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Mortars incorporating alum-sludge as sand replacement: Development and brick-wall calculation

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Serna Tormo, Ismael Esteban

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Tutor: *Dr. Jorge Juan Payá Bernabeu*

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Abstract

The sludge generation coming from the Water Treatment Plants is a worldwide scale problem, which generates economic losses and risk for the environment. As many researchers have proved, water treatment sludge can be used as a construction material due to its similarity with clay. In this study, mortars with 5% and 10 % sand replacement for alum-sludge were developed, testing mixtures with simple-dried sludge and with high-temperature treated sludge (to eliminate its organic matter content), plus the reference mortar, a total of 5 mortars. With this laboratory process mechanical and durability properties were determined. Compressive and flexural strength showed generally worse performance, however, bond strength showed higher values for most of sludge mixtures. Shrinkage values increased for 10% sludge content and at the same time for raw sludge mortars. The water capillarity absorption was smaller than reference for raw sludge mixture and higher for treated sludge mixtures. After testing, it was calculated different wall typologies of brick-walls with a residential purpose. Most of the sludge mixtures showed a good performance with free-standing walls up to 2 m and with walls as isolating layers supported in buildings, up to 2.75 m. Except for 10% raw sludge mixture, mortars incorporating alum-sludge seem a feasible and sustainable option as construction material.

Keywords

Mortar, Water Treatment Sludge, Alum-sludge, Mechanical Properties, Performance, Brick-wall, Sustainable.

1. Introduction

In the last decade, the worldwide population has increased around 12%, reaching 9 billion by 2037 (*World Population Clock*, 2019), a fact that clearly explains the growth in the potable water demand. In the procedure to purify the raw water and make it available to human consumption, in the Water Treatment Plants (WTPs) are being developed processes as filtration, coagulation, flocculation, sedimentation, and disinfection of the pollutants. The result generated of these processes is known as Water Treatment Sludge (WTS) and a WTP can produce an average of 100,000 tons/year of this raw material.

The production of WTS is an issue that affects the environmental -high risk of water contamination due to heavy metals present in WTS- and economic situation of most of the countries (Ooi *et al.*, 2018). Normally all this amount of residues are either discharged into waterways or disposed to landfills. In Australia, the amount of WTS generated could reach up to 43,500 tons per year. The costs associated with the sludge disposal through landfill or/and sewer disposal have an estimated cost of over 6.2 million per annum in the state of Victoria, Australia (Maiden *et al.*, 2015).

Many researchers have been studying the use of WTS, mainly in calcined form, for building new construction materials, as a substitute for cement in concrete pieces and mortars. However, there is not much literature on the use of WTS in the replacement of sand in the develop of mortars (de Oliveira Andrade *et al.*, 2018). The replacement of sand or cement for sludge in materials could solve two problems: the necessity of safe management of the sludge and the excessive consumption of raw materials in most countries. However, most of the experiments carried out showed significant lower mechanical properties in more than 10% material replacement with WTS.

This research will focus on the study of mortars for brick walls, remarking the differences of calcined sludge and raw sludge influence, and evaluating its suitability, properties and real performance in brick-walls.

2. Literature review

This section reviews the current literature about WTS, establishing the problem of the WTS management, passing through the different solutions suggested up to now, and showing previous works with the same or similar material that will be tested.

2.1. Problem statement

By the year 2007, the wastes generated from the raw water process were in general simply discharged into hydric resources, what is a less expensive solution, although it was not a proper solution due to the possibility of mud deposits. These undesired mud deposits may alter the natural water path and affect the aquatic life, as the contaminants present in the sludge do. However, other alternatives for the final disposal of the sludge were being considered, for instance, discharge in sewage pipelines, accumulation in mud containing reservoirs and direct soil applications (landfill) (Monteiro *et al.*, 2008).

Babatunde and Zhao (2007) further pointed out the extreme lack of information on the toxicity of WTS. This research showed that the metal concentration of aluminium in the sludge could reach up to 40% of dry weight, which may be considered potentially toxic. Even though one of the main uses of the WTS were land-based applications like structural soil improvement or nutrient reduction, some environmental issues were not considered as risk of metal accumulation, potential fixation of P, and phytotoxicity of inorganic aluminium. Nevertheless, Ahmad, Ahmad and Alam (2016) pointed that a controlled application of WTS as fertilizer could maximize benefits with minimal impact, a fact that leads to reconsider the use of WTS as use for lands.

According to Sales, De Souza and Almeida (2011), the chemical substances used in most of the WTPs are Aluminium salts ($Al_2(SO_4)_3{\cdot}18H_2O$), ferric ion salts and ferrous iron salts. The metal level depends on the processes involved in the treatment of the water since it may be higher if coagulants are added (even the metals that the raw water naturally may content). The concentrations of these metals may be sufficiently high to result toxic for the aquatic flora and fauna if the sludge is not previously treated. In the case of the Halley Valley Treatment Plant, the treatment incorporates aluminium salts that are present in the sludge generated up to 30%, which categorized it as aluminium-rich sludge.

Maiten *et al.* (cited in De Carvalho Gomes *et al.*, 2019) showed that in Australia the disposal in landfills of the WTS reaches an approximate cost of $6.2 million per year in the state of Victoria. Evuti and Lawal (cited in De Carvalho Gomes *et al.*, 2019) also showed the costs associated with sludge disposal for the Netherlands, this time reaching up to £40 million. In the UK the annual cost rounds the £5.5 million (Keely *et al.,* cited in

De Carvalho Gomes *et al.*, 2019). Therefore, proper management from a country of the sludge may save millions per year on average.

2.2. Sludge in construction materials

Hoppen *et al.* (2005) produced four concrete mixtures replacing the fine aggregates in 3, 5, 7 and 10 % of the weight with WTS. Since the sludge was not previously treated, the water content was adjusted with the moisture of the sludge. The sludge was composed of Si, Fe, and Al compounds, and the experiment showed that 10% of replacement could be limiting since the workability decreased as the compressive strength did, significantly. There was any notice of the sludge being previously treated in this study, so the presence of organic material may originate that high loss of properties. This study suggested that this kind of concrete may be used with non-structural purposes.

Tarafel *et al.* (cited in De Carvalho Gomes *et al.*, 2019), used alum-based sludge in the replacement of sand in proportions up 10%, to develop concrete samples. This research showed that only 5% of replacement met the strength requirements of the Brazilian Standards, pointing also that the water absorption increased up to 32% with a 10% sludge incorporation. Gomes *et al.* (cited in De Carvalho Gomes *et al.*, 2019) did similar research with sand replacement, but this time using the natural form (non-treated). This wet sludge led to a big decrease in the concrete properties: with just 5% of replacement, the compressive strength had a 50% reduction and the water absorption increased by 45%.

Production of hollow concrete blocks with different ratio of fine aggregate replacement with sludge could be a profitable disposal alternative for WTS management. It is also possible to develop load-bearing concrete hollow blocks with 20% of WTS and get savings up to 0.05$/block, and non-load bearing concrete hollow blocks with 50% of WTS replacement and get savings up to 0.11$/block (Kaoso, 2010). These amounts, combined with the high costs of sludge disposal through landfill could help to save thousands of dollars per year to companies and governments.

How it is appreciable, most of the researches about sand replacement with sludge were done to develop concrete members. However, de Oliveira Andrade *et al.* (2018) recently did an experiment executing rendering mortar containing sludge. The mortar was developed with River Silica Sand. After treat the sludge in the oven (first 24h at 105ºC and then 1h at 600ºC), mortar specimens were develop for 3 different water/cement ratios (0.4, 0.5, and 0.6) and with 4 different proportions of sand replacement (2.5%, 5%, 7.5%, and 10%). The results of testing the samples showed that the compressive strength was slightly lower in the mortars with WTS meanwhile the flexural strength showed no significant difference. With regard to the bond strength, it decreased with an increment of sludge, though some of the mortars with w/c ratio of 0.5 showed a higher value than the Brazilian standard. Hence, the w/c ratio used in the project will be 0.5 since it showed the most reliable results with the least amount of concrete.

