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Eco-friendly concrete: Combining treated wastewater and recycled aggregates

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ABSTRACT

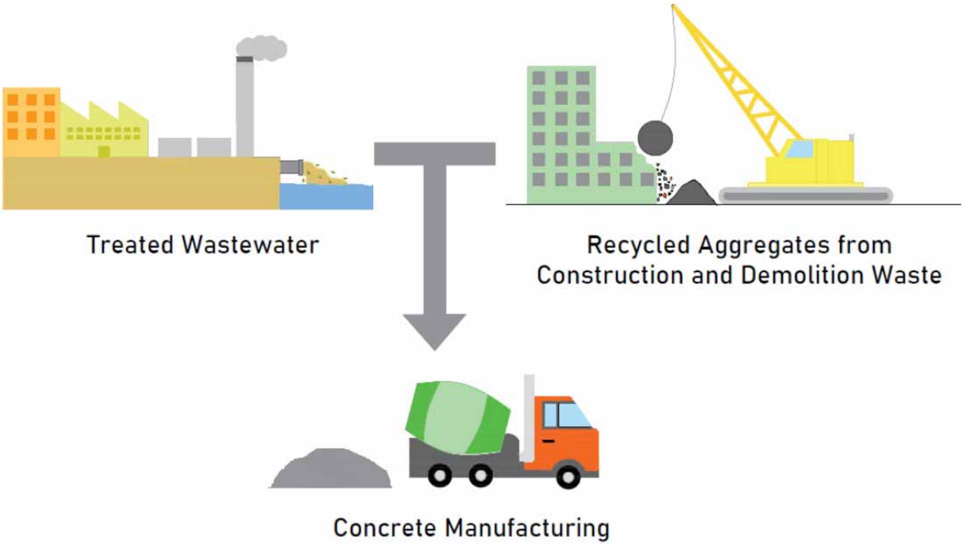
The concrete industry is a significant consumer of drinking water and natural aggregates, such as sand and gravel. However, the scarcity of water and aggregate resources and the challenges associated with the disposal of construction and demolition waste prompted the exploration of alternative materials. This study investigates the feasibility of incorporating secondary treated wastewater from UASB reactors followed by trickling filters and mixed recycled aggregates as potential alternatives. To assess the viability of these alternatives, the study considered the replacement of 100% potable water with treated wastewater, as well as varying proportions of recycled gravel (20, 40, 60, 80, and 100%) and recycled sand (10, 20, 30, 40, and 100%). Physical and mechanical properties were negatively affected, but it was possible to reach compressive results over 40 MPa and splitting tensile strength over 4 MPa for almost all mixes. Regarding physical properties, the use of alternative materials caused poorer outcomes for density, water absorption, and air-void ratio. The limited magnitude of these detrimental effects indicates the potential of manufacturing concrete with the addition of combined treated wastewater and recycled aggregate as a viable strategy while enhancing reuse practices.

Key words: cementitious composite, construction and demolition waste, reuse, sustainability, treated sewage

HIGHLIGHTS

- It is possible to obtain concrete with acceptable properties using mixed recycled aggregates and treated wastewater.
- A minimum detrimental effect was observed over concrete's fresh properties.
- Reduction in concrete's physical properties is not statistically significant.
- The mechanical properties were negatively affected with the increase in fine and coarse mixed recycled aggregates.
- Small amounts of recycled aggregates do not cause noticeable losses in concrete's performance.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Concrete is the most widely consumed construction material. Its extensive usage can be attributed to its exceptional strength, long-lasting durability, ease of mixing, and versatility in shaping. Concrete is a composite material formed by combining cement with natural resources such as water, sand, and gravel. However, despite water and aggregates being renewable resources over the long term, the growing population and urban development have led to alarming levels of concrete consumption.

The concrete industry stands as the largest water consumer (Asadollahfardi *et al.* 2016). In 2012, concrete manufacturing accounted for approximately 1.7% of global water consumption (Miller *et al.* 2018). Water plays a crucial role not only in the mixing and curing processes of concrete but also in activities like cleaning aggregates and mixer trucks. Yahyaei *et al.* (2020) state that the production of 1 m^3 of concrete requires a minimum of 800 L of water, with 500 L designated for mixing and the remaining 300 L used for cleaning mixer trucks. Moreover, to maintain the physical and mechanical properties of concrete, it is common practice to employ water that is safe for drinking.

