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# Use of sludge from water treatment decanter in cement composites

## Utilização de lodo de decantador de tratamento de água em compósitos cimentícios

## Uso de lodos de decantador de tratamiento de agua en composites de cemento

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**Abstract**
The objective of this manuscript is to present a sustainable alternative for the use of waste from Water Treatment Plants (WTPs), specifically water treatment sludge (WCS), in civil construction. The proposal is to use water treatment sludge as a construction material, more specifically in the partial replacement of cement in self-compacting mortars (SCC). Due to the significant use of natural resources in civil construction and the consequent environmental degradation, the use of water treatment sludge (WCS) as a construction material may be an option. However, the low quality of river water and the need for drinking water force water treatment plants to use greater quantities of chemical compounds, resulting in a significant waste known as WCS. The methodology used for dosing self-compacting concrete (SCC) follows the process described by the Gomes method, which is applicable to both concrete and self-compacting mortars. In this study, the partial replacement of cement at 2.5% and 10% with water clarification mud (WCS) in self-compacting mortars (SCC) was analyzed and it was found that the compressive strength increased from 27.3% to 30% for the specimens, with the addition of 2.5% and 10% of WCS, respectively. A life cycle assessment was carried out to prove the environmental benefits of replacing cement with WCS. The results preserve the feasibility of applying WCS in civil construction while at the same time highlighting the need for additional research on the topic.
**Keywords:** Concrete; Mortar; Replacement; Life cycle assessment.

**Resumo**
O objetivo desse manuscrito é apresentar uma alternativa sustentável para a utilização de resíduos provenientes das Estações de Tratamento de Água (ETAs), especificamente as lodo de tratamento de águas (WCS), na construção civil. A proposta é utilizar o lodo de tratamento de águas como material construtivo, mais especificamente na substituição parcial do cimento em argamassas autoadensáveis (CAA). Devido à significativa utilização de recursos naturais na

construção civil e à consequente degradação ambiental, a utilização de lamas de tratamento de águas (WCS) como material construtivo pode ser uma opção. No entanto, a baixa qualidade da água dos rios e a necessidade de água potável forçam as estações de tratamento de água a utilizar maiores quantidades de compostos químicos, o que resulta num resíduo significativo conhecido como WCS. A metodologia utilizada para a dosagem do concreto autoadensável (CAA) segue o processo descrito pelo método de Gomes, que é aplicável tanto para concretos quanto para argamassas autoadensáveis. Neste estudo foi analisada a substituição parcial do cimento em 2,5% e 10% por lama de clarificação de água (WCS) em argamassas autoadensáveis (CAA) e verificou-se que a resistência à compressão apresentou aumentou de 27,3% para 30,6% para os corpos de prova, com adição de 2,5% e 10% de WCS, respectivamente. Uma avaliação do ciclo de vida foi realizada para comprovar os benefícios ambientais da substituição do cimento por WCS. Os resultados preservam a viabilidade da aplicação do WCS na construção civil, ao mesmo tempo, em que destacam a necessidade de pesquisas adicionais sobre o tema.
**Palavras-chave:** Concreto; Argamassa; Substituição; Avaliação do ciclo de vida.

**Resumen**
El objetivo de este manuscrito es presentar una alternativa sustentable para el aprovechamiento de residuos de Plantas de Tratamiento de Agua (EDAR), específicamente lodos de tratamiento de agua (EDA), en la construcción civil. La propuesta es utilizar lodos de depuración de aguas como material de construcción, más concretamente en la sustitución parcial del cemento en morteros autocompactantes (SCC). Debido al importante uso de recursos naturales en la construcción civil y la consecuente degradación ambiental, el uso de lodos de tratamiento de agua (WCS) como material de construcción puede ser una opción. Sin embargo, la baja calidad del agua de los ríos y la necesidad de agua potable obligan a las plantas de tratamiento de agua a utilizar mayores cantidades de compuestos químicos, lo que genera un importante desperdicio conocido como WCS. La metodología utilizada para la dosificación del hormigón autocompactante (HAC) sigue el proceso descrito por el método de Gomes, aplicable tanto al hormigón como a los morteros autocompactantes. En este estudio se analizó la sustitución parcial del cemento al 2,5% y 10% por lodo clarificante al agua (WCS) en morteros autocompactantes (SCC) y se encontró que la resistencia a la compresión aumentó de 27,3% a 30%. % para las probetas, con la adición de 2,5% y 10% de WCS, respectivamente. Se llevó a cabo una evaluación del ciclo de vida para demostrar los beneficios ambientales de reemplazar el cemento con WCS. Los resultados preservan la viabilidad de aplicar WCS en la construcción civil, al mismo tiempo que resaltan la necesidad de realizar investigaciones adicionales sobre el tema.
**Palabras clave:** Concreto; Mortero; Reemplazo; Evaluación del ciclo de vida.

## 1. Introduction

The drinking water treatment plant (WTP) is the basic component of the water supply system. In it, the fine particles in suspension and solution present in the raw water are removed using physiochemical coagulation processes. Usually, iron or aluminum salts are used as coagulants to create flakes with insoluble hydroxides and are then removed in clarifiers and, to a lesser extent, in filters. In the processes and unit operations used at the plant, the sludge is produced as waste, which is deposited in and classified as solid waste, and therefore must be treated before its final disposal in landfills. According to (ABNT, 2004), WTS is classified as Class IIA Solid Waste – Non-Inert.

The most common treatment used in drinking water treatment plants in Brazil is conventional, which includes the processes of coagulation, flocculation, decantation/clarification, filtration, and disinfection.

The colloidal and suspended impurities present in water, along with the coagulant products (usually hydroxides of Aluminum and Iron), are removed during the clarification and filtration process and constitute the sludge or waste generated at the WTPs (Tafarel et al., 2016).

Increased water demand leads to increased sludge generation, resulting in the need for more space to dispose of waste. The most prominent final waste disposal methods are disposal in the soil, sanitary landfills, incineration, and raw materials in some industries, but these processes cause soil pollution, require monitoring, and are expensive, in addition to causing environmental impacts these procedures are not applied in most Brazilian WTPs.

The partial replacement of cement by water clarifiers sludge in the production of composite materials such as concrete/mortar/pulp reduces the price of these construction materials and provides an environmentally correct way to dispose of this waste (Alqam et al., 2011). In addition, the use of WTS in mortar or concrete helps reduce the release of this waste into the environment and reduces the extraction of raw materials for civil construction. In order to comprehend the principles and look into the implementation levels and obstacles of construction waste minimization during the construction stage, other authors offer a relevant review paper. In addition to highlighting important findings that will assist researchers and practitioners in the construction industry in comprehending the principles of construction waste minimization, this will also help identify gaps for future studies (Ciroth & Burhan, 2021). Therefore, this work's goal is to examine the partial replacement of cement by water clarifier sludge in the production of self-compacting mortar (SCC) in the fresh and hardened state, as well as to compare the variations of the results between the water clarifier sludge (WCS) and the water filter sludge (WFS) in the production of SCC.

### 1.1 Contextualization of the literature review

To more simply identify the most important works, we needed to define the tactics that would be employed in this literature review. Bibliometric techniques began to be developed in the beginning of this century to understand and quantitatively analyze data obtained from scientific publications (Treinta et al., 1983; Grácio, 2016). The bibliometric review seeks to find relevant research with a similar subject or that can add to the theoretical framework of research on the use of sludge in cement composites.

Two databases were used in the search: "Scopus and Web of Science", with the possible keywords that best describe the theme studied here. The research was conducted using the following keywords: Concrete, Mortar, Cement composite, Replacement, Substitution and Water Treatment Sludge.

Table 1 shows the number of articles found in the search in both databases on February, 2024, using the combination of keywords called string. In both databases, the filter selected was so that the search for these keywords was for "article title, abstract, and in the keywords themselves".

