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Physical and mechanical properties of concrete with added dry sludge from a sewage treatment plant

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Abstract

One of the main objectives of this study was to evaluate an alternative final destination for the growing production of sludge from sewage treatment plants. At present, a significant quantity of dry sludge is obtained in Catalonia. That is why this paper examines the possibility of adding this waste product to plain concrete with Portland cement.

Taking into account the authors' previous work, this study focused on making specimens of concrete containing different percentages of sludge from a sewage treatment plant, studying both their physical properties (density, porosity, and absorption capacity) and their mechanical properties (compressive strength, flexural strength, and elastic modulus) over time.

The results confirmed that up to 10% of treatment plant sludge can be added to concrete for use in certain very specific applications.

Keywords: Mechanical properties; Physical properties; Stability; Concrete; Waste management

1. Introduction and objectives

This work attempts to find an alternative for the large volume of sludge produced by sewage treatment plants. In Spain, this waste is used in agriculture in the form of composts. However, in some areas, the sludge produced does not just contain a large percentage of organic material but also environmentally toxic heavy metals, which makes it unsuitable for some purposes.

Taking this as our starting point, we examined the possibility of using the dry sludge from treatment plants as an additional component in construction materials and, in this particular case, as an addition to plain concrete.

This work aimed to evaluate the physical and especially the mechanical properties of concretes containing dry sludge from treatment plants together with Portland cement.

2. Characterization of dry sludge

The sludge used was dry biological sludge that came from the Sabadell–Riu Sec sewage treatment plant (near Barcelona). The industrial drying process, which was performed (up to 200 °C), did not totally dry the sludge—lumps with humidity inside them were detected. The average humidity of the sludge was about 15%. In these conditions, the majority of microorganisms disappear.

The following parameters were characterized:

- physical properties (humidity, density, and granulometry);
- chemical properties (pH, percentage of organic material, main elements, and leaching DIN 38414-S4 [1]); and
- mineralogical properties of the inorganic crystalline fraction using X-ray diffraction of the sludge without sieving.

2.1. Physical characterization

As the use of the sludge as an addition to concrete was considered, it was necessary to characterize the granulometric fraction (see Fig. 1). The granulometry was performed after the sludge had been totally dried at 105 °C. Because the sludge had a residual humidity (about 15%), the dried industrial process was not complete.

The granulometry of the dry sludge was similar to that of a fine agglomerate. Furthermore, it was a very spongy material with a very low density—of the order of 1 g/cm^3.

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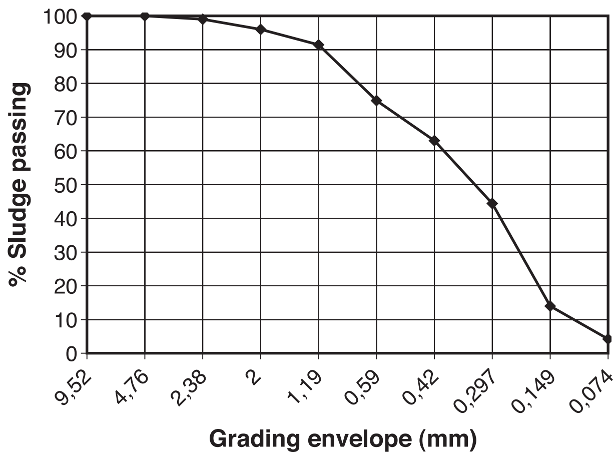

Fig. 1. Dry sludge granulometry.

2.2. Chemical characterization

Tables 1, 2, and 3 show the results of the chemical characterization of the dry sludge from Sabadell–Riu Sec, and Table 4 shows its biochemical and microbiological characterization.

The leaching results showed that according to the DIN 38414-S4 standard [1], the sludge is a special waste product. The nickel content is 1.06 mg/l, which slightly exceeds the limit (1 mg/l) set by Decree 34/1996 of the Generalitat (government) of Catalonia, dated 9th of January 1996 [2].

