. The uniaxial compressive strength (UCS) and the elastic dynamic moduli were selected as the checking parameters. Three different concrete sample sets were produced with the same aggregates but with different contents and types of foaming agents with which aggregates were saturated. In particular, for one set, the aggregates were saturated with water, one with a solution 5 % (v/v) of product A (referred to hereafter as Condition A) and one with a solution 5 % (v/v) of product B (referred to hereafter as Condition B), to evaluate to what extent the presence of surfactant influences the mechanical properties.

2. EPB soil conditioning

In EPB-TBM tunnelling, foam is mixed with soil as it is detached from the excavation face to create a material with desired properties in a process called soil conditioning.

Specifically, the conditioned soil has to show good flowability, high compressibility, reduced permeability, and wear potential [7,16,28,30,35]. An example of the change in soil behaviour with respect to the flowability is shown in Fig. 1.

This material, pressurised in the excavation chamber, provides support to the excavation face and acts as a plug that dissipates the pressure along the screw conveyor through which is extracted.

After the extraction, the material is typically left at the jobsite until the added foam decays. In fact, from the moment at which foam is injected into soil, it starts to decay. This process has two main components: One refers to the physical structure of foam that progressively collapses [11]; the other refers to the biodegradation of the surfactant used in the foam production process [4,15].

In order to guarantee the presence of surfactant on the aggregate during all the saturation phase, the aggregate was wetted with the liquid phase only instead of foam, that is subjected to decay and volume reduction, as will be described in Section 3.2.1, and, by performing the test immediately after the first day, the contribution of biodegradation has been minimised.

3. Experimental research

To conduct the research three sets of cubic samples of concrete were produced using the same mix design and procedure, then tested. Two sets had aggregates with some conditioning agent on its surface and one, as reference, without it. For each sample a set of tests were carried out as described in the following chapter. The obtained results are then presented and compared. The outcomes give a preliminary indication of the influence of the conditioning on the concrete's mechanical properties.

3.1. Method

3.1.1. Materials

For the production of concrete, the authors used a Portland-Limestone Cement CEMII/A-LL 32.5R, that is widely used in the construction industry and whose main characteristics are given in Table 1.

3.1.2. Surfactants

As previously stated, three conditions were set for the saturation of the aggregates:

- Condition 0 – Water;
- Condition A – Product A, solution with concentration 5 % (v/v);
- Condition B – Product B, solution with concentration 5 % (v/v).

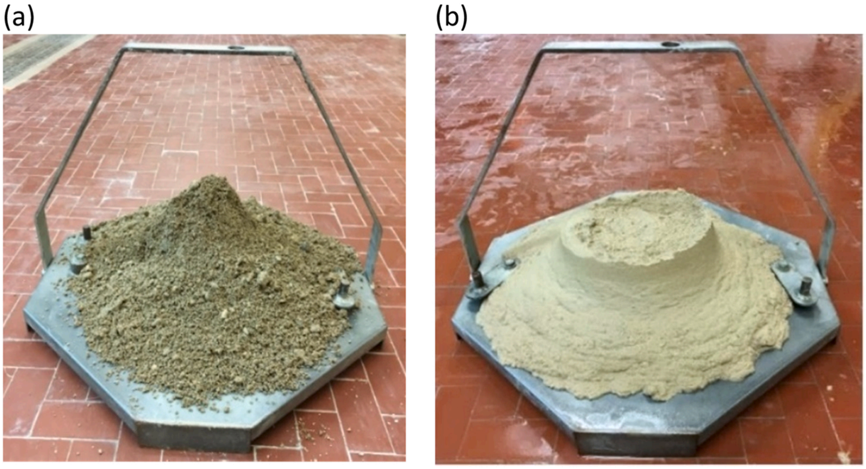

Fig. 1. Soil before (a) and after (b) the conditioning.

Table 1
Cement characteristics.

Clinker	80–94 %
Natural pozzolan	6–20 %
TOC	0.2 %
Sulphates (SO_3)	< 2.8 %
Chlorides (Cl^-)	< 0.06 %
Soluble hexavalent chromium	< 0.0001 %
Blaine specific surface	4200–4600 cm^2/g
Initial setting time	130–150 min
Stability	0 mm
Specific weight	3.03 g/cm^3

This 5 % concentration was used since it represents a superior limit of the possible concentration achievable on a jobsite [13]. In detail, Condition A has the following known components:

- Alcohols, C12-14, ethoxylated, sulphates, sodium salts, CAS: 68891-38-3, Concentration (w/w): 10–20 %;
- Mixture of 5-chloro-2-methyl-2H-isothiazol-3-one and 2-methyl-2H-isothiazol-3-one, CAS: 55965-84-9; Concentration (w/w): 0.0002–0.0015.