2.3. Knowledge gap

From the studied literature, even though one of the most feasible utilities of sludge may be the sand replacement, most of the research already done is about concrete members. Since the loss of properties that the material suffers after adding the sludge, it seems to be difficult to get structural members with reasonable quality. However, only de Oliveira Andrade *et al.* (2018) tested mortar specimens for brickworks. For this reason, it will be developed a brick-wall calculation to confirm its suitability as a construction material.

The existent knowledge gap clearly points to research on mortar development. For this material, it will be the first time that dry and autogenous shrinkage are measured. At the same time, compressive strength, flexural strength, bond strength, and water absorption will be determined to confirm previous works, however, it will be defined the differences in the influence of raw sludge and treated sludge in mortars. It will be the first time measuring Shrinkage for mortars incorporating WTS.

Should be also pointed out that for these alum-sludge mortars, for the first time in a research project with mortar, will be used Concrete Sand. The proper sand used for mortars is Silica Sand, but due to the lack of this sand in countries like Australia, most renderers are using Concrete Sand nowadays. The achievement of a sludge-based mortar with enough quality will mean less dependence on this scarce material.

3. Research Aim and Objectives

This research aims to investigate the behaviour, properties and performance of mortars with a different replacement of sand with alum-sludge from the Halley Valley Water Treatment Plant. The main objective of the study is to investigate the effect of non-treated and treated sludge on the properties of mortars, including:

- To determine mechanical properties (compressive, flexural and bond strength).
- To investigate shrinkage (total, dry and autogenous).
- To determine the durability of mortar (Water capillarity absorption and submersion).
- To establish differences between raw and treated sludge in mortars.
- To calculate brick-walls with the new material.

4. Research Methods

4.1. Materials

The basic materials for the execution of the mortars will be cement, concrete sand, sludge, and water. All the materials will match the requirements presented in *AS3700-2011: Masonry structures.*

The sludge will be treated in the oven for 24 hours at 105 ºC to remove all the moisture, and after this, part of the sludge will be treated at 600 ºC for 1 hour (see *Figure 1)*. A 28.25% mass loss was detected after carrying out the treatment, what points that organic content is around 25%. Since high organic matter content normally affects cement materials like mortar, this treatment may help to achieve better performance.

***Figure 1**. Sludge before treatment (on the left) and after treatment (on the right).*

Besides this treatment, all the sludge will be sieved to dismiss sizes bigger than 1.68 mm. For the concrete sand, the same treatment will be done to remove all the moisture content. The sieve analysis for both materials is presented in *Figure 2.*

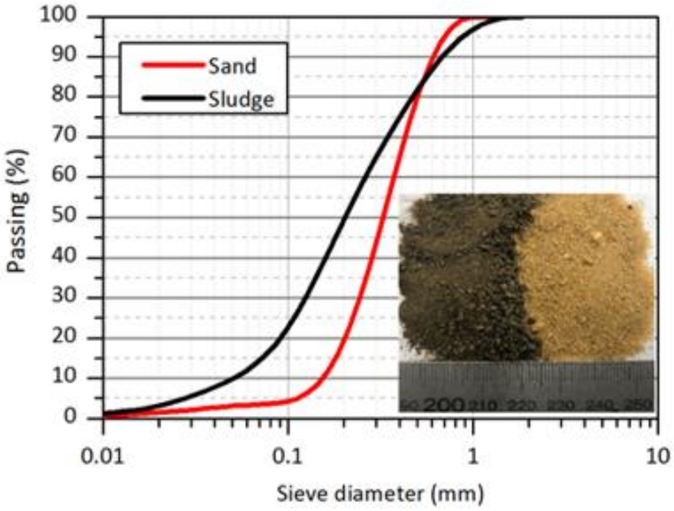

***Figure 2**. Sieve analysis of concrete sand and sludge.*

The cement used for this experiment is General Purpose cement (GP). ´

The properties of the aggregates are reflected as follows:

***Table 1**. Properties of aggregates.*

Notation	GP cement	Concrete Sand
Origin of the aggregates	Happy Valley Water Treatment Plant	South Australia construction material supplier
Specific gravity	2.27	2.61
Maximum size (mm)	1.63	1.18
Water absorption (%)	28.82	0.50

In *Table 2* it is shown the chemical composition of the sludge. Aluminium content is almost 30% of the weight.

***Table 2**. Chemical composition of WTS.*

Compositions	Weight percentage (wt%)
Al_2O_3	28.27
SiO_2	26.43
Fe_2O_3	7.66
CaO	5.36
K_2O	1.23
MgO	1.11
CuO	0.71
TiO_2	0.53
Na_2O	0.20
LOI	29.5

In *Figure 3* it is appreciable how the materials' microstructure looks really similar, getting more homogenous particles for treated sludge than for raw sludge.

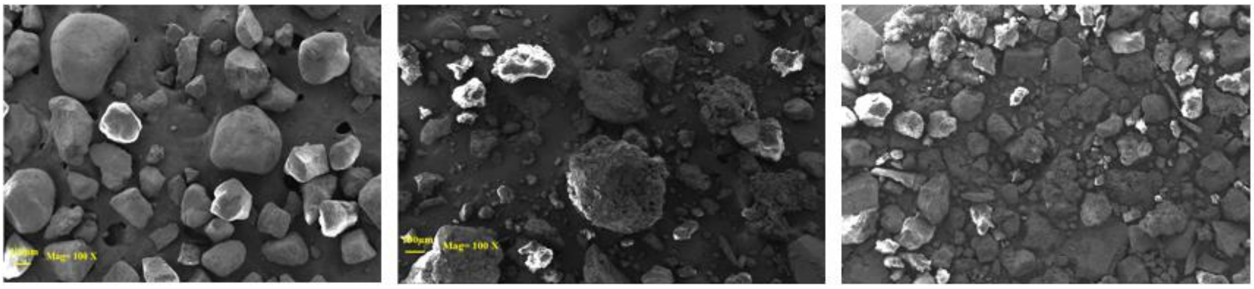

__Figure 3__. SEM images for concrete sand, raw sludge, and treated sludge, in that order.

4.2. Mix design and mortar sample preparation

For the mix design, the theoretical water/cement ratio will be 0.47, however, it will be controlled in the laboratory due to the absorption of water that the dry sand and sludge could have. The relation between cement and sand is 1:2.75 in weight. The relations between materials were set following *ASTM C109 / C109M.*

__Table 3__. Mix proportion in kg/m3.

MIX ID	GP cement	Concrete Sand	%sludge replacement	Sludge	Water
M0	542.0	1490.4	0	0	254.7
M5US	542.0	1415.9	5	74.5	260.7
M10US	542.0	1341.3	10	149.0	269.5
M5TS	542.0	1415.9	5	74.5	284.4
M10TS	542.0	1415.9	10	149.0	304.8

The designed mortars are M0, M5-US, M10-US, M5-TS, and M10-TS. The number reflects the percentage in weight of sand replacement with sludge. The series with US are executed with un-treated sludge and the series with TS are executed with treated sludge. As mentioned before, 10 % seems to be the limit to get a proper performance, hence the composition of the mortars.