The inclusion of such a special waste product in a Portland cement matrix allowed the nickel to be fixed and in turn to precipitate in the form of nickel hydroxide [3,8]. The leaching of the waste was far less than it would have been in nonstabilized sludge.

2.3. Mineralogical characterization

X-ray diffraction analysis was performed to establish the inorganic crystalline composition of the sludge. The inorganic minerals that formed the sludge were quartz and calcite.

It is important to point out that there were no clays in the dry sludge that could have caused stability problems in the concrete.

3. Method

3.1. Introduction

The solidification/stabilization mechanisms for sludge from treatment plants in a Portland cement matrix have previously been evaluated by the authors [3–6]. It has been shown that it is possible to use this matrix as a system for achieving inertness, whilst guaranteeing both physical and chemical stability [7]. Once we had checked that the compound was inert, the ultimate objective was to explore the possibilities of obtaining materials containing sewage treatment plant sludge which could be used in the construction industry. To do this, this study investigated the possibilities of plain concrete containing dry sludge.

Introducing a waste material, such as the sludge, into a matrix with cement causes changes in the normal behaviour of the cement, mainly due to the organic material which acts as a setting retardant and also due to some heavy metals which interfere with the hardening reactions [3,5,8].

It was therefore essential to find out the extent of the influence of the sludge to establish the maximum dose and to predict and control the final behaviour.

We have showed that for a sludge content of more than 10% in the cement mix, the final setting time was extremely high, so it was not advisable to exceed this percentage [5].

3.2. Manufacturing specimens

To study concrete consisting of Portland cement with added dry sludge, we studied four percentages of sludge in the cement mix: reference concrete or 0% sludge; 2.5% sludge; 5% sludge; and 10% sludge.

Table 5 describes the proportions used in the concrete.

3.2.1. The process of making the mixture for the concrete specimens

The process of making the specimens followed the UNE 83-301 standard [9] as far as possible, except that the sludge was added. The sludge was mixed with the cement to achieve a homogeneous mixture.

All the concretes had a fluid consistency (Abram's cone slump of between 10 and 15 cm). They were made accord-

Table 1
Chemical characteristics of dry sludge from waste water treatment plant in Sabadell (near Barcelona)

PH	7.08
% Loos at 500 °C	41.5%–52%

Table 2
Main elements of Sabadell calcine dry sludge determinate by XRF

Na_2O	$1.11 \pm 0.07\%$	CaO	$22.7 \pm 0.2\%$
MgO	$2.73 \pm 0.08\%$	Cr_2O_3	$0.24 \pm 0.02\%$
Al_2O_3	$12.9 \pm 0.2\%$	Fe_2O_3	$10.1 \pm 0.1\%$
SiO_2	$29.7 \pm 0.2\%$	NiO	$0.127 \pm 0.010\%$
P_2O_5	$12.4 \pm 0.2\%$	CuO	$0.23 \pm 0.02\%$
SO_3	$3.22 \pm 0.08\%$	ZnO	$0.84 \pm 0.04\%$
Cl	$0.20 \pm 0.01\%$	SrO	$0.29 \pm 0.02\%$
K_2O	$1.83 \pm 0.06\%$	ZrO_2	$0.16 \pm 0.01\%$

Table 3
Heavy metals' concentration in mg/l by DIN 38414-S4 leaching standard [1] of dry sludge—Sabadell

Ba	0.75 ± 0.02	Mn	0.23 ± 0.01
Zn	1.23 ± 0.06	Cd	< 0.01
Ni	1.058 ± 0.003	Cr	0.052 ± 0.012
Pb	< 0.05	As	< 0.1
Cu	0.31 ± 0.07		

Table 4
Biochemical and microbiological characterization of dry sewage sludge

Components	Percentages
Proteins	0.41%
Fats	0.33%
Carbohydrates	65.47%
Relation C/N	1.93
Organic nitrogen	0.09%
Phosphorus	0.38%
Ashes	31.79%
Aerobics	26 ufc/g
Enterobacterium	< 10 ufc/g
E. coli	< 3 nmp/g
Coliform	< 3 ufc/g
Mushroom	< 10 ufc/g
Clostridium	< 10 ufc/g

ing to the UNE 83-313 standard [10] and compacted using a rod—UNE 83-301 [9].