However, the issue of water scarcity is a stark reality in various regions worldwide. Consequently, the provision of potable water for concrete manufacturing has emerged as a significant concern in modern societies, prompting the exploration of alternative water sources that do not have drinking water quality. Municipal and industrial wastewater, after undergoing appropriate treatment, have gained recognition as viable alternatives due to their composition of 99.9% water and 0.01% solids. Such treated wastewater can achieve suitable quality for multiple reuse purposes, offering a promising solution. In addition, the continuous generation of wastewater, particularly in densely populated urban areas, further highlights its relevance as a significant water source. Consequently, numerous researchers have explored the potential of utilizing effluents derived from various wastewater treatment processes as a substitute for potable water in concrete production. Their investigations have revealed that it is indeed feasible to produce concrete with acceptable properties using such wastewater, as discussed in Almeida & Tonetti (2022).

While certain authors (Tay & Yip 1987; Tay 1989; Al-Joulani 2019; Duarte *et al.* 2019; Tonetti *et al.* 2019; Bouaich *et al.* 2022) have documented positive outcomes when potable water was substituted with wastewater, the majority of extant studies employing wastewater have indicated reductions in compressive strength. Nonetheless, these reductions remain within the 10% threshold prescribed by relevant standards (Asadollahfardi *et al.* 2016; Asadollahfardi & Mahdavi 2018; Brandão *et al.* 2019; Catanzaro *et al.* 2019; Saxena & Tembhurkar 2019; Hassani *et al.* 2020a; Yahyaei *et al.* 2020).

Another significant concern within the construction industry is related to the management of construction and demolition waste (CDW). Globally, the annual generation of CDW exceeds 10 billion tons, with the United States, the European Union, and China being the primary contributors, producing 700 million tons, 900 million tons, and 2,300 million tons, respectively (Cantero *et al.* 2020). Furthermore, the process of urbanization has made it increasingly challenging and costly to obtain natural sand and gravel due to the distance between consumers and producers, as well as the depletion of natural aggregate sources. Consequently, the utilization of CDW as recycled aggregates has emerged not only as an alternative to mitigate the consumption of natural aggregates but also as one of the most effective means to reduce the environmental impact caused by the civil construction industry (Silva *et al.* 2015). As a result, the incorporation of CDW in concrete manufacturing has become the subject of extensive study by numerous researchers in recent years (Martínez-Lage *et al.* 2012; Beltrán *et al.* 2014; Etxeberria & Vegas 2015; Silva *et al.* 2018, 2019; Cantero *et al.* 2020; Plaza *et al.* 2021).

With the increasing dissemination of this practice, CDW was classified into two categories: concrete recycled aggregates (CRA) and mixed recycled aggregates (MRA). Compared with CRA, the MRA inherently exhibits higher variability, reduced strength, and increased water absorption due to the presence of crushed mortar, bricks, and tiles (Etxeberria & Gonzalez-Corominas 2018; Martínez-Lage *et al.* 2020), and is consequently less frequently considered for concrete manufacturing activities.

However, it is important to note that depending on the intended application of the concrete (i.e. paving, blocks, filling, non-structural or structural use, etc.) and the desired performance requirements, it is indeed possible to incorporate recycled materials and achieve composites of excellent quality with satisfactory mechanical performance, all while reducing the consumption of natural resources.

Hence, the use of treated wastewater and recycled aggregates in concrete manufacturing becomes particularly relevant to the concrete industry when considering the escalating challenges posed by water and aggregate scarcity, and the disposal of construction debris in urban areas. However, it is important to note that the combined utilization of treated wastewater and recycled aggregates in concrete production is still a relatively incipient field of study, with limited research available on this subject and its impact on the physical and mechanical properties of concrete (Elchalakani & Elgaali 2012; Ramírez-Tenjhay *et al.* 2016; Raza *et al.* 2020, 2021; Ahmed *et al.* 2021). Therefore, the objective of the present study is to produce concrete by combining both materials and evaluating their performance (physical and mechanical properties), aiming to encourage their utilization if positive outcomes are found.