Knowing the relation for each mixture, the mortar will be prepared and the specimens will be moulded in accordance with *AS 2350.12: Preparation of a standard mortar and moulding of specimens.*

Since the mechanical mixer has a maximum capacity of 5 litres, the volume of material required has to be calculated to determine how many mixings are required. For all the tests the required is 4 litres, hence it is possible to execute all the quantity of a type of mortar in one mix, which will reduce project times. The dimension and number of samples for each mortar is shown in *Table 4.*

Table 4. *Samples distribution for each mortar.*

Laboratory Test	**Dimensions (cm)**	**Nº of Samples / mortar**
Compressive Strength	5x5x5	3
Flexural Strength	4x4x16	3
Dry Shrinkage	4x4x16	3
Autogenous Shrinkage	4x4x16	3
Bond strength	2 Hollow bricks (225x110x75) with 1 cm thickness layer of mortar	3
Water capillarity absorption	5x5x5	3
Microstructural analysis	Small piece	3

As indicate in *AS2701-2001: Methods of sampling and testing mortar for masonry construction*, the mixing procedure will be:

1. Bring all materials to a temperature 23±5ºC.
2. Measure the required quantities of materials, and select a mixing bowl of appropriate size.
3. Place cement and water in the bowl, in this order. Mix for 30 s at low speed.
4. Introduce immediately the sand and mix for 30 s at low speed.
5. Without stop, mix for another 30 s at high speed (a total of 90 s).
6. Stop the mixer and quickly clean down the blade and sides of the bowl.
7. Remix the mortar for 60s at high speed.
8. Record the time at commencement and completion of mixing.

4.3. Experimental programme

4.3.1. Compressive strength

Compressive strength test will be carried out with the laboratory certificated machinery, and following the indications pointed in *AS 2350.9: Compressive strength test – Concrete, mortar and grout specimens.* 3 cubes of 5x5x5 cm will be executed for each mixture. As it is reflected in the code, the procedure was carried out placing the specimen in the machine, and applying the force without shock increasing continuously at a rate equivalent to 0.33 MPa/s.

***Figure 4**. Compressive machine used in the research.*

4.3.2. Flexural strength

Flexural strength test will be carried out following the same steps of testing a standard concrete beam, using the laboratory certificated machinery. 3 samples of 4x4x16 cm will be developed for each mixture, and after placing the specimen in the machine, the force will be applied without shock and will increase continuously at a rate equivalent to 0.05 ±0.01 MPa/s. The basic scheme of the test is shown in *Figure 5*, and the flexural strength is calculated applying basic equilibrium equations.

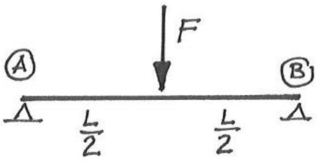

***Figure 5**. Scheme of the flexural strength test.*

4.3.3. Bond strength

Bond strength test will be carried out with a wrecking machine *according to AS3700, Appendix 6.* To develop this test on brickworks, 2 hollow bricks will be stick together with each mortar mixture with 1cm thickness and cured for 28 days. After anchored the bottom of the sample to the fixed part, and the top of the sample to the wrecking part, a box located in the opposite side is filled with sand with a constant velocity (around 5 kg/min) until sample is broken as shown in *Figure 6.* Then the box weight is measured, and knowing all the distances, bond strength is calculated with basic equilibrium equations defined in *AS3700, Appendix 6* as:

$$f_{sp} = \left(\frac{M_{sp}}{Z_d}\right) - \left(\frac{F_{sp}}{A_d}\right)$$

where:

- f_{sp} = bond flexural strength of the specimen, in MPa
- M_{sp} = bending moment about the centroid of the bedded area of the test joint failure, in N·mm, as:

$$= \quad 9.81 m_2 \left(d_2 - \frac{t_u}{2} \right) + 9.81 m_1 \left(d_1 - \frac{t_u}{2} \right)$$

- Z_d = section modulus of the design cross-sectional area (A_d) of the member, in m^3
- F_{sp} = the total compressive force on the bedded area of the tested joint, in N, as:

$$= \; 9.81\,(m_1 + m_2 + m_3)$$

* All distances and masses are taken as defined in this section, for this specific test.

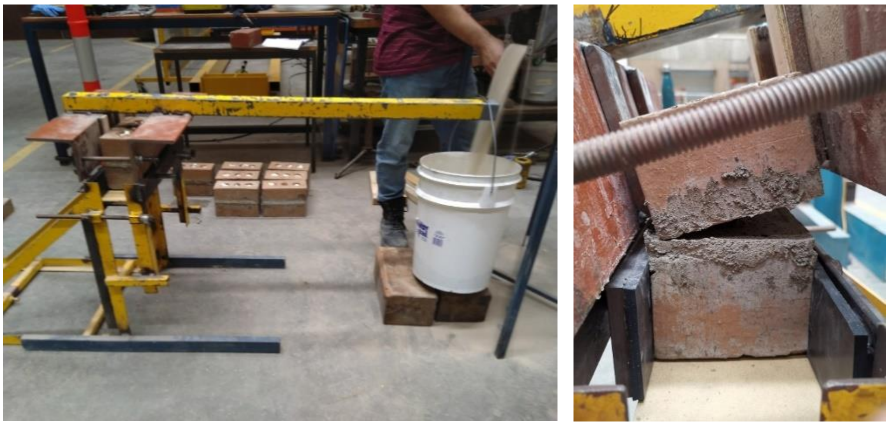

Figure 6. *Wrecking machine set (on the left) and final tested sample (on the right).*

4.3.4. Dry and autogenous shrinkage test

Dry shrinkage test will be developed measuring the change in the length of 3 of the 4x4x16 samples for each mortar. According to *AS 2350.13: Determination of drying shrinkage of cement mortars*, the shrinkage will be calculated as:

$$\Delta L = \frac{L_i - L_m}{L_i} * 10{,}000 \; (in\; microstrain)$$

To carry out the shrinkage tests, 2 pair of demec points will be fixed in each sample with an instant glue just after demoulding, and when it gets hard enough (around 30s) the first measurement will be taken (L_i). The demec point's distance will slightly vary, but they are fixed with the calibration tool included in the measurement tool. For the autogenous shrinkage test, the same process will be followed but the samples will be covered with aluminium foil to avoid the water loss of the sample. Measurement and mass check of the specimens will be carried out on demoulding and at the age of 7d, 14d, 21d, and 28d. However, denser measurements will be taken in the first stages of the shrinkage to adjust properly the graphs. The length (L_m) is taken calibrating each time the measurement tool, always in the same direction, and adjusting it perpendicularly to the demec points.

***Figure 7**. Shrinkage samples (on the left) and measurement tool (on the right)*

4.3.5. Water absorption

The samples for water capillarity absorption are firstly dried at 50ºC (to avoid cracks) during 3 days, then the lateral surfaces of the cubes are covered with an epoxy layer, leaving the bottom and top surface free. The samples are put back in the oven for 2 days to get the epoxy hard enough. A tray with granular material in the bottom and a 3 cm water depth is prepared, with all the samples located properly on these gravel layer. The bottom surface will allow all moments the water flow. Measurements will be taken before the test and until the mass gets constant. The first measurements have to be dense on time to adjust properly the curve, so they will be taken for 3’, 7’, 12’, 30’, 45’, 60’, 90’, 120’, and 180’. Results are calculated as an increment of weight divided by the area.

For the water submersion test, all the samples will be submerged in a tank for 2 days and oven-dried for 3 days at 105ºC. Weight before and after the oven will be taken, and the percentage of mass loss will ve calculated.