The type of test to be performed determined the shape and the size of the specimens, which meant that the degree of compaction varied according to the mould (Table 6).

3.2.2. Conserving the specimens

The specimens were placed in a moist chamber at a temperature of 20 °C and a minimum relative humidity of 95% until they were removed from their moulds. The time of removal of the specimens from the moulds is not fixed for this type of material and depends on the dose tested; in this case, it depended on the increase in the proportion of sludge compared to cement.

Generally, the minimum time for removing the specimens from the moulds was 24 h, and the maximum was 48 h. Table 7 shows the times that were used.

Once the specimens had been removed from the moulds, they were returned to the moist chamber under the same conditions as before, and their curing process were continued until they were used in the corresponding tests.

4. Results

The physical and mechanical properties of the concretes produced determine whether they are useful for certain applications.

Table 5
Mixing mass concrete

Mass concrete	
Material	1 m^3 of concrete
Sand 0/5	847 kg
Sand 0/2	200 kg
Additive—Melcret PF-75	1.68 l
Water	160 l
Aggregate 5/12	85 kg
Aggregate 12/18	816 kg
CEM II/32,5-R	287 kg

Table 6
The shape and the size of specimens depending on the test

Test	Mould
Compressive strength	Cylindrical (15 × 30 cm)
Flexural strength	Prismatic (7.6 × 7.6 × 25.4 cm)
Elastic modulus	Cylindrical (15 × 30 cm)
Physical properties	Cubic (10 × 10 × 10 cm)

We determined different physical properties such as density, porosity, and absorption. Tests were also preformed to determine mechanical properties: compressive strength, flexural strength, and elastic modulus. The tests were performed on concretes of different ages.

4.1. Physical properties

To determine the densities of the concretes containing sewage treatment plant sludge, we followed the UNE 83-312 standard [11]. However, there is no Spanish standard for determining the porosity or the capacity for water absorption.

The results are shown in Figs. 2, 3, and 4. Four doses of sludge were studied after three different curing times in the case of the density and after two different curing times for porosity and absorption.

Fig. 2 shows how the density varied according to the sludge content. The lines are almost parallel, showing that the density decreased in approximately the same proportion as the dry sludge increased. This means that the weight of a given volume of sample decreased as the amount of sludge increased. This is because the dry treatment plant sludge was quite a spongy material with a lower density than the dry aggregates that go into the concrete, which means that the density of the mixture decreased as more sludge was added.

We also observed that the net dry density increased over time in the concretes that contained sludge. It is important to note that the concrete is lighter at lower ages and with a greater sludge content. As the concrete containing sludge hardened, the weight of a given volume increased; that is, the density increased.

The porosity (Fig. 3) rose with an increasing sludge content. The porosity tended to decrease as the age of the concrete increased from 7 to 90 days. The hardening of the concrete has an effect of binding the particles, which, over time, decreases the number of pores.

The absorption capacity (Fig. 4) tended to increase with an increasing sludge content. This indicates that as sludge is added, the capacity to hold water increases together with a

Table 7
Time of removal from the moulds

Time of removal from the moulds	
% Sludge	Time (h)
0%	24
2.5%	24
5%	48
10%	48

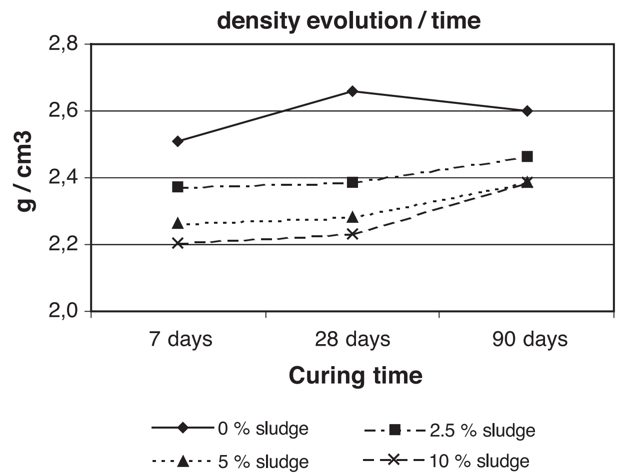

Fig. 2. Density varied according to the sludge content with three different curing times.