2. MATERIAL AND METHODS

2.1. Material characterization

To produce the concrete samples, we employed treated wastewater obtained from the municipal wastewater treatment plant (ETE Barão Geraldo) located in Campinas (Brazil). The treatment system comprises a series of upflow anaerobic sludge blanket reactors, followed by a trickling filter and clarifier. To ensure consistency in the study, all the effluent utilized was collected as a single batch, thereby minimizing variations in quality. Furthermore, the collected effluent was refrigerated throughout the entire concrete sample production process. As an additional precaution against potential contamination, the effluent was disinfected using calcium hypochlorite (12 mg/L) with a minimum contact time of 30 min. In contrast, the control samples were prepared using drinking water sourced from the public water supply and collected from a laboratory faucet. Figure 1 provides an overview of the materials employed in the study. The physicochemical properties (pH, total alkalinity, nitrate, COD, total solids, chloride) of treated wastewater were assessed in accordance with the standard methods currently established in the laboratory's routine outlined by APHA *et al.* (2012).

The mixed recycled aggregate, comprising both fine and coarse portions, was sourced from a recycling plant (SBR Reciclagem) located in Valinhos (Brazil). In addition, quartz sand and granite gravel were utilized as the natural aggregates in the study. All aggregates underwent thorough characterization with their respective properties assessed in accordance with the relevant Brazilian standards as detailed in Table 1.

A high early-strength cement, designed to achieve a 28-day expected strength of 59 MPa, was utilized in the study. The fresh properties of concrete, such as setting time and consistency, were assessed in accordance with the relevant Brazilian standards, as detailed in Table 1.

2.2. Concrete groups cast and mix design

The concrete samples were classified into three distinct families based on their respective mixing designs: C0, CX-E, and C100/Y-E, as depicted in Figure 2.

The control group (C0) exclusively employed natural aggregates and drinking water in its composition. In the CX-E family, treated wastewater completely replaced the drinking water component, while the mixed recycled gravel substituted X% (20, 40, 60, 80, and 100%) of the natural coarse aggregate. Within the C100/Y-E family, both the gravel and drinking water were

Figure 1 | Treated wastewater (a) and drinking water (b), natural sand (c), mixed recycled sand (d), natural gravel (e), and mixed recycled gravel (f) were used.

entirely replaced by their respective alternative materials. Furthermore, the finely mixed recycled aggregate replaced Y% (10, 20, 30, 40, and 100%) of the natural sand in this family.

The mix design for 1 m^3 of concrete for each specific mixture is provided in Table 2. A total of 319 cylindrical samples were carefully molded and subsequently subjected to a standardized curing process utilizing the same type of water employed during the mixing stage. For each mix design, a total of 29 samples were cast, of which 15 were utilized for compressive strength testing at different time intervals (7, 28, and 90 days). Furthermore, 10 samples were allocated for assessing splitting tensile strength at 7 and 28 days, while an additional four samples were employed for determining density, water absorption, and air-void ratio. All tests conducted, both in the fresh and hardened states, were conducted according to the relevant Brazilian standards as outlined in Table 1. Statistical analysis was performed utilizing analysis of variance (ANOVA), followed by the *post hoc* Dunnett's bilateral test. A significance level of $p < 0.05$ was considered to denote statistical significance.

3. RESULTS

3.1. Physicochemical quality

The water used in concrete manufacturing is typically required to be free from impurities in order to prevent any alterations in cement hydration and subsequent changes in concrete properties. Consequently, drinking water is commonly considered the safest and most widely adopted option. Nonetheless, recognizing the issue of water scarcity in various countries, certain

Table 1 | Evaluated properties and standards

Material		Property	Standard
Aggregate	Fine (sand)	Granulometric composition	NBR 17054:2022 (ABNT 2022)
		Density	NBR 9776:1988 (ABNT 1987)
		Unit weight and air-void content	NBR 16972:2021 (ABNT 2021a)
		Density and water absorption	NBR 16916:2021 (ABNT 2021b)
	Coarse (gravel)	Granulometric composition	NBR 17054:2022 (ABNT 2022)
		Density and water absorption	NBR 16917:2021 (ABNT 2021c)
		Unit weight and air-void content	NBR 16972:2021 (ABNT 2021a)
		Composition by visual analysis	NBR 15116:2021 (ABNT 2021d)
Concrete	Fresh state	Initial and final setting time	NBR 16607:2018 (ABNT 2018a)
		Workability	NBR 13276:2016 (ABNT 2016)
	Hardened state	Compressive strength	NBR 5739:2018 (ABNT 2018b)
		Splitting tensile strength	NBR 7222:2011 (ABNT 2011)
		Density	NBR 9778:2009 (ABNT 2009a)
		Water absorption	
		Air-void ratio	