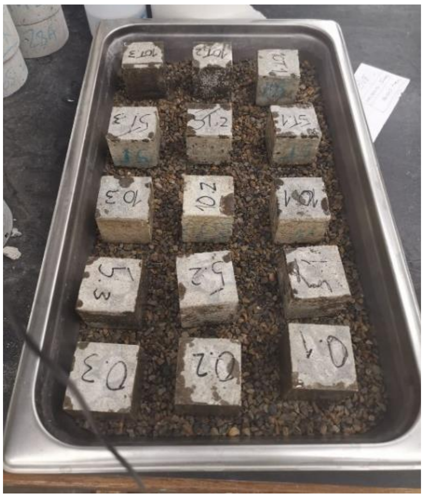

***Figure 8**. Water capillarity absorption set test.*

4.3.6. Microstructure analysis

The microstructure analysis was carried out taken a small piece of the already tested flexural strength samples (28 days). The area to analyse was kept untouched and clean to avoid problems during the SEM analysis. The samples were oven-dried at 50ºC for 3 days. These microstructural characteristics could explain the physical and mechanical properties of mortars with WTS aggregate. SEM analysis will be carried out to identify the microstructure morphology and compare it with previous results.

5. Results

5.1. Compressive Strength

The compressive strength at 28 days of the mixtures showed a decrease of 3.5 MPa for the M5-US mixture, and a 1.3 MPa increase for the M5-TS. However, mixtures with 10% of sand replacement had approximately 30% lower strength. Based on the results it is possible to determine that compressive strength is based on the performance of the aggregates, and organic matter affects negatively the mixture. Also, the more porous matrix of the 10% mixtures leads to a higher loss of mechanical properties as pointed for Mashaly *et al.* (2016). According to Ramirez *et al.* (cited in de Oliveira Andrade *et al.* 2018, p. 165), who replaced natural sand with treated sludge in concretes with a 0.55 w/c and obtained an increase of strength of 5%, 10% and 20%, what points that treated sludge can lead to increments in strength. However, the inclination is to see a decrease inversely proportional to an increase in the WTS content.

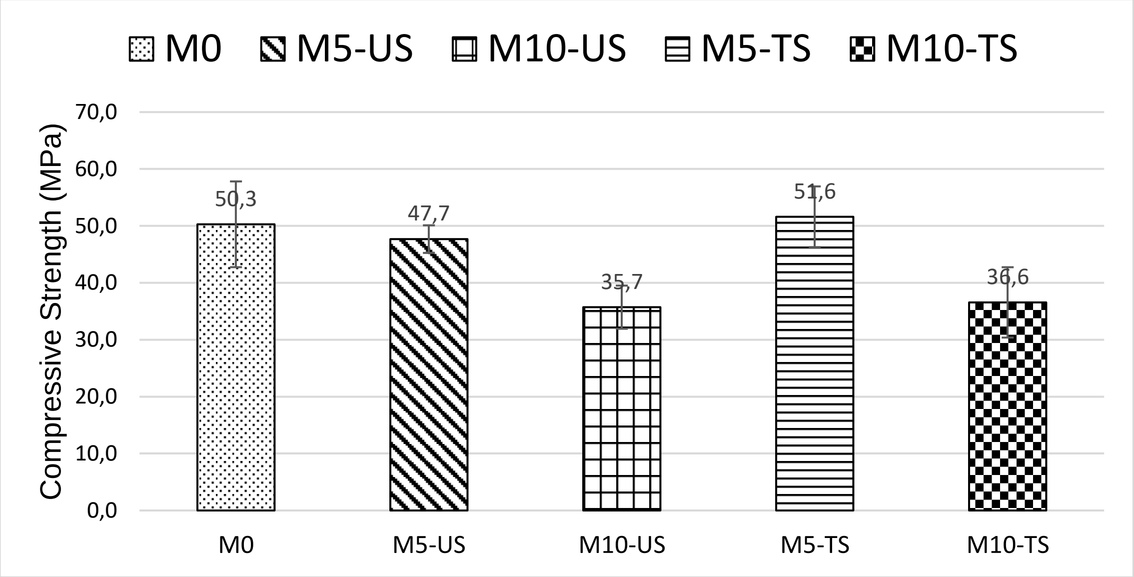

Figure 9. *Compressive strength at 28 days for each mixture.*

5.2. Flexural Strength

The flexural strength results show a minor decrease in the flexural strength of the mixtures. The mixtures with 5% and 10% replacement showed an approximate decrease of 1 MPa and 1.5 MPa, respectively. An increment in the sludge content means a decrease in the strength, really small for flexural strength (de Oliveira Andrade *et al.*, 2018). The higher demand on water of mortars containing sludge results in a higher specific surface area of WTS more than cement, leading a decrease in mechanical properties as flexural strength (Mashaly *et al.*, 2016).

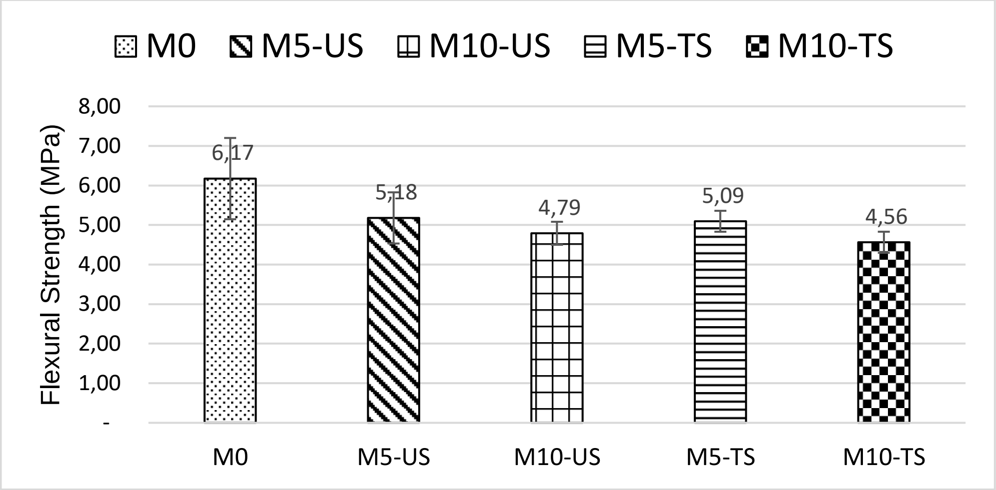

Figure 10. *Flexural strength at 28 days for each mixture.*

5.3. Bond Strength

The bond strength results reflected in *Table* 5 and *Figure 11* showed an increment for mixtures with 5% of sludge content. Furthermore, it is appreciable a better performance of the mixtures incorporating treated sludge, having increment even for the 10% treated sludge content. Since the nature of the sludge is similar to clay, it seems to have better adhesion with the clay units, so the bricks after testing showed some granular particles in the bonding surface (see *Figure 12)*.

According to Silve *et al.* (cited in de Oliveira Andrade *et al.* 2018, p.165), despite the importance of compressive strength, a mortar should be classified according to workability and bond strength, what would give the mortars with sludge a good-quality classification since the workability was maintained constant adjusting the water content of each mixture.

Another main reason that may explain the increase in bond strength is the coarse nature of the WTS. The mortar elaborated with fine sand shows the lower tensile bond strength as compared to the mortar prepared with coarse sand (Gupta and Vyas, 2018).