certain increase in the number of cavities inside the concrete. The porosity of the sludge resulted in the concrete having a greater absorption capacity. This in turn increased until the age of 90 days, a time in which it decreased. This is because once the concrete acquires greater hardness and resistance, it requires less water and is not able to assimilate it as well as it had done initially.

4.2. Mechanical properties

The mechanical properties that we tested were compressive strength, flexural strength, and elastic modulus. Different standards were followed for each of these tests: UNE 83-304 [12], UNE 83-305 [13], and UNE 83-316 [14], respectively.

4.2.1. Compressive strength

The results obtained with cylindrical specimens are given below (Fig. 5), always as mean strength in megapascals (MPa). Furthermore, after 28 days, we determined the characteristic strength of the concrete [15].

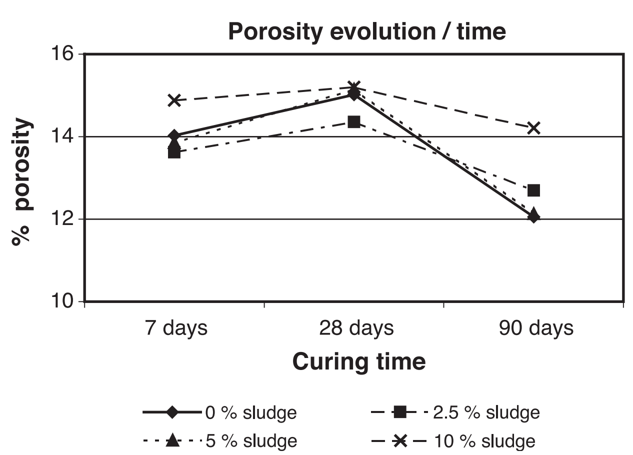

Fig. 3. Porosity varied according to the sludge content with three different curing times.

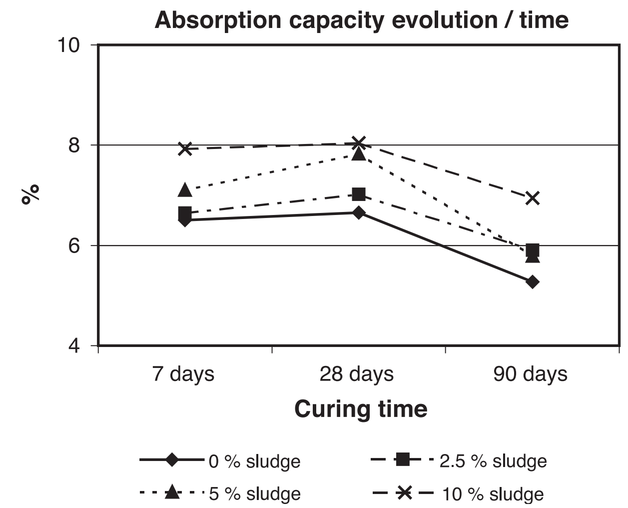

Fig. 4. Absorption capacity varied according to the sludge content with three different curing times.