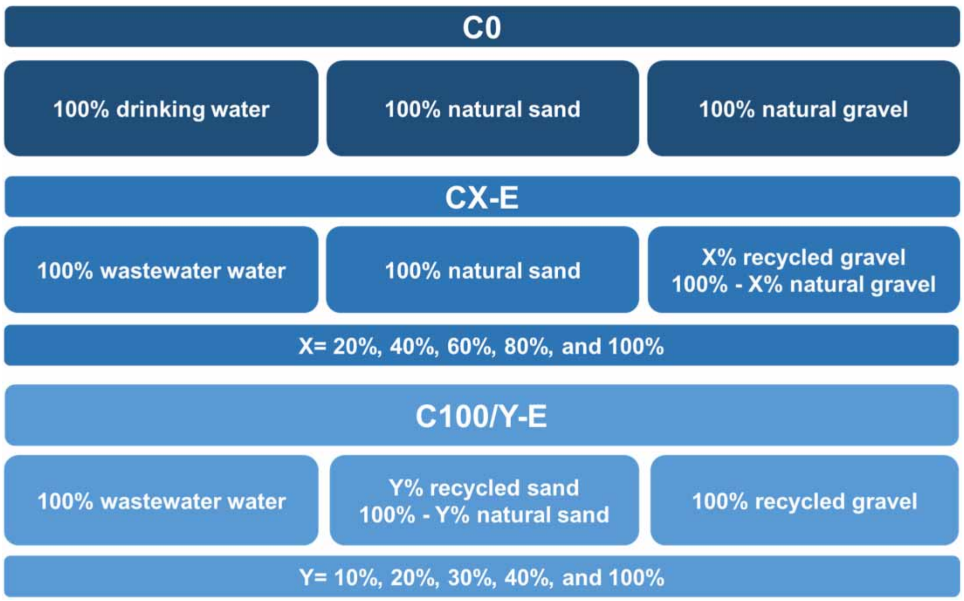


Figure 2 | Concrete families cast.

international standards provide recommendations regarding the utilization of alternative water sources, including specific guidelines outlining acceptable physical and chemical limits, as well as permissible variations in concrete properties such as compressive strength and setting time. Those recommendations are based on the threshold levels of substances that can have harmful effects on concrete. It is well known that chloride attacks the passive layer protecting steel reinforcement, leading to corrosion. Additionally, contact between concrete and high levels of sulfate can cause fissures and concrete disaggregation. Therefore, it is important to define safe concentrations of certain chemicals in the mixing water of concrete to ensure the production of a high-quality composite.

As demonstrated in Table 3, the effluent obtained from ETE Barão Geraldo exhibited physical and chemical properties that fell below the recommended limits outlined by Brazilian, British, and North American standards for concrete manufacturing, raising no concern about its influence over concrete strength and setting time. It is worth noting that the presence of total solids, which could potentially impact the mechanical and physical performance of cementitious composites, does not

Table 2 | Mix design of samples

Type	Cement (kg/m³)	Natural sand (kg/m³)	Fine mixed recycled aggregate (kg/m³)	Natural gravel (kg/m³)	Coarse mixed recycled aggregate (kg/m³)	Drinking water (L/m³)	Treated wastewater (L/m³)
C0	500	788.72	–	871.45	–	225	–
C0-E	500	788.72	–	871.45	–	–	225
C20-E	500	788.72	–	697.16	135.42	–	225
C40-E	500	788.72	–	522.87	270.84	–	225
C60-E	500	788.72	–	348.58	406.25	–	225
C80-E	500	788.72	–	174.29	541.67	–	225
C100-E	500	788.72	–	–	677.09	–	225
C100/10-E	500	708.85	72.54	–	677.09	–	225
C100/20-E	500	630.98	145.07	–	677.09	–	225
C100/30-E	500	552.10	217.61	–	677.09	–	225
C100/40-E	500	473.23	290.15	–	677.09	–	225
C100/100-E	500	–	725.37	–	677.09	–	225