Table 5*. Bond Strength results in MPa.*

Mixture	**Bond Strength (MPa)**	**σ**
M0	0,74	0,08
M5-US	0,93	0,04
M10-US	0,57	0,05
M5-TS	1,02	0,13
M10-TS	0,91	0,05

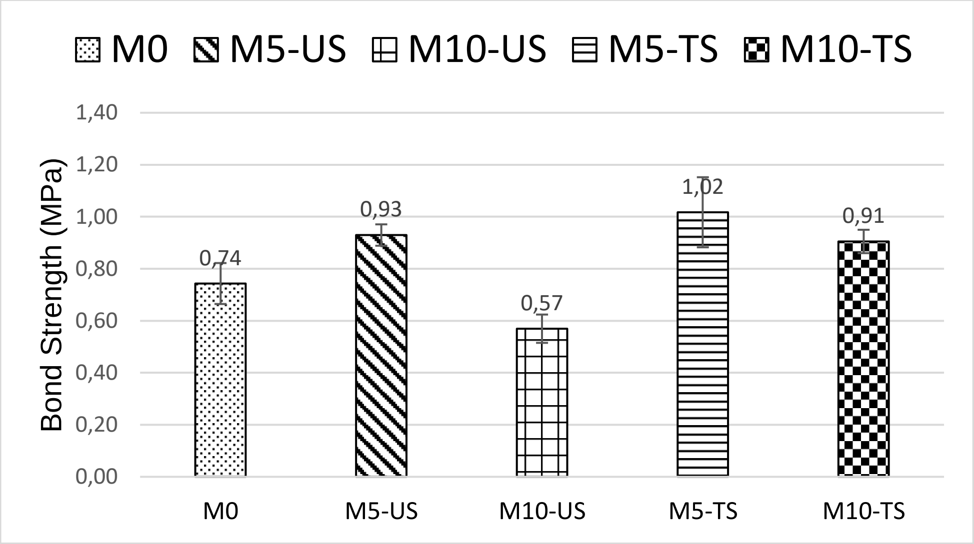

Figure 11. *Bond strength at 28 days for each mixture.*

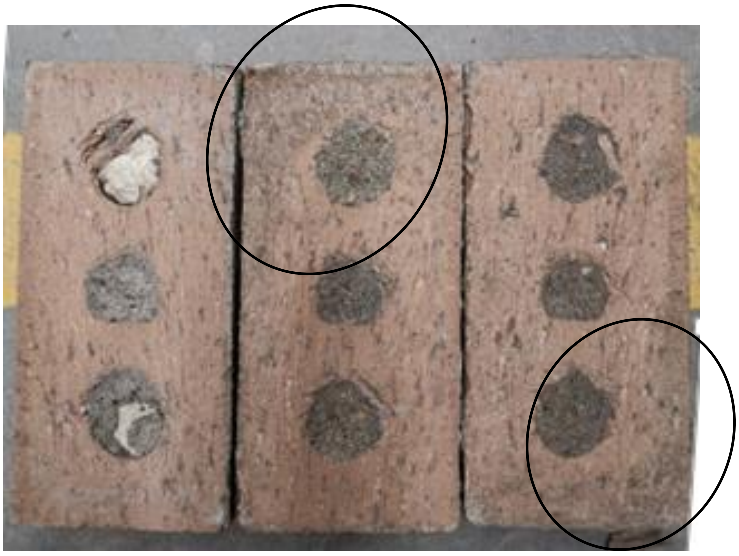

Figure 12. *Bricks after bonding test showing sludge particles on the bonding surface (from left to right, M0, M5US, and M5TS)*

5.4. Water absorption by capillary suction

The water absorption by capillary action or sorptivity coefficient is considered as a significant parameter to determine mortar durability, where it defines the water transmission within unsaturated specimens (Mashaly, Shalaby and Rashwan, 2018). According to *Rana et al.* (cited in Mashaly *et al.*, 2016), the pore size, pore distribution and their connectivity are considered main factors affecting the water capillarity absorption.

The results for water absorption indicate that mixtures with raw sludge have the lowest absorption rates. Within this mixtures, the one with 5 % of raw sludge shows the lowest (therefore most optimum) water absorption rate. Therefore, the organic matter of the sludge may have hydrophobic nature, so the organic matter may be repealing the water and leading to lower water absorption. Chao *et al.* (2014) reported a study to determine the hydrophobicity of diverse bacterial populations of Waste Water Treatment Plants of Hong Kong, pointing to this characteristic in the organic matter found in the sludge. Also, the raw sludge particles seem to have a filler effect associated with the capillary pores, reducing the connectivity of the capillary pores and leading to a smaller sorptivity coefficient.

However, the mixtures with the highest absorption values are the ones with 5% and 10% of treated sludge, in that order. Since the treated sludge needed more water to get a proper consistency (possibly due to the ash particles), the increase in water demands needed for lubrication leads to potential reduction in cementitious materials required for the binding activity between material mix giving higher porous microstructure and larger capillary pores, leading to a higher water absorption (Mashaly, Shalaby and Rashwan, 2018). Hence, the more water needed, the larger are the capillary pores, with a better pores interconnectivity and therefore a higher sorptivity coefficient. Furthermore, after treatment the sludge lost 25% of the mass, which may lead to creating some empty particles that are prone to the water absorption.

After 6 days the results kept practically constant as shown in *Figure 13.*

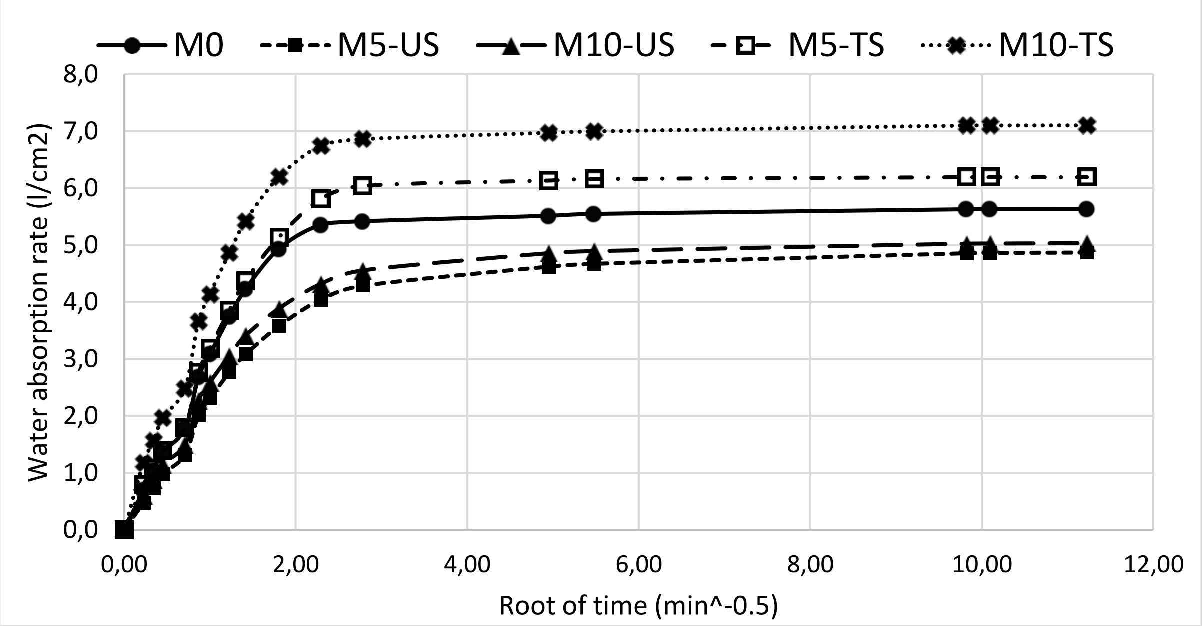

Figure 13. *Water capillarity absorption during the first 5 days.*

5.5. Water absorption by submersion

The results for water absorption by submersion show different results from the capillary absorption. Although the capillary pores are bigger for the treated sludge, the larger pores seem to be bigger for the raw sludge mixtures, since the porosity was appreciably higher (see *Figure 14).*

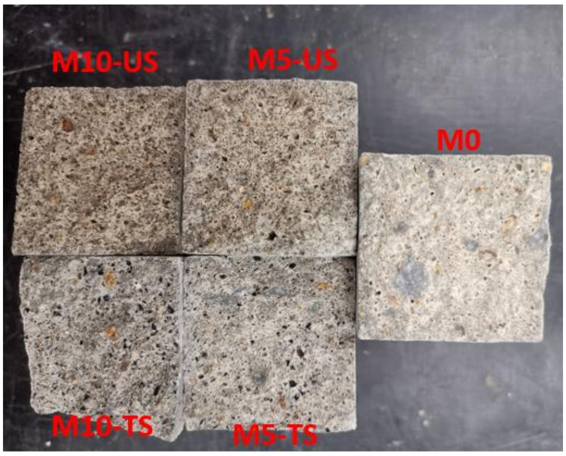

Figure 14. *View of the flexural samples after testing, showing the internal structure of the mortar.*

As the temperature for this test is 105ºC, the water from all the pores can get out the sample, and due to the higher porosity of samples with raw sludge, it is observed a decrease between non-treated and treated sludge mixture. The reference mortar had the most efficient water absorption percentage, due to the most homogenous cement matrix.