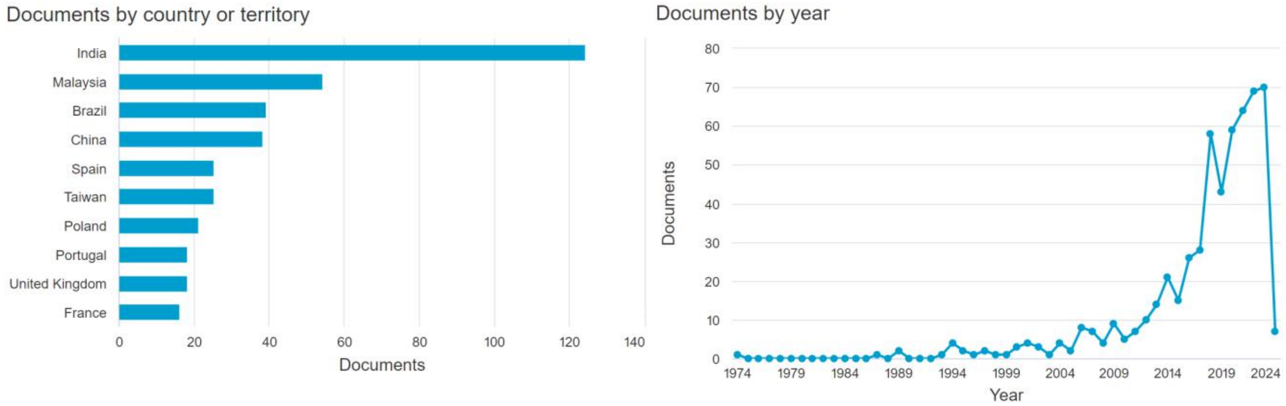
**Table 1 -** Search for keywords in the Web of Science (WOS) and Scopus databases.

| N$^0$ | Strings | WOS | Scopus |
|---|---|---|---|
| 1 | (mortar OR concrete OR (cement AND composite) ) AND Sludge | 2060 | 2294 |
| 2 | (mortar OR concrete OR (cement AND composite) ) AND Sludge AND Replacement | 488 | 498 |
| 3 | (mortar OR concrete OR (cement AND composite) ) AND Sludge AND Substitution | 123 | 110 |
| 4 | (mortar OR concrete OR (cement AND composite) ) AND sludge AND ( replacement OR substitution ) | 557 | 557 |
| 5 | (mortar OR concrete OR (cement AND composite) ) AND “Water Treatment Sludge” AND Substitution | 6 | 4 |
| 6 | (mortar OR concrete OR (cement AND composite) ) AND “Water Treatment Sludge” AND ( replacement OR substitution ) | 33 | 24 |

Source: Authors.

Analyzing the titles and keywords, string 4 was chosen due to greater compatibility between the database results. The countries with the largest publications and the evolution of publications with string 4 over the years were verified, as shown in Figure 1.

**Figure 1 -** Country/region and evolution of publications.




Source: Authors.

Analyzing Figure 1 it is verified that the country with the largest publication on the subject is India with more than 75 publications, the second place is Malaysia, with almost half of the publications. The other articles are better distributed, with countries such as Brazil, Spain, China, the United Kingdom, and Portugal. The topic was originally published in 1974 with increased interest in the area as shown in Figure 1, from 2018.

Water treatment sludge (WTS) management is a growing global problem that water treatment plants (WTPs) and governments face. Added to the scarcity of raw materials in many places on the planet and the unique properties of WTS, the use of alternative materials to incorporate in the production of building materials such as tiles, bricks, and concrete, among others, is a convenient and sustainable solution (De Carvalho Gomes et al., 2019).

The results of the research show that it is satisfactory to mix ≤10% aluminum-based sludge in ceramic tiles, and the mechanical properties of the mortar are slightly reduced. Using iron-based sludge, the brick exhibited better mechanical strength than the reference clay brick. Regarding the application of WTS in concrete, 5% replacement of cement or sand by WTP sludge was considered the ideal value for application in a variety of structural and non-structural concrete without adverse effects on the mechanical performance of the concrete. In addition, this article discusses sludge-corrected concrete in terms of durability, potential leaching of toxic elements, and cost, and suggests topics for future research on the sustainable management of WTS (De Carvalho Gomes et al., 2019).

The production of Common Portland Cement (CPC) consumes a large amount of energy and raw materials and sends a significant amount of carbon dioxide ($CO_2$) into the atmosphere. The world production of CPC in 2014 was estimated at 4300 million tons, 6.7% higher than in 2013, increasing the environmental impacts.

Another study investigates the potential of using "drinking water treatment sludge (WTS)" as a sand substitute in Concrete Paving Blocks (BPC). Five BPC mixtures were designed and the sand substitution ratio by LTAP was 0% up to 20% with a 5% increment by weight. The outcomes showed that the substitution had a negative impact on the concrete block's characteristics above 10% of WTS (Liu et al., 2020). The study aimed at exploring the possibility of adding WTS to BPC as a substitute for sand. The experimental results proved that WTS can be used to replace fine aggregates and the maximum WTS content in BPC can be up to 10%, depending on the paving criteria without impairing the needed physical characteristics (Liu et al., 2020).

In most water treatment systems with elevated suspended particles, inorganic coagulants are most used (Kashyap & Datta, 2017). They are mainly composed of iron and aluminum salts, such as ferric chloride, aluminum sulfate and ferric sulfate.

In the softening process, with high levels of hardness, the main coagulant used is quicklime (Sales; de Souza; do Couto Rosa Almeida, 2011). These coagulants are effective in removing a wide variety of impurities from water, including colloidal particles and dissolved organic substances. The final water treatment process results in a range of by-products known as WTS, which consists of a mixture of microorganisms, suspended organic compounds, coagulants, and chemical oxides [9-10]. The final composition of WTS is the result of impurities contained in raw water and coagulant-type and other chemical treatments used for water purification (De Carvalho Gomes et al., 2019).

The disposal of WTS in waterways is still common in Brazil, although WTS is classified as Class IIA Solid Waste Non-Inert by (ABNT NBR 10004 (2004) and, therefore, must be treated and disposed of appropriately. Global demand for drinking water has increased due to rapid population growth and lifestyle changes, meaning that water utilities must generate more potable water. Conventional drinking water treatment involves several steps, including coagulation-flocculation, sedimentation, and filtration. The term "drinking water treatment sludge (WTS)" refers to all precipitates or remnants created throughout the drinking water treatment processes. The abundant management of water treatment sludge in landfills remains a critical issue to be resolved. The reuse of WTS as a building material can contribute to the development of a greener concrete product and mitigate the harmful environmental effects of excessive WTS production.

Regarding similar studies that applied LCA, in the literature, there are works such as those of Pavlík et al. (2019) that applied sewage sludge in the mortar mixture as a substitute for cement in the proportions of 10, 20, and 30% (Pavlík et al., 2019). The results pointed to an energy saving of almost 10% for the case study that used the proportion of 10% of sewage sludge.

Another similar study by Nakic (2018) applied sewage sludge ash (in the proportion of 10%) as a substitute for cement in concrete (Nakic, 2018). The results showed a 9% reduction in the environmental impact of global warming when this substitution was applied. The study by de Azevedo et al. (2020) added 10% of sludge from the cellulose pulp and paper industry in the mortar mixture and obtained satisfactory results from an environmental point of view, as it reduced $CO_2$ emissions by approximately 10% in comparison to the composition of the commonly used mortar (de Azevedo et al., 2020).

In the study carried out by (Liu et al., 2020) the effects on mortar properties were investigated by replacing 30% of cement with silt and limestone, and with the mass ratio of silt to limestone designed for 1:2, 1:1 and 2:1. The results obtained indicated that the mechanical performance of the mortar samples, e.g. compressive strength, flexural strength and water sorptivity, was improved with the combination of silt and limestone in the mass ratio of 1:1 and 2:1. This improvement can be explained by the increased reactivity of limestone in a limestone-sludge-cement system due to enrichment with aluminates.