The compressive strength after 7 days provided us with some clear results indicating that the strength decreased appreciably as the proportion of sludge increased. The strength of the specimens containing 10% sludge after 7 days was very low and was totally insufficient for many uses, especially structural ones. For all the different mixtures, after 28 days, the compressive strength increased in comparison with that of the previous period but not uniformly. The reference concrete increased normally, but as the proportion of sludge in the specimens increased, the rise in compressive strength was less sharp. However, for the same age, the comparison of compressive strengths was similar to that of the previous period, and the compressive

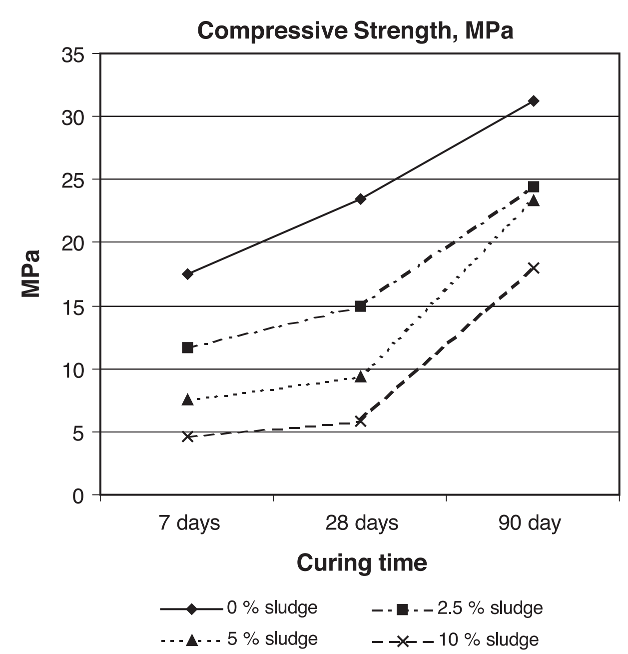

Fig. 5. Compressive strength according to the sludge content with three different curing times.

strength was still lower at higher proportions of sludge in the specimens.

The fact that sludge delayed the increase in compressive strength, especially at low ages, can be clearly seen. In contrast, as time went by, the concretes containing sludge recovered, and their compressive strength increased faster than that of the reference concrete, which underwent the opposite process: a rapid increase early on followed by a slower increase as the curing time increased.

After 90 days, the compressive strength had recovered, and, for example, the specimens containing 10% sludge reached 58% of the compressive strength of the reference concrete, and those containing 2.5% sludge reached 78% of the reference value.

4.2.2. Flexural strength

To test flexural strength, three prism-shaped specimens of concrete were used for each dose of sludge. The samples used were cured for 28 and 90 days.

Fig. 6 shows the average flexural strengths for the different mixtures of concrete after the two curing periods. The flexural strength decreased with the increase in the amount of sludge in the different samples and increased with the curing time.

4.3. Elastic modulus

To design the test for determining the elastic modulus, we followed the UNE 83-316 standard [14], as mentioned above. The modulus was determined for cylindrical samples measuring 15 × 30 cm, made according to the UNE 83-301 standard [9] and kept in a moist chamber for 90 days.

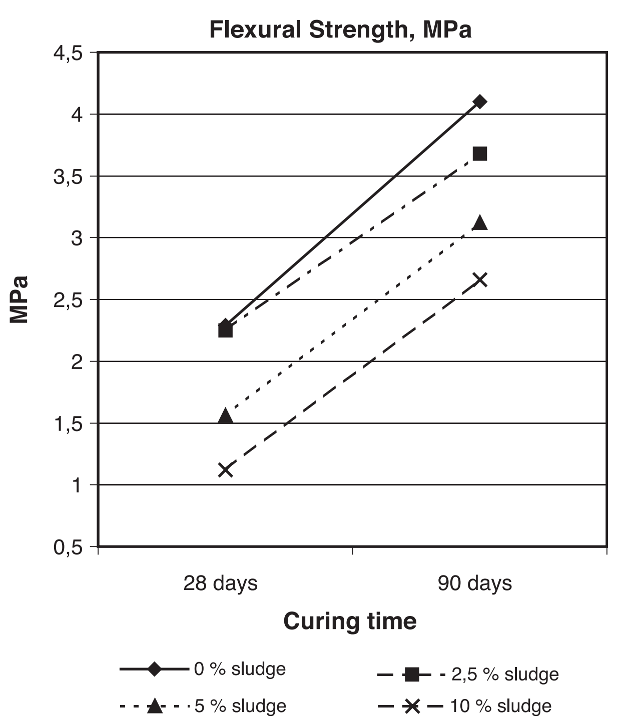

Fig. 6. Flexural strength according to the sludge content with different curing times.