Table 6*. Water absorption results in percentage.*

	Water absorption (%)	**σ**
M0	7,57	0,045
M5-US	9,85	0,110
M10-US	11,07	0,072
M5-TS	9,57	0,023
M10-TS	10,75	0,045

5.5. Shrinkage

The results for total shrinkage showed, as expected, a worse performance from the raw sludge mixture. This untreated sludge seems to have problems bonding with the cement matrix, which leads to higher porosity, hence to higher values of shrinkage. However, the mixtures with 5% of WTS had non-significant differences. The Australian Standard *AS3972* sets the limit for total shrinkage in 750 microstrains and recommends not to exceed 600 microstrains. All mixtures meet the standard requirements except for M10-US that overpasses the recommended value.

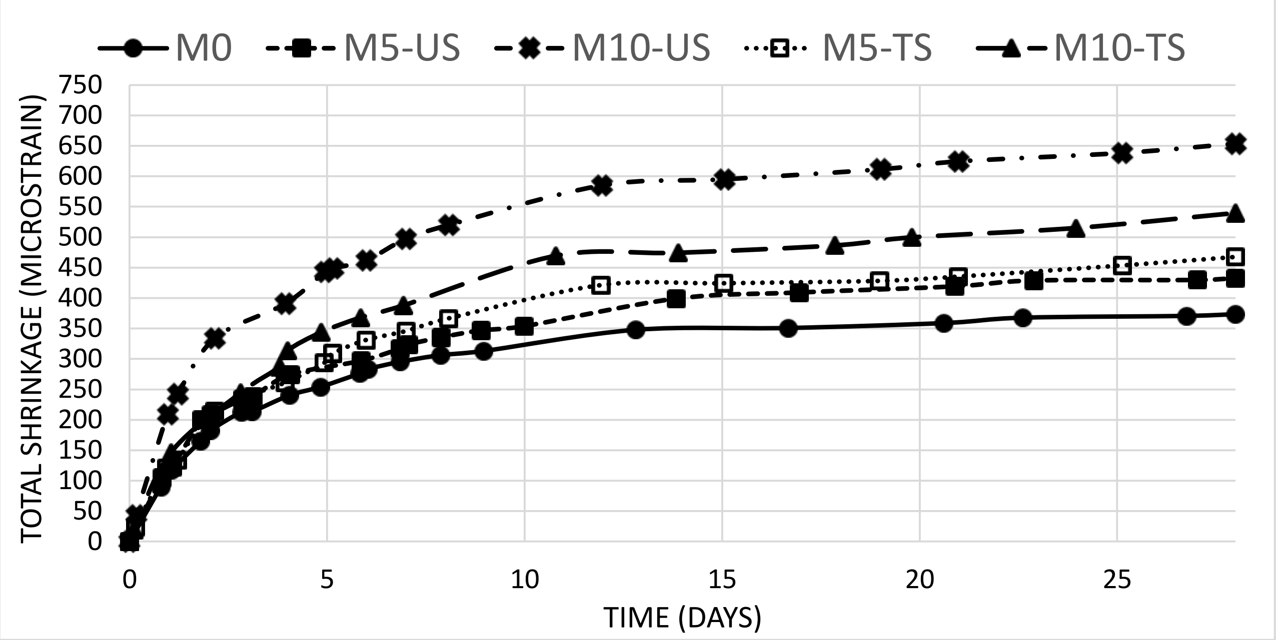

Figure 15. Total shrinkage values for 28 days.

The autogenous shrinkage has similar values for all the samples. Also, the values show that autogenous shrinkage is minor for the samples with WTS content, which points that dry shrinkage due to the water loss is highly predominant for mortars incorporating sludge.

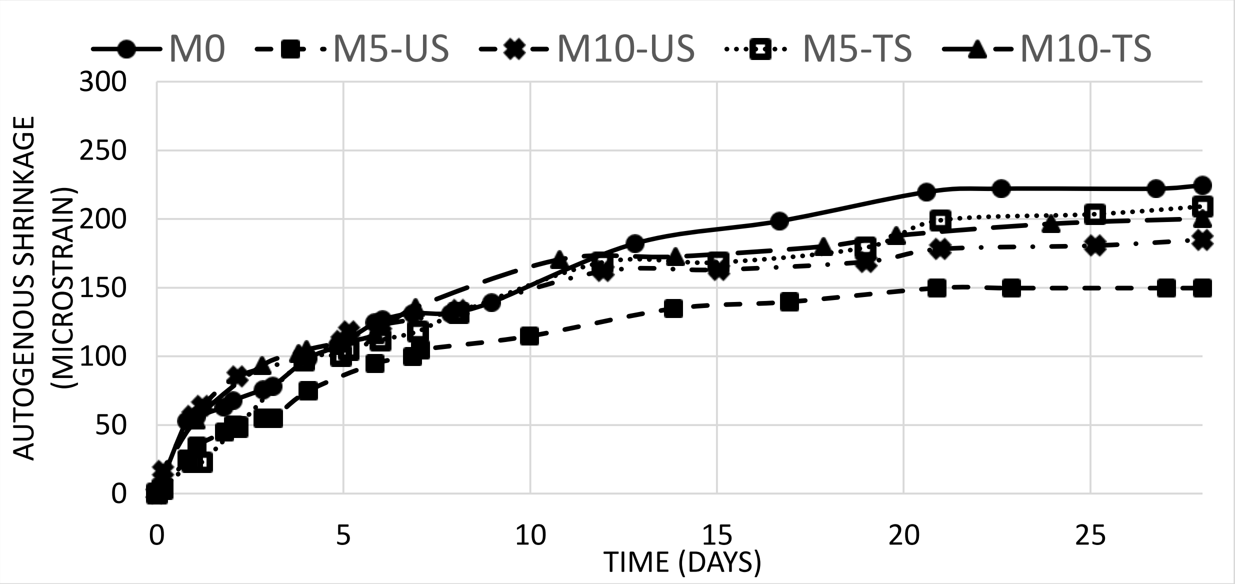

Figure 16. Autogenous shrinkage values for 28 days.

Values for dry shrinkage confirmed the previous hypothesis. It is appreciable that 5% mixtures have similar values and the difference becomes significant for 10% mixtures.

Most of the dry shrinkage happens during the first 5 days, as it happens the mass loss (*Figure 13),* the reason why it would essential to water the mortar in real constructions during the first 5 days to avoid that high water loss due to the porosity.