Table 3 | Drinking water and treated wastewater quality and standard recommendations

Parameter	Drinking water[1]	Treated wastewater	Standards recommendation		
			Brazil (ABNT 2009b)	UK (BS 2002)	USA (ASTM 2012)
pH	6.73	8.00	≥5.00	≥4.00	–
Total alkalinity (mg $CaCO_3$ L^{-1})	14	306.16	≤2,422[2]	≤2,422[2]	≤600
Nitrate (mg NO_3-N L^{-1})	0.87	1.50	≤112.9[3]	≤112.9[3]	–
COD (mg L^{-1})	–	61	–	–	–
Total solids (mg L^{-1})	–	437	≤50,000	≤4 mL of sediments	≤50,000
Chloride (mg L^{-1})	50	98.05	≤500 (prestressed concrete or grout) ≤1,000 (reinforced concrete) ≤4,500 (without reinforcement)	≤500 (prestressed or grout) ≤1,000 (reinforced concrete) ≤4,500 (without reinforcement)	≤500 (prestressed or grout) ≤1,000 (reinforced concrete)
Zinc	0.009849	–	≤100	≤100	–
Lead	<0.0017	–	≤100	≤100	–
Phosphate		–	≤100	≤100	–
Sulfate	4.6	–	≤2,000	≤2,000	≤3,000

[1]Data taken from the water quality report provided by the public water supply company (SANASA).
[2]2,422 mg $CaCO_3$/L is equivalent to 1,500 mg Na_2O/L as determined by the standard.
[3]112.9 mg NO_3-N/L is equivalent to 500 mg NO_3-/L as determined by the standard.

raise concerns in this case. Although parameters, such as zinc, lead, phosphate, and sulfate, were not evaluated in this study due to technical limitations, Duarte *et al.* (2019) conducted an analysis of the same effluent from ETE Barão Geraldo and determined that these particular parameters remained well below the maximum levels suggested by the standards (BS 2002; ABNT 2009b; ASTM 2012). Albeit drinking water does not require testing prior to its use in concrete manufacturing, Table 4 presents its physicochemical properties to facilitate a comparison between the different types of water utilized in the study.

Other authors using secondary treated effluent also obtained quality parameters within the standard limits, such as Al-Ghusain & Terro (2003), Terro & Al-Ghusain (2003), Asadollahfardi *et al.* (2016), Ghrair & Al-Mashaqbeh (2016), Oliveira *et al.*

Table 4 | Physical properties of natural and recycled aggregates

	Fine		Coarse	
Property	**Natural**	**Recycled**	**Natural**	**Recycled**
Fineness modulus	2.72	2.34	–	–
Maximum aggregate size (mm)	–	–	12.50	12.50
Density (g/cm³)	2.577	2.370	–	–
Saturated surface-dry density (g/cm³)	–	–	2.929	2.412
Dry density (g/cm³)	–	–	2.883	2.240
Unit weight (kg/m³)	1,280.71	1,409.21	1,570.18	1,280.71
Saturated surface-dry unit weight (kg/m³)	1,379.45	1,553.75	1,595.39	1,379.45
Air-void ratio (%)	43	40	46	43
Water absorption (%)	0.66	10.26	1.61	7.71

(2016), Saxena & Tembhurkar (2019), Catanzaro *et al.* (2019), Tonetti *et al.* (2019), Hassani *et al.* (2020a), Ahmed *et al.* (2021) and Arooj *et al.* (2021). Although it is important to highlight that both the British and Brazilian standards do not advocate in favor of using treated wastewater to produce concrete, the North American standard does not explicitly expose any prohibition. However, due to the satisfactory results obtained by the present and the aforementioned authors, we should question these rejections and encourage future research since wastewater is a continuum source of water and reuse is becoming a necessity.

3.2. Aggregates characterization

The composition of the recycled aggregate, determined through visual segregation of the coarse fraction, was found to be as follows: 80.06% concrete and mortar, 8.32% asphalt, 8.66% bricks, 2.60% tiles, and 0.36% floating particles. Given that both the coarse and fine aggregates originate from the same source, and that the fine fraction was obtained by the simple crushing of the coarse fraction, it is considered that both fractions have a similar composition. In accordance with the classification proposed by Agrela *et al.* (2011), both fractions are considered as mixed recycled aggregates.