Condition B has the following known components:

- Sodium lauryl ether sulphate, CAS:9004-82-4, Concentration (w/w): 5–10 %

3.1.3. *Aggregates*

Regarding the aggregate used for the concrete production, a unique aggregates grain size distribution was expressly prepared. Different granulometric classes were used, and a careful metering phase was carried out in order to obtain a grain size distribution (Fig. 2) of the final product as similar as possible to the Fuller distribution [12].

3.2. *Method*

3.2.1. *Aggregates saturation*

The saturation of aggregates was performed with the three conditions only for what concerns the medium and coarse fractions. The finer fraction ($\Phi < 1$ mm) of aggregates was saturated only with water since the recovery of finer fractions from the muck is much more difficult and may be impractical on the jobsite.

The aggregates were submerged according to the three conditions described in Section 3.1.2 above for 24 h.

3.2.2. *Aggregates washing*

To simulate the washing of the aggregates that would be required for a conditioned soil to eliminate the finer particles and respect the limits stated by ASTM-C33-07 [2], the aggregates were lightly washed with water after the 24-h period of saturation. A scheme of the procedure is given in Fig. 3. The washing was kept to the bare minimum to maximise the potential effect of surfactants on the UCS. Each sample of aggregates kept in Conditions A and B was extracted and placed into another container, submerged with water for 1 min, and then extracted again. Each sample was then left to drain for 1 h, with all samples in the same conditions of temperature and relative humidity.

As stated above, the washing was performed in order to wash out the possible fines present that have to be removed from the aforementioned norms but was kept as light as possible with two main scopes in mind: first, to remove the smallest quantity of

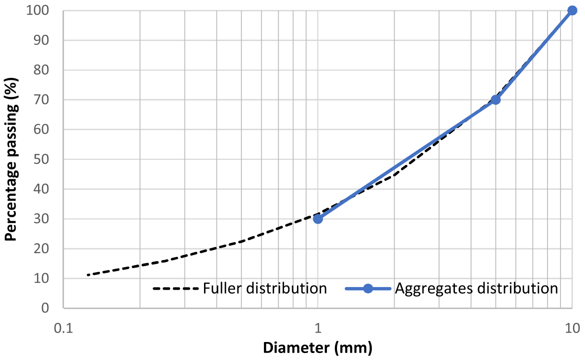

Fig. 2. Aggregate grain size distribution.

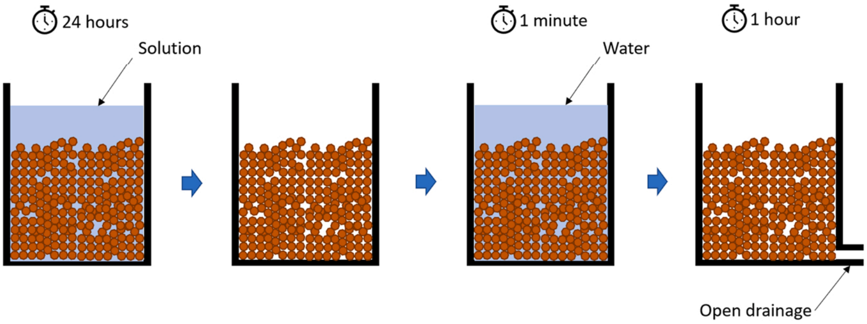

Fig. 3. Scheme of inert preparation.

surfactant possible and test the high-end range of concentrations; second, to simulate what could be economically feasible on a jobsite.

3.2.3. Mix design

The mix design was drawn according to the procedure described in Collepardi [12] using a water-cement ratio equal to 0.5. Dosages are reported in Table 2.

3.2.4. Concrete production

The 15 samples were produced in three batches, one for each condition.

The mixing was performed with a 0.25 m^3 concrete mixer that was carefully wetted and left to drain upside down for 30 min before adding the aggregates. The samples were then mixed for 30 s, after which cement and water were added. They were then mixed for 60 s more.

Finally, the samples were poured into cubic moulds and vibrated for 30 s.

3.2.5. Curing

For each condition, we produced five cubic samples of 15 cm poured into polystyrene moulds. The curing was performed at room temperature, and the moulds were kept separated in order to avoid localised increments of temperature due to hydration heat that may have influenced the curing process.