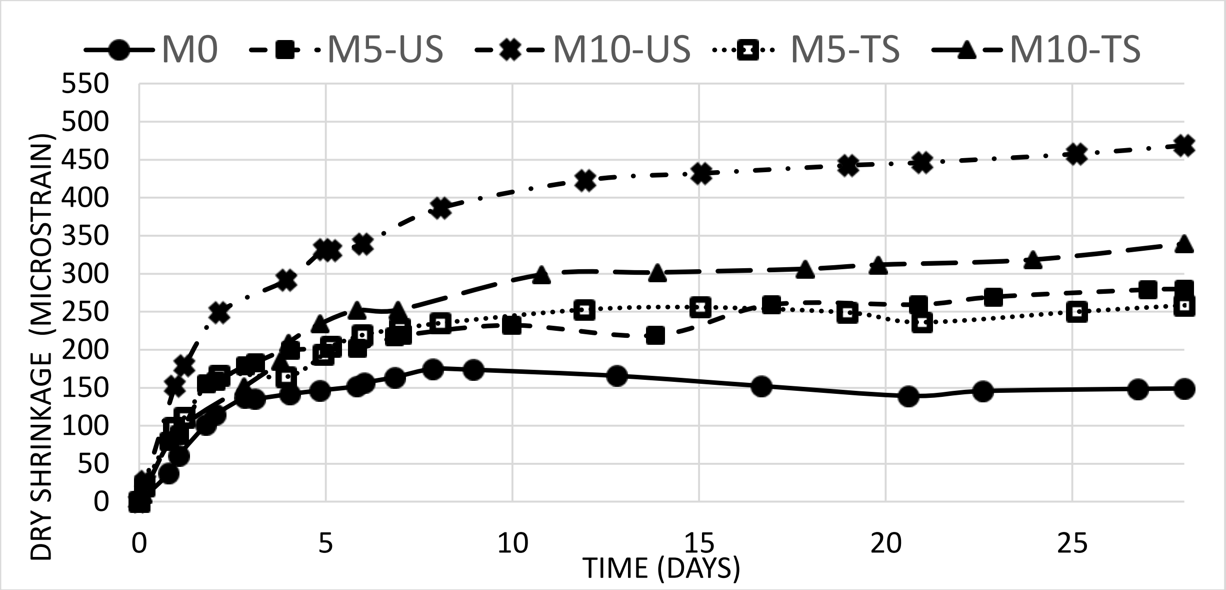

Figure 17. *Dry shrinkage values for 28 days.*

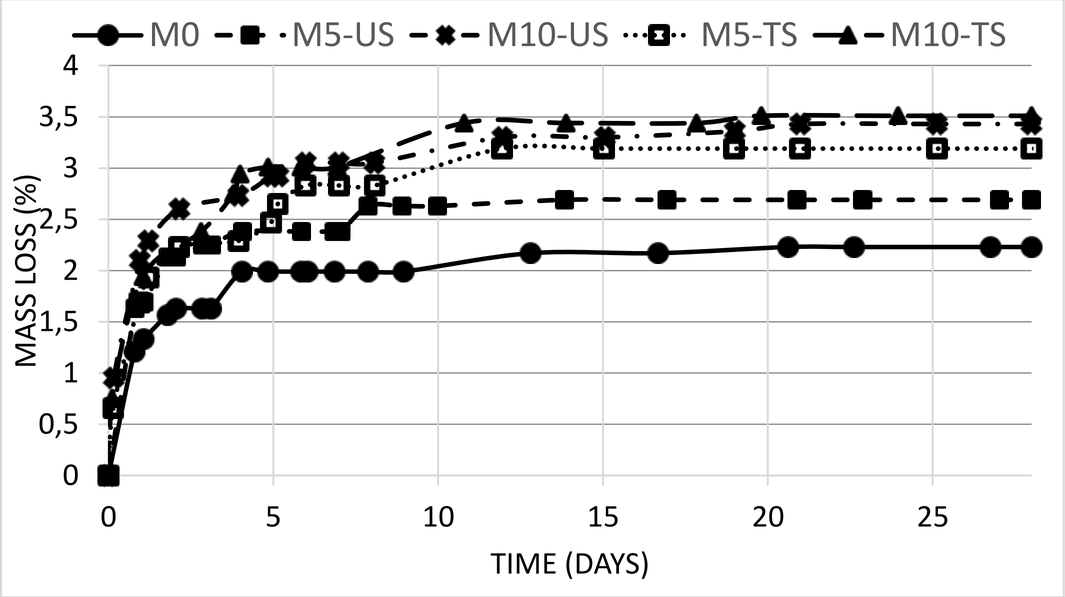

Figure 18. *Mass loss percentage for 28 days.*

The mass loss seems to be slightly higher for the mixtures with treated sludge, probably because they needed more water during the mixing process to get the proper consistency.

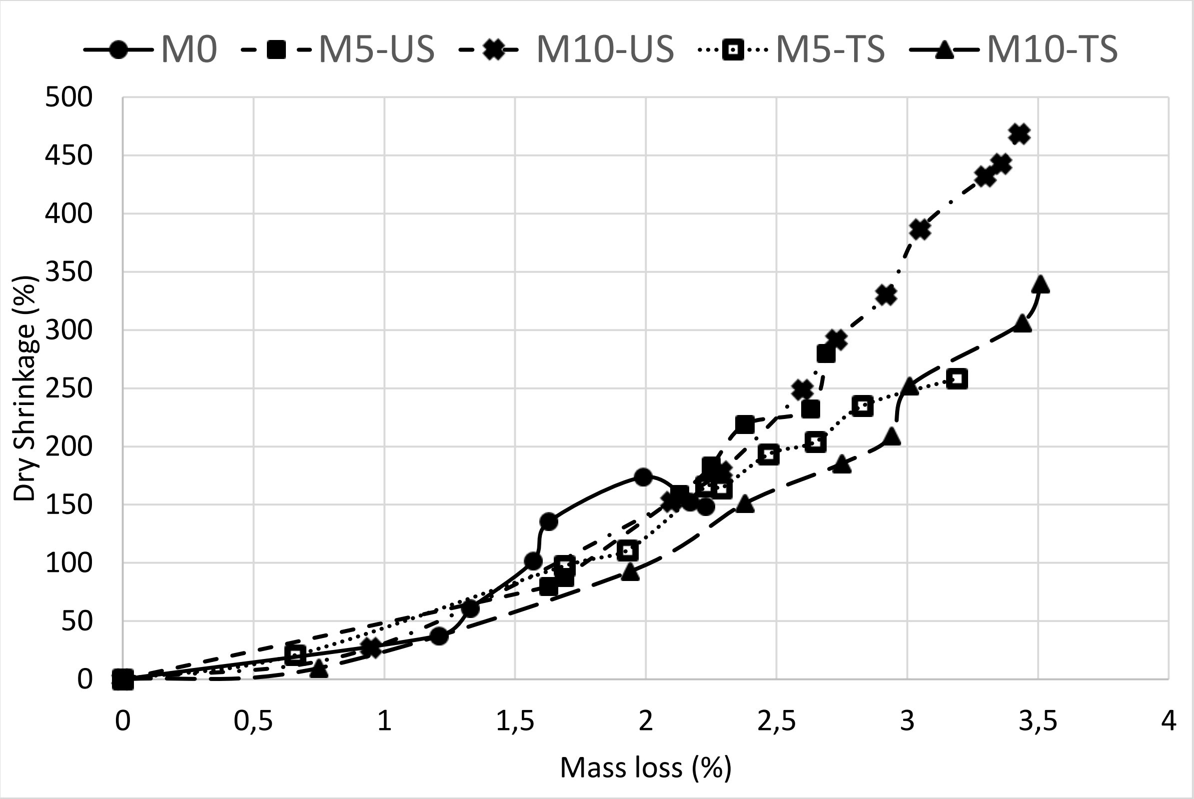

Figure 19. *Dry shrinkage against mass loss, for 28 days.*

In *Figure 19* it is represented the dry shrinkage against the mass loss for all the mixtures. In this graph, the branch OA corresponds to the departure of the water of the capillaries and the branch AB corresponds to the beginning of the water of the larger pores (*Verbeck et Helmuth*, cited in *Chapitre and Tableau*, 2010). For all the mixtures the first slope does not have appreciable differences, however, the slope related with larger pores -therefore porosity of the mortars-, gets clearly higher for untreated mixtures due to their porosity. Also, since the respective mass loss (between 5% mixtures and 10% mixtures) is practically the same, the only fact that explains the higher shrinkage is the presence of organic matter.