The reaction between the limestone and the sludge, together with the pozzolanic reaction of the sludge, contributed to improving the strength and densifying the pore structure, especially for the refinement of the capillary pores. The authors concluded that the proportion of cement replacement could be even greater if a combination of sludge and limestone was used instead of using one of them alone.

In addition to the application of sludge in the mortar mixture, there are other residues being applied in the literature, such as mining residues (Almeida et al., 2021). The result of the LCA performed in the study showed that the use of mining residues resulted in the reduction of the following environmental impacts: photochemical oxidant formation (-99%), ozone depletion (-76% to -98%), and terrestrial acidification (-90% to -94%).

## 2. Methodology

The cement used in this experiment is CPIIF-32 with the addition of limestone filler, in content between 6 and 10%, with a compressive strength class of 32MPa, thus adding a material with favorable granulometry to obtain SCC. In this case, the specific mass and laser granulometry was performed using the Malvern Instruments, and Mastersizer equipment and were evaluated according to current standards. In accordance with the standards in effect, tests of granulometry, specific mass, and water absorption for the sand were also carried out.

The sludge was collected in the clarifiers of the Water treatment station (WTP) of Itajubá (MG). The Water treatment station is of the conventional type and with a treating capacity of 0.45 $m^3/s$. The WTP processes an average of 17 thousand $m^3$ of material every day. Hydrated lime ($Ca(OH)_2$), cationic polymers, polyaluminum chloride (PAC), chlorine gas ($Cl_2$), and fluosilicic acid ($H_2SiF_6$) are the chemicals used in water treatment. One Parshall trough, fourteen flocculators, four decanters, and six descending filters make up the treatment units.

The cleaning of the clarifiers is done every 15 days, 2 units at a time, the duration of washing is of 45 minutes and the volume of water used in each wash is 470 $m^3$.

The filters are washed in countercurrent (ascending direction), every 70 hours 1 filter is washed, the duration of the wash is 12 min, and 180 $m^3$ of water are utilized. Cleaning the decanters and filters requires 125.3 $m^3$ of water each day. Sludge with a solids content of 2% is produced on a dry or wet basis on an average of 2 $m^3$ per day. Without any prior treatment, the trash is discharged into the drainage network of the municipality and flows back to the Sapucaí River.

The sludge (just over 0.38 kg) was collected from the clarifier during the months of 08 and 09/2021. Following collection, the water clarifier sludge (WCS) was first dried using the technique described by Ribeiro (2012). This involved placing the WCS in a structure that had a geotextile blanket attached to a cylindrical gallon so that was kept inside the blanket and the gallon holding the water that had been sieved. Figure 2 also shows the WCS after filtering, leaving only the solid part.

**Figure 2 -** Water clarifier sludge (WCS) filtration in the blanket (a) Before filtration. (b) After filtration.

(a) (b)

Source: Authors.

The process of drying the sludge is done using the blanket as a filter, and the blanket is used to separate the water and the remaining retained by the blanket is the sludge to be worked on, as shown in Figure 2. The drying of the sludge was conducted occurs at temperature 100°C for 48 hours with total evaporation of water. WCS was brought to the rotating steel ball mill, where, following preliminary testing, a ball/sludge ratio of roughly 1/0.1—that is, 1 kg of balls to 0.1 kg of sludge for three hours. Following this procedure, the WTS began to resemble powder. Following the WCS collecting, drying, and grinding operations, the material was tested using the same cement standard for specific mass and laser diffraction granulometry.

The superplasticizer additive used in the self-compacting mortar (SCC) was the Aditibras adi-super H25 additive. It was also decided to add metakaolin HP ULTRA to raise the proportion of fines, enhancing the cohesion of the mixture. The tests performed on the metakaolin were specific mass and laser granulometry. By maximizing the granulometric distribution of the paste, the high specific surface area enhances the rheological characteristics by promoting water retention, enhanced cohesiveness, and decreased exudation and segregation.

Regarding the SCC dosage, we opted for the process described by the Gomes method (Gomes et al. (2019), which is used for self-compacting concretes (CAA) (De Carvalho Gomes et al., 2019). This method proposes that the fluidity and viscosity of the paste control the behavior of the concrete/mortar, considering that its composition is determined by how much cement is used and the ratio between the components and the mass of the cement. These ratios are determined by the expected properties of the concrete, and the aggregates are chosen by the density of the mixture that has the lowest number of voids (Gomes, Alexandre; Barros, 2009).

The approach is predicated on the idea that the mortar may be produced by independently adjusting the paste and granular skeleton compositions. Tests are conducted to determine the optimal ratio (f/c) of cement to mineral filler when the superplasticizing ingredient (sp/c) is present, in order to produce the better paste.

A certain quantity of cement (c), water (a), filer (f), and superplasticizer (sp) make up the paste. It is customary to begin paste optimization experiments for water with a 40% water/cement ratio (w/c=0.4) and, if necessary, adjust.

Consequently, the sp/c and f/c ratios are the only characteristics that need to be investigated in order to optimize the paste. The w/c ratio employed in this investigation was 0.42%.

After fixing the cement and water volumes, the optimization procedure starts with determining the filer ratio (f/c). In regard to cement, this number is frequently varied between 1 and 5% while looking for the perfect paste. Metakaolin was the filler utilized, and the ratio was 5%.

The superplastificant dosage was initially determined via Marsh cone tests and was applied to pastas with predetermined amounts of cement, water, and filer. A performance curve is obtained by testing various masses with varying ratios of superplasticizer, which enables the identification of this component's saturation point. As of right now, adding more superplasticizer to the dough does not much improve its fluidity; in this instance, it was 1.9%.

The following answer provides the volume of paste tested (Vp) at this point in the procedure Equation (1):

$$Vp = Vcim + Vfiler + Vspl + Vw - Vasp \qquad (1)$$

where: $V_p$ = paste volume; $V_{cim}$ = cement volume; $V_{filer}$ = filer volume; $V_{spl}$ = liquid superplasticizer volume; $V_w$ = water volume and $V_{asp}$ = superplasticizer water volume.

Then, the cement mass required for the unit volume of concrete in m3 is corrected using Equation (2).

$$C = Vp/(1/\rho c+(a/c)/\rho a+(f/c)/\rho f+(spl/c)/\rho sp-(asp/c)/\rho a) \qquad (2)$$

where: C is the mass of cement in $kg/m^3$; a/w= mass of water in relation to cement, f/c= mass proportion of filler in relation to cement, spl/c= mass proportion of liquid superplasticizer in relation to cement; and asp/c= mass of the superplasticizer water in relation to the cement and $\rho_i$= is the specific mass of each component (i).

To achieve the self-compacting characteristics of both concrete/mortar/paste in the fresh state, changes in the quantities of materials in the mixture must be made, as another material is added. Table 2 shows the quantities used in the base mixture with substitution of 2.5 and 10% of WCS by cement weight.

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**Table 2 -** Quantity of materials used in the mixtures 0%, 2.5% and 10% Water clarifier sludge (WCS).

| Mixture | Cement (g) | WCS (g) | Metakaolin (g) | Sand (g) | Water (g) | SP (g) |
|---|---|---|---|---|---|---|
| 0% | 1203.00 | 0.00 | 60.07 | 2219.82 | 500.00 | 22.74 |
| 2.5% | 1173.00 | 28.55 | 58.65 | 2061.53 | 530.00 | 21.60 |
| 10% | 1068.02 | 106.80 | 60.90 | 2285.56 | 593.76 | 21.78 |