The sieve analysis of the aggregates revealed that both the natural and recycled aggregates exhibit a well-graded distribution, as depicted in Figure 3. Upon comparing the natural and recycled sand and gravel, it is evident that the recycled aggregates consist of finer particles, likely attributable to the inclusion of crushed ceramic and mortar wastes. The physical properties of the utilized aggregates are presented in Table 4. As anticipated, the recycled aggregates, both in fine and coarse forms, exhibited inferior properties when compared with the natural aggregates, which can be attributed to the presence of

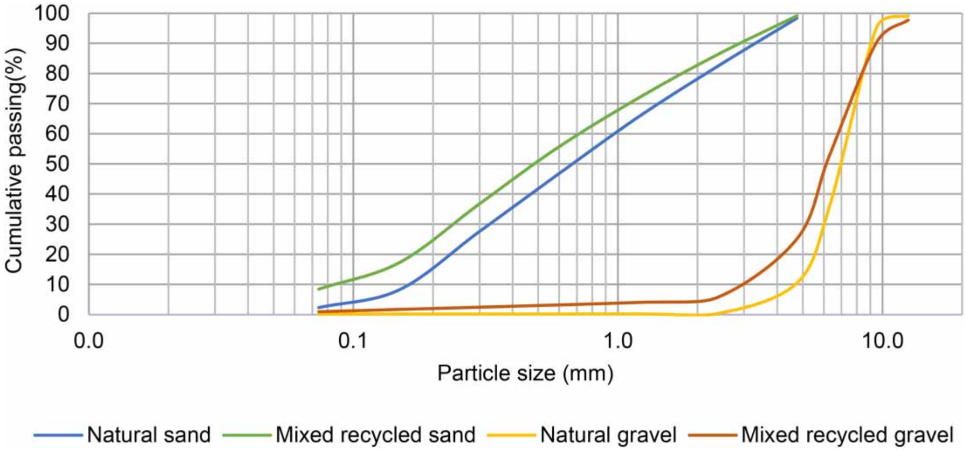


Figure 3 | Fine and coarse aggregate sieve analysis results.

impurities, finer particles, and their porous microstructure. It is worth noting that the water absorption of fine and coarse recycled aggregates is, respectively, 15.5 and 4.8 times higher than that of natural ones. The presence of old adhered materials, which have micro-cracks and pores, and ceramic materials, which are naturally more porous than natural rocks explain the higher water absorption rates of MRA (Salgado & Silva 2022).

3.3. Setting time

The cement paste prepared using drinking water and treated wastewater achieved the normal consistency with the same water-to-cement ratio of 0.32, consistent with the findings reported by Lee *et al.* (2001). The initial and final setting times using drinking water were 2 h 49 min and 3 h 47 min, respectively. When using treated wastewater, the initial and final setting times were 2 h 57 min and 3 h 50 min, respectively. Then, the incorporation of treated wastewater resulted in an 8-min delay in the initial setting time and a 3-min delay in the final setting time. However, it is important to note that these delays remained within the acceptable limits specified by the American (ASTM 2012), British (BS 2002), and Brazilian (ABNT 2009b) standards.

Similar findings were reported by Tay (1989), Lee *et al.* (2001), Ghrair & Al-Mashaqbeh (2016), Brandão *et al.* (2019), Catanzaro *et al.* (2019), and Ahmed *et al.* (2021), which corroborate the observed delays in setting times. These delays were expected due to the presence of residual materials, which can inhibit the hydration of C_3A and subsequently impede the development of ettringite, resulting in prolonged setting times (Asadollahfardi *et al.* 2016; Peighambarzadeh *et al.* 2020; Abushanab & Alnahhal 2021; Bouaich *et al.* 2022). Comparing wastewater from different treatment levels, Al-Ghusain & Terro (2003), Ghrair & Al-Mashaqbeh (2016), and Terro & Al-Ghusain (2003) observed that the lower the treatment level, the greater the delay in cement paste setting time. However, Bouaich *et al.* (2022) emphasize that these delays can be advantageous in hot weather conditions and for concreting projects involving long distances and large volumes.