The curing time was set to 28 days during which the average temperature was 22 °C.

3.2.6. Compression test

The compression test was conducted according to the UNI EN 12390-3:2003 [40] with a rate of loading of 0.2 MPa/s. Pictures of one sample before and after the test are given in Fig. 4.

3.2.7. Pulse velocity test

3.2.7.1. Testing procedure. The ultrasonic pulse velocity (UVP) method is frequently used to estimate the dynamic mechanical properties of concrete [24] by determining the wave path of the first arrival wave, both longitudinal and shear.

The test is performed, according to ASTM C597-16 [3], by attaching two transducers onto opposite sides of the concrete specimen surface (direct transmission) and then measuring the transmission time and velocity of waves between them, as shown in Fig. 5.

For the pulse velocity tests, we used a Pundit ®PL-200, a device fully integrated and designed for ultrasonic pulse velocity tests with pulse generator, receiver amplifier, and time-measuring circuit incorporated, with the test frequency set to 250 kHz [38].

A pressure of about 0.4 MPa (according to ISRM [21]) was applied through a laboratory press to grant a strong coupling between the transducers and the concrete surface.

3.2.7.2. Data processing. Basic processing was performed to estimate the first arrival of the longitudinal and shear wave travel times. The processing flow was based on displaying the signal as wiggle traces, application of automatic gain control to recover energy,

Table 2
Mix design.

Ingredient	Dosage
Water (w)	210 (kg/m^3)
Cement (c)	420 (kg/m^3)
Sand (s)	510 (kg/m^3)
Medium aggregate (ma)	680 (kg/m^3)
Coarse aggregate (ca)	510 (kg/m^3)
Trapped air (a)	25 (dm^3/m^3)

Fig. 4. Sample before (left) and after (right) the test.

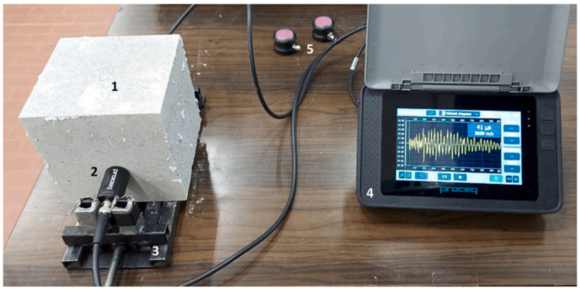

Fig. 5. UPV test setup. *Note.* On the left, the sample (1) and the P-wave transducers (2) are held in position with a press (3). On the right, the Pundit ® instrument (4) consists of a pulse generator, a receiver amplifier, and a time-measuring circuit. The same configuration with the S-wave transducers (5) was applied for the relative tests.

bandpass filtering to remove unwanted electronic noise, and finally, manually picking the travel times.

By measuring the P-wave and S-wave travel times, we determined the bulk modulus (K) and the dynamic shear modulus (G) using the following equations:

$$K = \rho V_p^2 - \frac{4}{3}G$$

where ρ is the density of the material and V_p is the pulse velocity of the P-wave;

Table 3
Summary of the results of the tests.

Condition (-)	Sample ID	UCS (MPa)	Vp (m/s)	Vs (m/s)	γ (g/cm^3)	Poisson's ratio (-)	E (GPa)	G (GPa)
0	1	21.99	3930	2504	2.12	0.158	30.766	13.282
	2	23.60	3989	2459	2.17	0.188	31.222	13.146
	3	20.96	3902	2435	2.15	0.202	30.673	12.760
	4	21.38	3989	2475	2.21	0.197	32.470	13.565
	5	22.08	3916	2504	2.10	0.181	31.073	13.150
	Avg.	**22.00**	**3945**	**2476**	**2.15**	**0.185**	**31.241**	**13.181**
A	1	11.33	3475	2222	1.98	0.154	22.557	9.773
	2	15.02	3557	2206	2.00	0.188	23.056	9.708
	3	12.01	3557	2174	2.03	0.202	23.027	9.579
	4	13.66	3644	2239	2.02	0.197	24.211	10.115
	5	13.25	3557	2219	1.97	0.181	22.896	9.690
	Avg.	**13.05**	**3558**	**2212**	**2.00**	**0.184**	**23.149**	**9.773**
B	1	18.65	3830	2385	2.12	0.183	28.522	12.051
	2	18.00	3734	2340	2.12	0.188	27.586	11.615
	3	21.42	3734	2396	2.05	0.202	28.266	11.759
	4	20.12	3734	2443	2.03	0.197	29.029	12.127
	5	19.18	3930	2415	2.07	0.181	28.469	12.048
	Avg.	**19.47**	**3792**	**2396**	**2.08**	**0.190**	**28.374**	**11.920**

$$G = \rho V_s^2$$

where V_s is the pulse velocity of the S-wave.