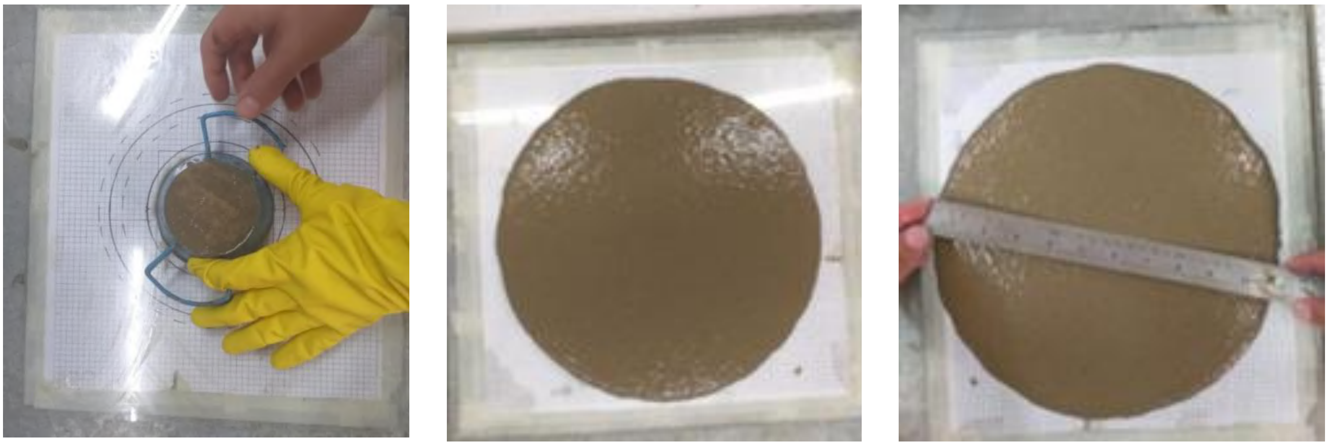
Source: Authors.

The combination of 0% was adopted by the researchers (Silva et al., 2022), with the variation occurring in the type of cement and WCS. In the case of the mixture with 2.5%, this amount of WCS was incorporated into the cement mass, following the same procedure for the 10% proportion.

### 2.1 Fresh and hardened state

The evaluation of the self-compacting mortar's fresh state characteristics required conducting both the mini slump test, assessing slump flow, and the V-funnel test, monitoring composition flow, for classification purposes. The mini slump test can be seen in the Figure 3.

**Figure 3 -** (a) Scattering and scattering test with the aid of a ruler. (b) Spreading of the mixture (c) Measuring the diameter of the spreading with the ruler.



(a) (b) (c)

Source: Authors.

Considering the mixture slump-flow test, the mini-slump was used, supported under a leveled surface, and then the mixture was placed inside the equipment until it was fully filled, as shown in Figure 3(a). Then the mini slump is removed as evenly as possible, without interfering with the spreading. It is necessary to wait for the spreading to end naturally, as shown in Figure 3(b), and then with the aid of a ruler, measure the spreading diameter, as shown in Figure 3(c).

A V-shaped funnel was used for the funnel test. First, it was filled with mortar to its maximum capacity, without overflowing or surpassing the upper edge of the funnel. After the completion of the process, the end of the funnel was opened and, with the aid of a clock, it was possible to establish the exit time of all the mortar from the V-funnel.

After the completion of the tests in the fresh state, six cylindrical specimens were molded with dimensions of (5x10) cm for the compressive strength tests. The specimens were immersed in a calcium hydroxide solution for a period of 28 days for the curing process. After this time, the specimens were removed from the molds. After the 28 days, the specimens were submitted to axial compression and flexing tests to obtain the mechanical strength of the self-compacting mortar. The tests performed in this article and the standards used are shown in Table 3.

**Table 3 -** Standards used for the tests performed in this study.

| Tests | Materials | ABNT Standard/Equipment |
|---|---|---|
| Specific mass | CPIIF-32 | ABNT NBR 16605 (2017) (NBR 16605, 2017) |
| Laser granulometry | | Malvern Instruments Ltda, Mastersizer |
| Granulometry | Sand | ABNT NBR NM 248 (2003) (NBR NM 248, 2003) |
| Specific mass | | NBR16916 (2021) (NBR16916, 2021) |
| Water absorption | | NBR16916 (2021) (NBR16916, 2021) |
| Specific mass | WTS | ABNT NBR 16605 (2017)(NBR 16605, 2017) |
| Laser granulometry | | Malvern Instruments Ltda, Mastersizer |
| SEM and EDS | | - |
| Specific mass | Metakaolin | ABNT NBR 16605 (2017) (NBR 16605, 2017) |
| Laser granulometry | | Malvern Instruments Ltda, Mastersizer |
| Mini slump | Fresh state | Gomes; De Barros (2009) |
| Funnel-V | | Gomes; De Barros (2009) |
| Compressive strength | Hardened State | ABNT NBR 5739 (2018) (NBR 5739 2018:, 2018) |

Source: Authors.

The results obtained from these tests played a fundamental role in establishing the assurance and evaluating the intrinsic performance of self-compactability of mortar, as well as its physical and mechanical properties.

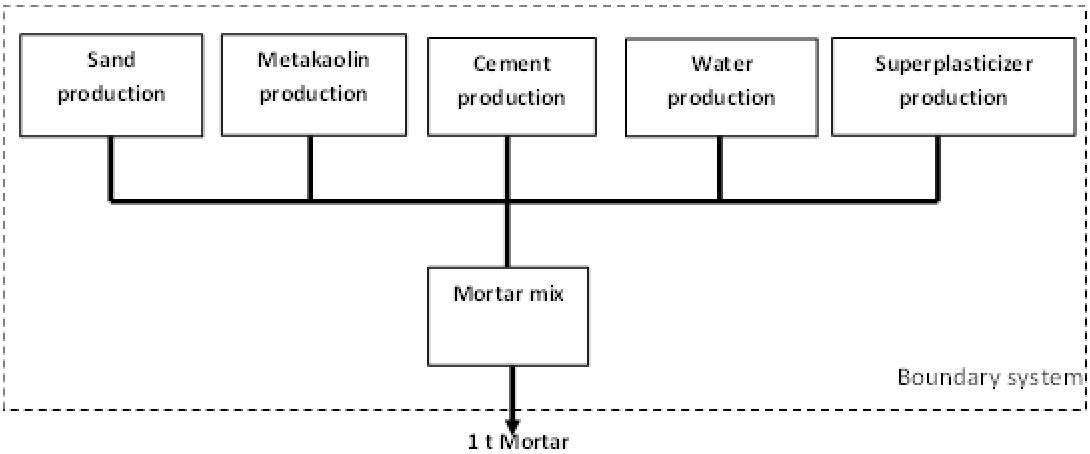
### 2.2 Life cycle assessment

To conduct the LCA, the four phases recommended by ABNT NBR ISO 14040 (2009) were followed: a) Defining the objective and scope: This step includes the system boundary and the level of detail that depends on the objective of the study (ABNT NBR ISO 14040, 2009). This step is also defined as the functional unit that describes how the product's identified functions (performance attributes) are quantified. The functional unit's goal is to offer a reference to which the inputs and outputs are related; b) Inventory analysis: This phase involves the collection of input/output data associated with the system under study and necessary to achieve the objectives of the study in question. Impact assessment: This step involves associating inventory data with specific impact categories and category indicators; c) Interpretation: In this phase the findings of the inventory analysis and the impact assessment are considered together, providing results that are consistent with the defined objective and scope and lead to conclusions and suggestions for the research that was done.

To obtain the input data of each production process, we used the database present in the SimaPro 8.0.3.14 program, specifically the U.S. Life Cycle Inventory (Ciroth & Burhan, 2021) and Ecoinvent v3.0 databases (Pfister et al., 2016). To determine the environmental impacts, the ReCiPe 2008 method was selected (Goedkoop et al., 2009). This method has Dutch origin, developed by Pré (Product Ecology Consultants) and it is considered a renewal of two other widely used models, the Eco-Indicator 99, and the CML methods. The method has the characteristic of converting pollutant emissions and natural resource extractions into impact indicators (Goedkoop et al., 2009). The study inventory was inserted into SimaPro 8.0.3.14, simulating 3 different scenarios. In the first with 0% WCS, in the second it considered the insertion of 2.5% of WCS in the mortar mixture, which reduces the need to consume 7.37 kg of cement per ton of mortar. In the third case, 10% of WCS was added to the same mixture, consequently reducing the cement demand by 25.82 per ton of mortar.