Table 8
Elastic modulus at 90 days

Elastic modulus	
Samples	MPa
0% Sludge	31,500
2.5% Sludge	26,000
5% Sludge	23,000
10% Sludge	20,000

The test consisted of applying an initial tensile strain, performing at least two load–release cycles that compressed the specimens to 33% of their estimated breaking loads and recording the deformations. The deformation measurements were made using Linear Variable Differential Transformers (LVDTs). Three successive load–release cycles were applied. During each one, the values of the corresponding deformations were recorded. Then, the LVDTs and their supporting rings were removed, and the specimen was compression-split.

To perform this test, a Normatest electromechanical press with a maximum pressure of 20 tons was used.

To calculate the elastic modulus, three series of values were taken, each consisting of two readings of the deformations for the initial tensile strain and for the tensile strain at one third of the breaking strain. Taking the mean of the six values gave us the average deformation for each tensile strain. Finally, we determined the elastic modulus by dividing the difference in tensions by the difference in deformations. The results are given in Table 8 and Fig. 7.

The results confirmed our expectations—the modulus clearly decreases as the amount of sludge in the concrete increases. Under the same strain, the specimen with the highest proportion of sludge showed the greatest deformation. This fits in with the fact that the number of pores increased as the proportion of sludge increased.

We have worked also the durability and dimensional variations of this product, this will be published with interesting results.

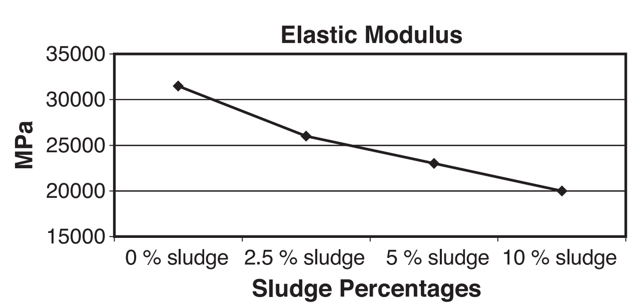

Fig. 7. Elastic modulus according to the sludge content at 90 days.

5. Conclusions

In the light of these results, we can conclude that the main objective of using treatment plant sludge as an additional component in a construction material, Portland cement concrete, is possible. The most important physical and mechanical properties of concrete containing treatment plant sludge were evaluated. Nevertheless, it was first necessary to analyse other characteristics such as the origin of the sludge, the materials used, the compatibility of the sludge within the cement matrix, and the production of specimens.

Our conclusions are

- Dry sludge can be used as an addition to concrete without the need for large changes in its preparation.
- Its granulometric properties mean that it can be used as fine sand in production.
- Adding dry sludge from the Sabadell treatment plant causes variations in the physical and chemical properties of the cement.
- A sludge content of 10% or more cannot be used because it significantly delays the setting of the cement and reduces its mechanical properties, especially in the short term.
- In all cases, the presence of sludge reduces the mechanical strengths of the concrete, and this decrease increases as the sludge content increases.
- For all sludge contents, the strengths increase as the curing time of the concrete increases.
- In the worst case (after 7 days for concrete containing 10% sludge), the compressive strength was 4.5 MPa. After 28 days, the same concrete had reached a strength of 6 MPa, and after 90 days, it reached 18 MPa, which would allow it to be used for road bases and subbases, and as a filling material. In general, it would be suitable for any application that does not require high strengths, especially not in the short term.
- The deformability of the concrete increases with an increasing sludge content.
- The density of the concrete decreases with an increasing sludge content and increases as the curing time increases. The value varies from 1.8 to 2.0 g/cm^3. It is a light material that can be used to meet diverse needs in the field of filling materials and compacted flooring [16].
- The porosity and the absorption coefficient increase with an increasing sludge content and decrease as the curing time increases.

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