5.6. Microstructural analysis

From the SEM analysis, it is possible to see how the untreated sludge has problems bonding with the cement matrix since it shows micro-fractures between the sludge particles and the cement matrix, as same reported for many authors as de Oliveira Andrade *et al.* (2018). However, the sand particles are perfectly bonded in all mortars. The treated sludge has appreciable better bonding with the cement matrix, showing a more homogenous surface, explaining its better performance.

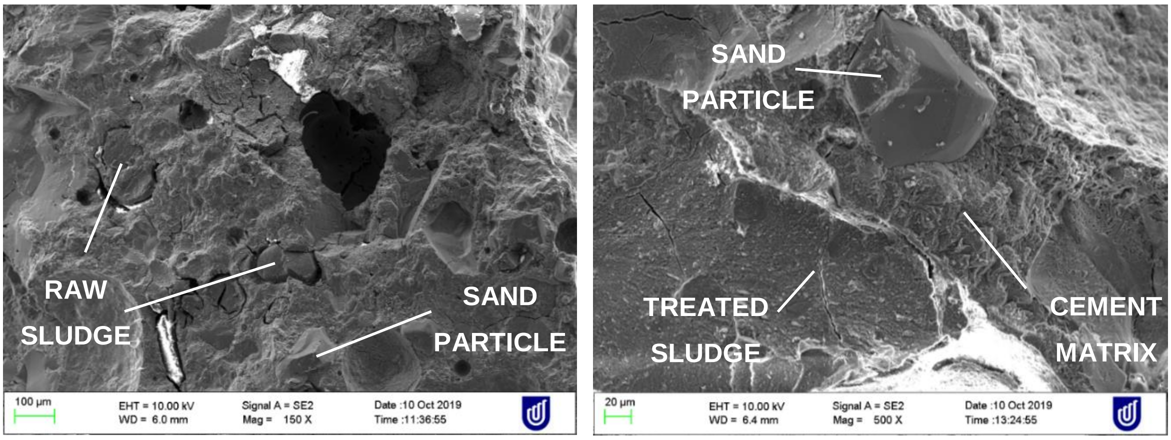

Figure 20. *SEM images for M5-US (left side) and M10-TS (right side).*

In the EDS spectrums, it is confirmed the high levels of alum of the sludge. The EDS analysis also showed that in the cement matrix of the treated mixtures there was some Alum content, which indicates that treated sludge is present in the cement matrix, probably due to the thinnest ash particles has similar characteristics that the cement particles.

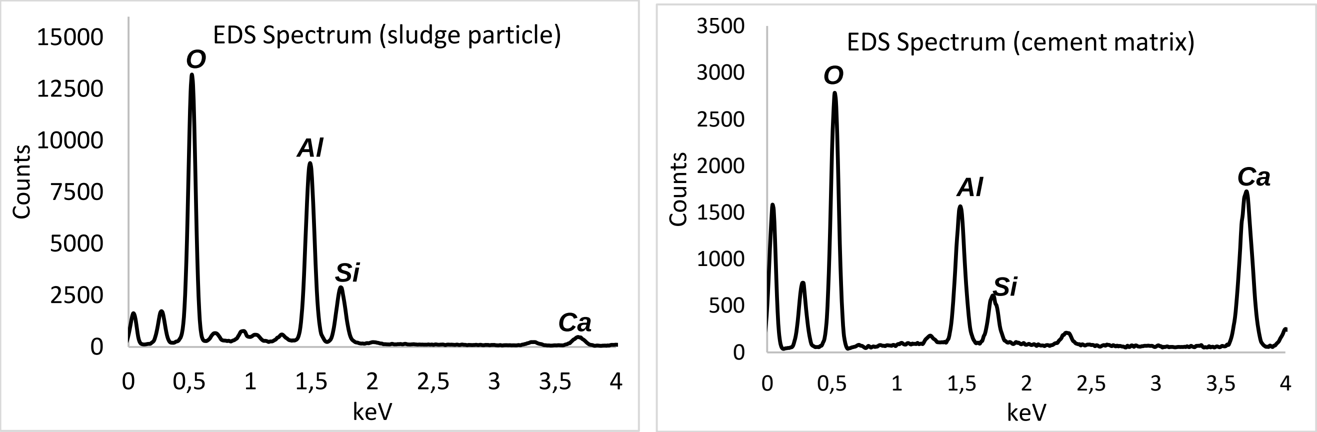

Figure 21. EDS Spectrum for a sludge particle (left side) and the cement matrix in the M10-TS mixture (right side).

6. Brick-Walls suitability

The performance of the mortars is tested in practical brick-wall calculations in *ANNEX 1*. Two different typologies of brick-wall are calculated: free-standing wall and residential wall. In total, 5 different walls are modelled with the software *SAP2000* with the following characteristics:

Table 7. *Height of each wall with its typology.*

Wall ID	Typology	Height
Wall 1 (4b layer)	Free-standing	3 m
Wall 2 (4b layer)	Free-standing	2 m
Wall 3 (4b layer)	Free-standing	1.5 m
Wall 4 (2b layer)	Residential-wall	3 m
Wall 5 (2b layer)	Residential-wall	6 m

The wind forces are calculated following *AS/NZS 11170.2:2011* and the results, for a wall placed in a building of a residential suburb of Adelaide (Australia), is:

- Pressure normal to surface:

$$p_N = 1.02\ \frac{kN}{m^2}$$

- Frictional drag force:

$$p_D = 0.04\ \frac{kN}{m^2}$$

The results showed that a height of 2 m is the maximum using the reference mortar, with better performance than the reference for mixtures M5-US, M5-TS, and M10-TS in free-stranding walls due to higher bond strength. For the residential wall (as isolating layer in buildings), the mixtures M5-US, M5-TS, and M10-TS show good performance for a height 2.75 m in walls supported in the structural beams, outpacing M0 which did not meet the requirements. All mixtures show good performance up to 2 floors (6 m height) in residential walls just anchored to the structural members.

Although these calculations have an academic purpose, mortars incorporating sludge seem a feasible option in the construction of brick-walls, having the most efficient performance incorporating 5% of sludge.

7. Conclusion

In this research paper it was determined the mechanical properties of mortars incorporating sludge, as well as durability properties, and with all these data practical brick-wall calculations were developed. From the results it is possible to conclude:

- Compressive strength showed slight differences with 5% sludge mixtures (even an increase for 5% treated sludge replacement), with an affected performance for 10% sludge mixtures, up to 30% weaker. Flexural strength does not show big changes with the incorporation of sludge (although slightly smaller for sludge mixtures).
- Bond strength showed an improved capacity with M5-US, M5-TS, and M10-TS mortars, due to a better bonding of sludge coarse particles with the clay brick surface, a fact that gives these new mortars an adequate quality classification.
- Water absorption showed higher values for mixtures with treated sludge and smaller values than the average for raw sludge mixtures, which may indicate bad interconnectivity between pores (due to filling effect) in these mortars and the presence of hydrophobic organic matter.
- Shrinkage values increase when sludge content increases, having a worse performance of the raw sludge mixtures due to their high porosity.
- SEM analysis showed a worse bonding of the raw sludge with the cement matrix, having a more homogenous surface and better bonded particles for treated sludge.
- The mixtures showed practical performance in brick-wall calculations, with 2 m height limit in free-standing walls, 2.75 m in supported isolating walls, and up to 2 floors in anchored isolating walls. The mortar M5-TS has the best performance.

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