The objective, in this study of the LCA was to verify the advantage from the environmental viewpoint of replacing, in the mortar mixture, cement by WCS. Figure 4 shows the stages that were defined for this study.

**Figure 4 -** Stages defined by the LCA study.




Source: Authors.

Thus, the boundary of this study (Figure 4) considered the production of the main components of mortar, follow: Cement, metakaolin, sand, water, and superplasticizer. The functional unit established was 1 ton of mortar since it represents a significant amount for its application in civil construction.

## 3. Results and Discussion

### 3.1 Characterization of materials

The results of the specific mass, absorption and fineness module for CPIIF, metakaolin, sand, and sludge water clarifier (WCS) can be seen in Table 4.

**Table 4 -** Results of the characterization of the materials used in Self-compacting Concrete (SCC).

| Material | Specific mass (g/cm³) | Absorption (%) | Fineness module (MF) |
|---|---|---|---|
| Cement CPIIF | 2.99 | - | - |
| Metakaolin | 2.56 | - | - |
| Sand | 2.58 | 0.37 | 2.63 |
| WCS | 2.10 | - | - |

Source: Authors.

The outcomes shown in Table 4 are comparable to those of Silva et al. (2022), who used CPV-ARI cement and water filter sludge (WFS) (Silva et al., 2022). In the study by Silva et al. (2022), they used CPV-ARI and found a specific mass of 3.04

g/cm³, which represents a variation of less than 2% when compared to the CPIIF-32 used in this study (Silva et al., 2022). Silva et al. (2022) found a specific mass value of 2.35 g/cm³ for filter sludge (WFS), which demonstrates a significant increase of more than 10% between sludge from water treatment clarifiers and filters (Silva et al., 2022).

Table 5 presents the data of the two types of cement, metakaolin and WFS and WCS, in the laser granulometry test in the diameters (d10, d50 or mean diameter and d90). The diameters d10, d50, and d90 are points of the particle size curve to measure the fineness of the materials, which is 10%, and 10% of the particles have diameters lower than it, respectively for 50% and 90%.

**Table 5 -** Particle size distribution of fine materials.

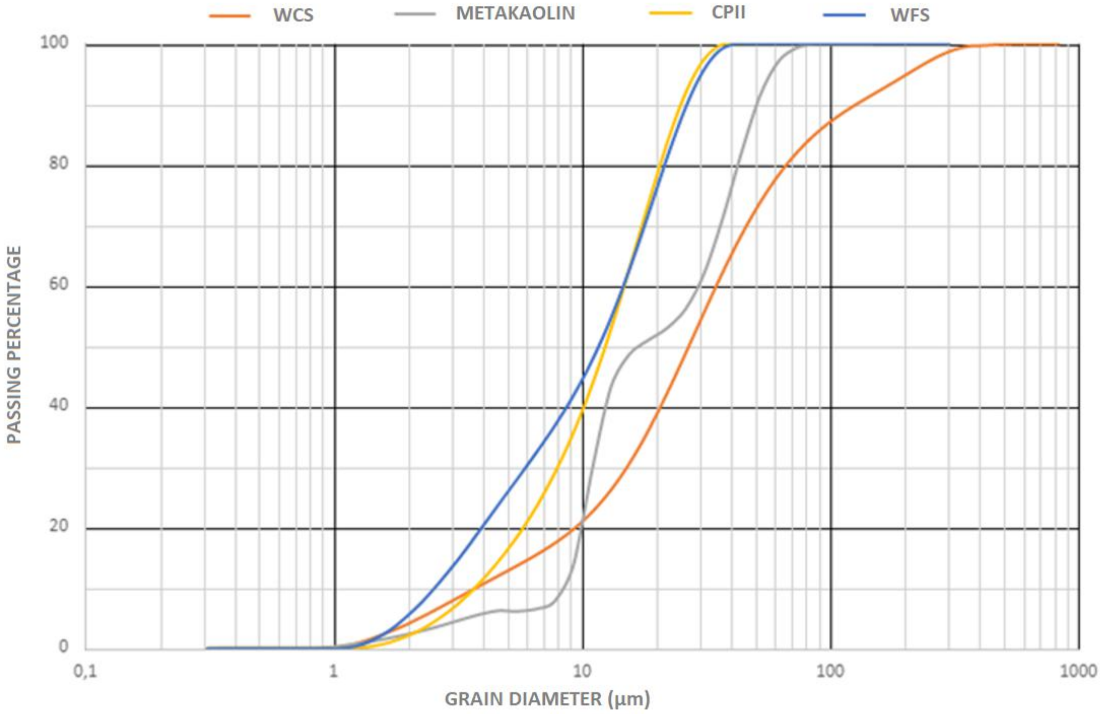
| d | CPIIF | CPV | Metakoalin | WCS | WFS |
|---|---|---|---|---|---|
| | (μm) | | | | |
| d10 | 3.70 | 2.32 | 2.51 | 3.69 | 2.55 |
| d50 | 12.47 | 12.29 | 12.40 | 27.02 | 11.69 |
| d90 | 25.20 | 35.23 | 30.64 | 126.87 | 26.48 |

Source: Authors.

Comparing the d10, d50, and d90 diameters of the two types of cement and the slurries used (WFS and WCS), it is observed that, for the d90 particle size, there was a significant variation when comparing WCS and WFS. This value indicates that 90% of the particles have diameters below 126.87 μm, almost five times larger than in the case of WFS.

Figure 5 shows the granulometric curves of the materials used for the execution of this mortar (CPIIF, metakaolin, and WCS) and WFS. A significant approximation exists for the granulometry of the WFS with the cement, also showing that the sludge used in this WCS research has a larger particle size than the metakaolin.

**Figure 5 -** Particle size analysis of materials.

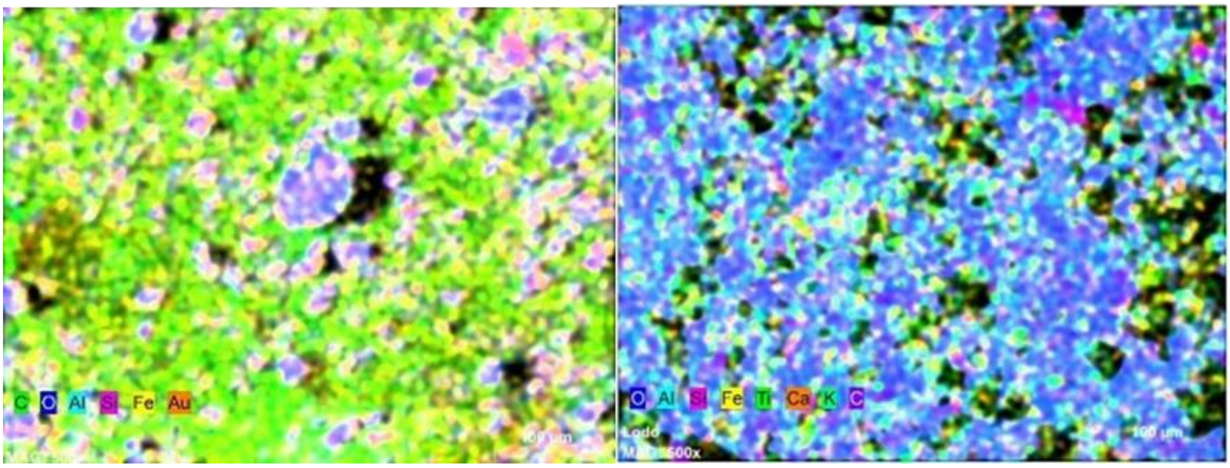



Source: Authors.

Figure 5 allows for the comparison between the granulometry of the decanter sludge (orange) and the filter sludge (blue), allowing the interpretation that the WCS is better graded in relation to the WFS used by Silva et al. (2022), which in turn presents a more uniform size of its grains (Silva et al., 2022).