Poisson's ratio was determined using the following relationship:

$$\nu = \frac{V_p^2 - 2V_s^2}{2V_p^2 - 2V_s^2}$$

Once the Poisson's ratio was known, the dynamic Young's modulus was calculated as follows:

$$E = 2G(1 + \nu)$$

4. Results

The results of the research are given in Table 3 where it is possible to see that the different conditions affected the results as explained in Section 5. The average values are both written in bold in Table 3 and given in Fig. 6.

5. Discussion

From the results above, it is possible to note how the presence of surfactant, introduced into the mix by the aggregates, has a deleterious effect on both the compressive strength and the elastic moduli.

This effect is probably due to the increase of porosity consequent to the higher air quantity in the mix, as shown by the specific weight data where, on average, Condition A showed a decrement of 7 % and Condition B a decrement of 3 % compared to Condition 0. The higher effect in Condition A can be explained by the different concentration of the foaming chemical constituents.

In the same way, there was a similar decrement in the average UCS that reduced by 11 % in Condition B and 41 % in Condition A.

For the elastic moduli, longitudinal and transverse (E and G), the reductions for Condition A were both about 25 %, but both were about 9 % for Condition B.

The outcomes in terms of UCS and E were consistent since theoretical equations pertaining to concrete reported by NTC in 2018 were respected.

The results are coherent with the scientific literature about foamed concrete. In particular, the reduction of UCS, elastic moduli and specific weight was already found by Kashani et al. [23] and Sahu and Gandhi [34]. Nevertheless, these authors addressed a material specifically designed to be foamed. Conversely, in the present work, the increment of porosity is a side effect and the scientific literature does not address and does not quantify its magnitude.

6. Conclusions

The presence of a history of conditioning of the inert cannot be disregarded in its reuse for concrete production. The presence of surfactants on inert surfaces has deleterious consequences on the mechanical properties of the concrete. Specifically, the reductions of UCS (up to 41 %), specific weight (up to 7 %), and longitudinal and transverse dynamic elastic moduli (25 % and 9 %, respectively) may be due to a higher presence of air in the mix design.

The aim of this paper was to determine if the worst conditions that may be encountered in the EPB-TBM excavation concerning the amount of surfactant present on inert surfaces do or do not affect the mechanical characteristics of the produced concrete. The obtained results can be useful to identify a potential issue in the reuse of muck as aggregate for concrete and gives a preliminary order of magnitude on the reduction of the mechanical properties of the produced concrete.

With the presence of relevant effects, it is clear that these results are preliminary and the topic needs to be more fully investigated. In particular, the concentration of the saturating solution, the washing modalities, and the cement type will vary. Also, the time between the contact of the inert surface and its use in the mix may have some effect.

Lastly, it is worth noting that the observed reductions are not inherently negative. In fact, if used for the prefabrication of tunnel segmental lining, the reduction of the elastic moduli may lead to a reduction of the load acting on the lining due to the convergence-confinement method, and the reduction of specific weight may facilitate the transport and installation phases.

CRediT authorship contribution statement

Carigi Andrea: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Saltarin Simone:** Investigation, Data curation. **Di Giovanni Alfio:** Investigation, Data curation. **Todaro Carmine:** Writing – review & editing. **Peila Daniele:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

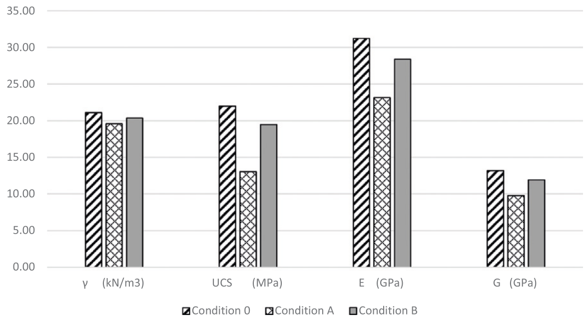

Fig. 6. Average results of the tests.

Data Availability

Data will be made available on request.

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