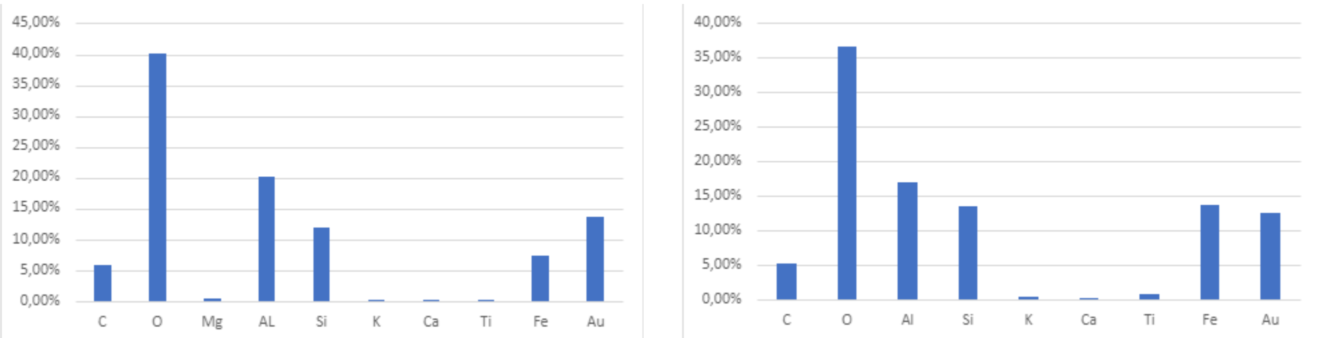
Figure 6 shows the mapping of the chemical composition that allows the approximate composition of the LTA to be known and thus compare them. Figure 7 shows the percentage composition of the main elements present in the WCS and WFS used by Silva et al. (2022).

**Figure 6 -** Approximate chemical composition of Water clarifier sludge (left) and Water Filter Sludge (right).




Source: Authors.

**Figure 7** - Approximate proportion of the elements present in the Water clarifier sludge (left) and Water Filter Sludge (right) sample.




Source: Authors.

Analyzing Figures 6 and 7 it is possible to observe a predominant composition of oxygen, it is also observed, in a representative way, the presence of aluminum, iron, silicon, and carbon. The usage of coagulant in the WTP of the study is related to the notable amounts of aluminum (15–20%) found in both samples of the municipality of Itajubá, aluminum polychloride is used as a coagulant for water treatment. Both have a similar composition, with no significant difference between the sludge removed from the clarifier and the one removed from the filter.

Figure 8 shows the analysis of scanning electron microscopy by means of secondary electrons. Approximately 500 times magnification was applied on a 100 µm scale.

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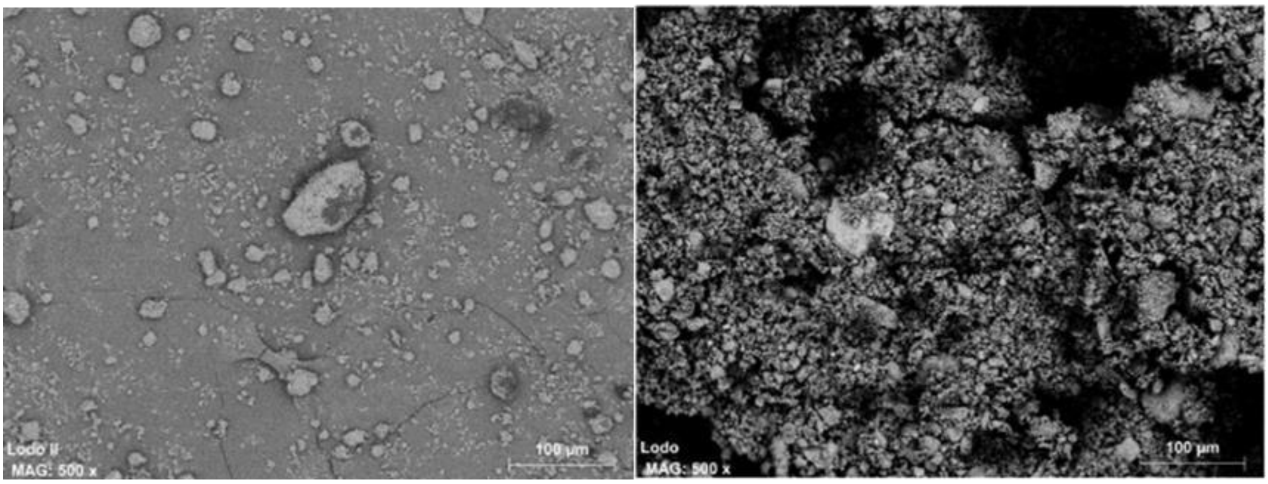
**Figure 8 -** Analysis of Water clarifier sludge and Water Filter Sludge grains, respectively.



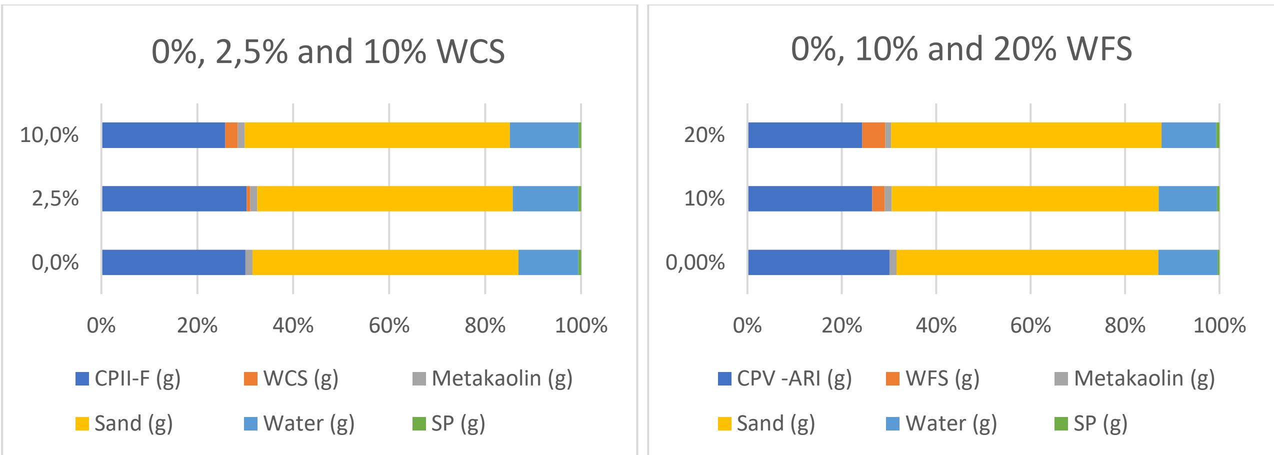

Source: Authors.

The studied particle morphologies exhibit varied forms and irregularities, with a predominant presence of powdery particles that envelop the bigger particles in both samples analyzed WCS (left) and WFS (right).

### 3.2 Dosage

The amounts of each component used in the basic mixtures as well as the percentages of 2.5% and 10% of WCS were compared with the work of Silva et al. (2022), who used WFS and CPV as shown in Figure 9.

**Figure 9 -** Comparison in grams of the traits used in the mixture 0%, 2.5% and 10% Water clarifier sludge (WCS).




Source: Authors.

Analyzing Figure 9 there are no significant differences between the percentages of 0 and 10% in the amount of material when using different cements and WCS. It is thus confirmed that the base mixture has a somewhat lower proportion of sand to cement than the other combinations. This happened in order to add fines (cement and metakaolin) in order to remedy the exudation that was present in the mortar according to the work of Silva et al. (2022).

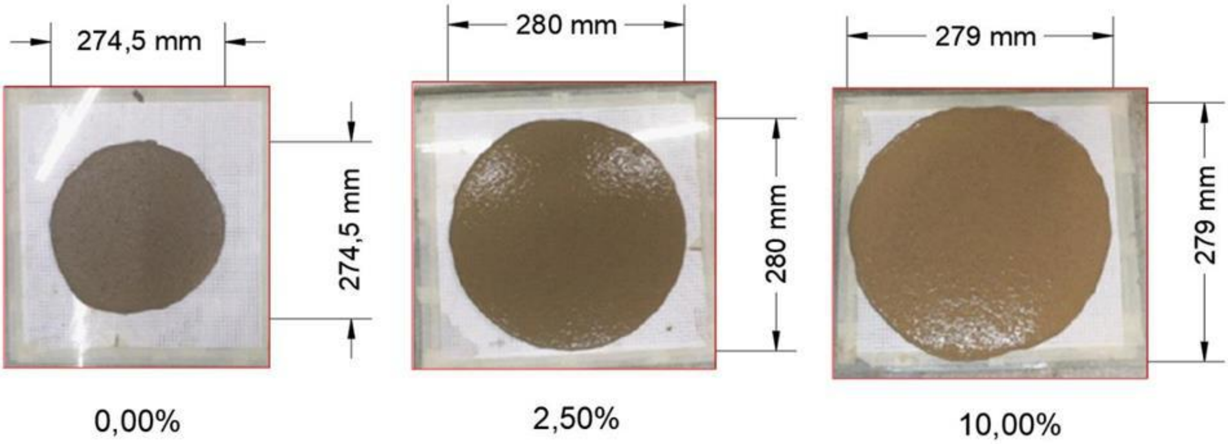
Compared using Brachini et al., (2020), it's evident that the water/cement ratio (a/c) was in the same range as this work and of Silva et al. (2022) but the amount of superplasticizer used was doubled to achieve sufficient results in the fresh state.

Another difference that should be highlighted is the fact that the WCS of this study and of Silva et al. (2022) was not treated, while the one used by Brachini et al. (2020) was calcined, thus reducing the amount of organic matter in the residues (Brachini et al., 2020). Another fact is that the percentage of sludge used in this and in the work of Silva et al. (2022) was altered both a/c of 39%, 42%, 48%, and the amount of superplasticizer of 1.8%, 1.7%, and 1.8 adapting the mixture to meet the necessary requirements in the fresh state (Silva et al., 2022).

### 3.3 Fresh and hardened state

Regarding the fresh state tests, the slump-flow test was first performed using the mini-slump, obtaining the visual impressions, as shown in Figure 10.

**Figure 10 -** Proportion of reference mixture, 0%, 2.5%, and 10% Water clarifier sludge (WCS), respectively.




Source: Authors.

Analyzing Figure 10 is verified that both mortars did not present segregation or exudation, maintaining homogeneity throughout the fluid state tests. In addition, the numerical results of the slump and slump-flow tests are shown in Table 6.

**Table 6 -** Results of mini-slump and funnel-V tests.

| | 0% | 2.5% | 10% | Reference |
|---|---|---|---|---|
| Mini Slump (mm) | 274.5 | 280.0 | 279.0 | 200 mm a 280 mm |
| V-Funnel (s) | 9.43 | 7.31 | 5.59 | 3.5 s a 10.0 s |

Source: Authors.

Table 6 show the values of the V-funnel test to define the flow parameter (Gm) and the viscosity parameter (Rm). Upon observing the results for both tests and comparing them with the reference values, it is noted that in both cases, the values fall within the specified limits, indicating that all percentages are considered self-compacting.

The results presented in Figure 11 and Table 7 showed that all mixtures can be considered self-compacting. The results of the compressive strength tests are shown in Table 7 for the eight results of 0% and six of 2,5% and 10% with WCS.

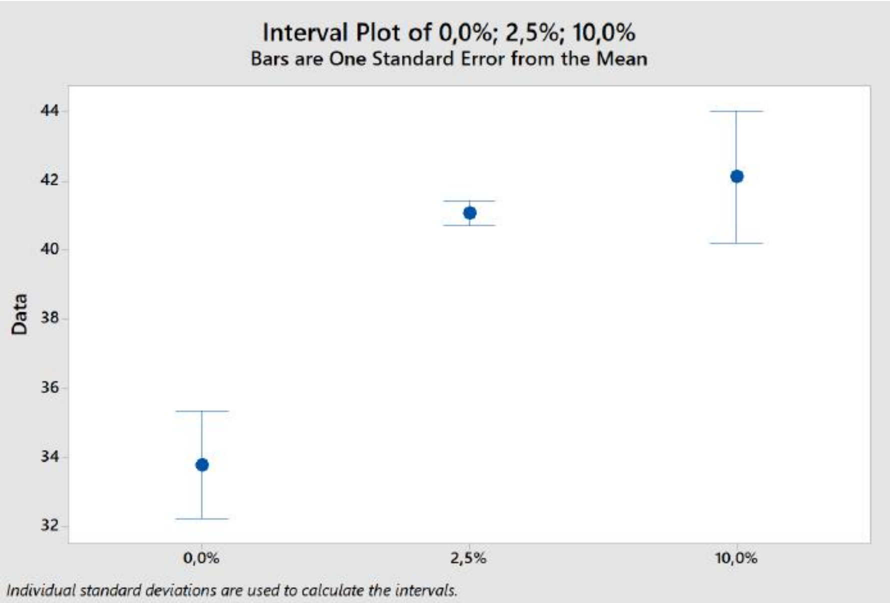
**Table 7 -** Results of compressive strength tests.

| CP | 0% (MPa) | 0% (MPa) | 2,5% (MPa) | 10% (MPa) |
|---|---|---|---|---|
| **CP1** | 27.02 | 27.02 | 41.74 | 37.48 |
| **CP2** | 38.40 | 38.39 | 40.50 | 41.65 |
| **CP3** | 35.47 | 35.47 | 39.35 | 37.50 |
| **CP4** | 49.56 | - | 41.50 | 49.56 |
| **CP5** | 35.37 | 35.37 | 41.25 | 45.40 |
| **CP6** | 22.24 | - | 41.62 | 41.12 |
| **CP7** | 33.25 | 33.25 | - | - |
| **CP8** | 33.14 | 33.14 | - | - |
| **Standard deviation** | 8,04 | 3.82 | 0.89 | 4.68 |
| **Mean** | 34.31 | 33.78 | 41.06 | 42.12 |

Source: Authors.

Considering the 0% WCS, eight specimens (CP) were made to obtain the standard deviation of 7.52 MPa. It was decided to remove two of the results farthest from the mean reducing the deviation to 3.49 MPa. The mean compression results of the base CP (0%) and with the addition of the WCS (2,5% and 10%) were 33.78 MPa, 41.06 MPa, and 42.32 MPa respectively (Figure 11). As observed, the averages found for compressive strength were close to 2.5% and 10%, increasing 25% when compared to the base SCC.

**Figure 11 -** Mean compressive strength results of 0%, 2.5%, and 10% Water clarifier sludge (WCS), respectively.




Source: Authors.

Table 7 allowed for the analysis of the difference in the values of compressive strength of the base SCC and the replacement of WCS by the cement mass. The work done by Silva et al. (2022) was to replace CPV-ARI cement in 10% and 20% by WFS, in the results of the compression test, results showed a 65% and 70% deterioration for the mixes containing 10% and 20% sludge, respectively (Silva et al., 2022). de Oliveira Andrade et al.(2018) also found lower compressive strengths, with the largest reductions occurring in the higher replacements. In addition, the author found that the resistance increased over time, and the traits with calcined WTS had an increment that was marginally higher than the reference (de Oliveira Andrade et al., 2018). The drop in compressive strength may be linked to the higher a/c ratio of mixtures with sludge (de Oliveira Andrade et al., 2018). Tafarel et al. (2016) also discovered that for extended curing durations, mixes with wet sludge had an increase in compressive strength, despite the values not reaching the resistances of the base mix (Tafarel et al., 2016).

In contrast to the base mix, Brachini et al. (2020) observed an increase in compressive strength. This fact may be linked to the lower a/c ratio used by the authors and the greater amount of superplasticizer introduced in the mixture. The calcination of WTS can have an impact because of the decrease in organic matter, but it opposes the results obtained by (de Oliveira Andrade et al., 2018).

### 3.4 Environmental impact assessment

The results of the environmental impacts of each case study are presented in Table 8.

**Table 8 -** Environmental impacts obtained to produce 1 ton of mortar.

| Environmental impact | Unit | 0% WCS | 2.5% WCS | 10% WCS |
|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | $4.29x10^2$ | $4.22x10^2$ | $3.33x10^2$ |
| Ozone depletion | kg CFC-11 eq | $1.36.10^{-6}$ | $1.33.10^{-6}$ | $1.07.10^{-6}$ |
| Terrestrial acidification | kg $SO_2$ eq | 1.84 | 1.81 | 1.43 |
| Freshwater eutrophication | kg P eq | $3.08x10^{-3}$ | $3.03x10^{-3}$ | $2.86x10^{-3}$ |
| Marine eutrophication | kg N eq | $4.33x10^{-2}$ | $4.26x10^{-2}$ | $3.37x10^{-2}$ |
| Human toxicity | kg 1,4-DB eq | $1.65x10^1$ | $1.62x10^1$ | $1.28x10^1$ |
| Photochemical oxidant formation | kg NMVOC | 1.24 | 1.22 | $9.60x10^{-1}$ |
| Particulate matter formation | kg PM10 eq | $6.60x10^{-1}$ | $6.49x10^{-1}$ | $5.12x10^{-1}$ |
| Terrestrial ecotoxicity | kg 1,4-DB eq | $4.76x10^{-3}$ | $4.68x10^{-3}$ | $3.71x10^{-3}$ |
| Freshwater ecotoxicity | kg 1,4-DB eq | $1.40x10^{-1}$ | $1.38x10^{-1}$ | $1.23x10^{-1}$ |
| Marine ecotoxicity | kg 1,4-DB eq | $1.28x10^{-1}$ | $1.26x10^{-1}$ | $1.08x10^{-1}$ |
| Ionizing radiation | kBq U235eq | $6.02x10^{-1}$ | $5.91x10^{-1}$ | $5.58x10^{-1}$ |
| Agricultural land occupation | $m^2a$ | 2.17 | 2.13 | 2.01 |
| Urban land occupation | $m^2a$ | $1.23x10^{-1}$ | $1.21x10^{-1}$ | $1.14x10^{-1}$ |
| Natural land transformation | $m^2$ | $9.37x10^{-4}$ | $9.21x10^{-4}$ | $8.69x10^{-4}$ |
| Water depletion | $m^3$ | $2.11x10^1$ | $2.07x10^1$ | $1.95x10^1$ |
| Metal depletion | kg Fe eq | 1.11 | 1.09 | 1.03 |
| Fossil depletion | kg oil eq | $3.86x10^1$ | $3.80x10^1$ | $3.03x10^1$ |

Source: Authors.

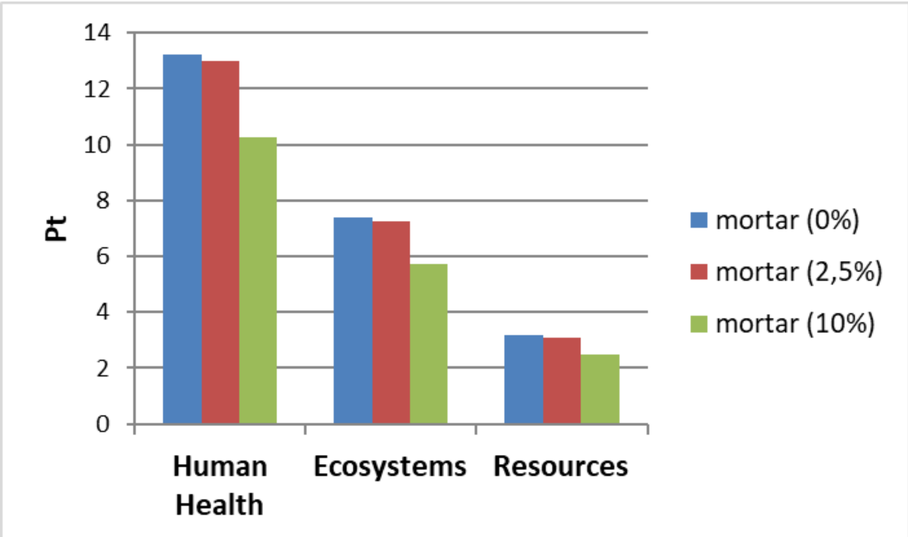
The results showed that there was a reduction in environmental impacts in the two case studies in which cement was replaced by WCS. In the case where the substitution was 2.5%, the environmental impacts of climate change, ozone depletion, terrestrial acidification, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, marine ecotoxicity, and fossil depletion had their values reduced by 1.6% on average in relation to the study with 0% of WCS.

The other impacts for the same study: Freshwater eutrophication, freshwater ecotoxicity, ionizing radiation, agricultural land occupation, urban land transformation, water depletion, and metal depletion had an average reduction of their values around 1.7% compared to the study with 0% of WCS.

Considering the case where the substitution by WCS was 10%, the environmental impacts: Freshwater eutrophication, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, reduced by an average amount of 7%, while the impacts: Climate change, Ozone depletion, Terrestrial acidification, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity and Fossil depletion, had their impacts reduced by 20 to 22% on average. The other impacts: Freshwater ecotoxicity and Marine ecotoxicity, reduced their values by around 12% and 15%, respectively.

Another result obtained in this study was the normalization and grouping of environmental categories into three (human health, ecosystem, and resources). Normalization consists of calculating the magnitude of an environmental impact in relation to reference information. In this method the reference is a global area on a per capita basis, referring to the year 2000. The result of this stage is an average in Points (Pt) which represents one-thousandth of the annual environmental load of an inhabitant in the world. Figure 12 shows the results for the respective step.

**Figure 12 -** Grouped and normalized environmental impacts for the different scenarios.




Source: Authors.

The results presented in Figure 12 show that the application of WCS in the proportion of 2.5% caused a reduction of approximately 1.6% in the damage to human health, ecosystem, and resources of nature compared to the mixture of mortar without WCS. Considering the proportion of 10% this reduction was more expressive, in the range of 20 to 22%.

This significant 20% reduction in impacts is directly related to the replacement of cement with WCS, specifically at a rate of 10%. Cement production is an expressive emitter of pollutants and a consumer of natural and energy resources. Among atmospheric pollutants, the following pollutants stand out: Particulates (2.35 g/kg cement), volatile organic compounds (50 mg/kg cement), carbon monoxide (1.10 g/kg cement). Such pollutants directly impact human health, consequently reducing cement consumption leads to a reduction of this impact.

Following the same reasoning for the ecosystems and resources impacts. For the first, it has as an example the emission into water of pollutants such as: Aluminum (0.36 mg/kg cement), nitrate compounds (5.89 mg/kg cement), Chloride (0.72 g/kg cement). For the second, there is high consumption of cement production of energy and material resources, follow some examples: Limestone (1.37 kg/kg cement), Iron ore (0.013 kg/kg cement), coal (0.11 kg/ kg cement), electricity (0.14 kWh/kg cement).

## 4. Conclusion

The incorporation of WCS in the fresh state resulted in slight alterations in the slumps properties. The Mini Slump test showed an increase 2.5% and 10% of the WCS. While for the Funnel V test, there were also changes in flow properties, and for the 2.5% and 10% WCS, there was a significant decrease. This is due to the use of sludge, which, when added, resulted in worse results. When compared to the base concrete, the hardened state showed an increase in compressive strength for 2.5% and 10% of WCS.

Through the results and analysis of the literature, the authors advise using WTS in cement materials with caution, which may generate changes in some properties, especially the physical properties. From the environmental point of view, LCA proved the benefits of the partial replacement of cement by WCS, the results pointed to a reduction of around 20 to 22% in environmental impacts that harm human health.

To suggest future work, flexion tests could be carried out to verify the flexural strength of the material, which is important to determine its ability to withstand distributed loads, and a tensile test to evaluate the material's resistance to traction, as it is important to determine its ability to resist pulling forces during use.

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