3.4. Consistency

Figure 4 presents the consistency results obtained for each mix design. A comparison between the C0 and CX-E families reveals a decrease ranging from 7.3 to 15.1% due to the utilization of treated wastewater and various percentages of

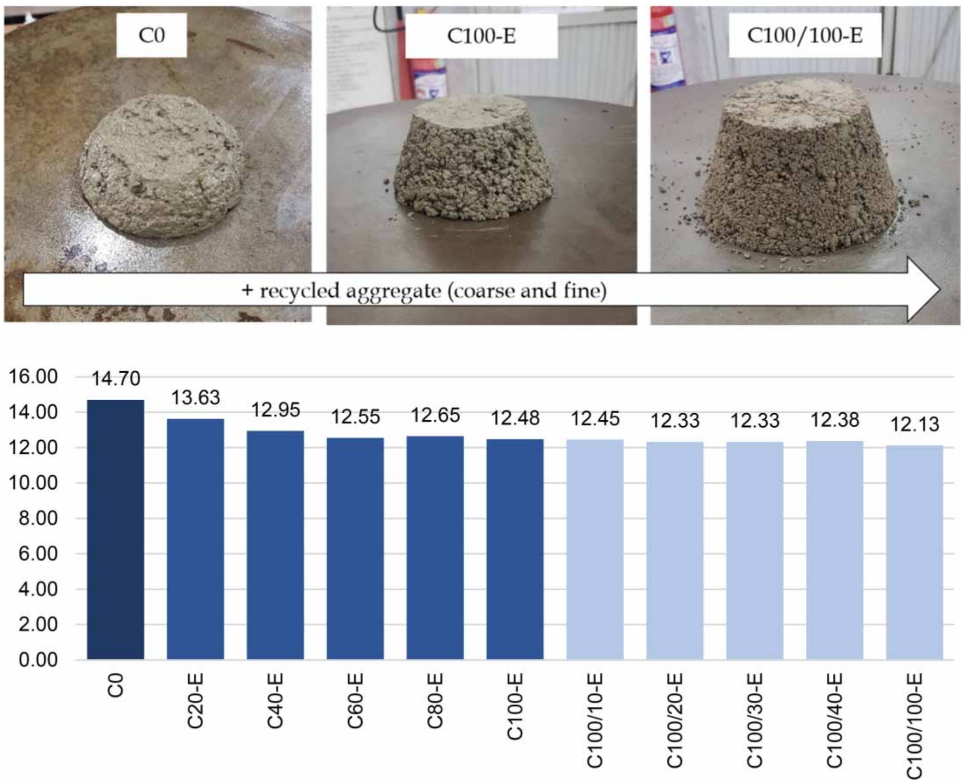


Figure 4 | Concrete's consistency results, values in cm.

mixed recycled coarse aggregate. On the other hand, when comparing the C0 and C100/Y-E families, significantly higher declines of 15.3–17.5% are observed. These reductions in consistency were anticipated, as there has been considerable discussion regarding the loss of consistency resulting from the incorporation of treated wastewater (Shekarchi *et al.* 2012; Ghrair & Al-Mashaqbeh 2016; Ghrair *et al.* 2018) and recycled aggregates (Martínez-Lage *et al.* 2012; Mas *et al.* 2012; Lima *et al.* 2013; Cartuxo *et al.* 2015).

The decrease observed when using treated wastewater can likely be attributed to the spongy surface of residual sludge particles, which have a tendency to absorb water. This absorption reduces the availability of free water and negatively affects the consistency of the mixture (Meena & Luhar 2019; Bouaich *et al.* 2022). Similarly, the use of recycled aggregates, characterized by their inherently higher porosity, rough and irregular surfaces, can result in the absorption of free water to fill the pores, contributing to a decrease in consistency (Agrela *et al.* 2011; Lima *et al.* 2013; Silva *et al.* 2014; Cartuxo *et al.* 2015). The dry consistency, in turn, affects the effective compaction of samples, leading to the formation of voids. Consequently, this results in concrete with reduced resistance and durability. Although it is common practice to pre-saturate aggregates or use admixtures or additional water to mitigate workability loss, the present study did not employ any of these methods in order to evaluate the natural variation in consistency resulting from the combined use of alternative materials.

It is noteworthy that the utilization of treated wastewater and increasing proportions of recycled aggregate led to a noticeable reduction in consistency. However, it is important to emphasize that compaction difficulties were observed exclusively in the samples of mix C100/100-E. This issue is attributed to the complete replacement with recycled aggregates, which have significantly higher water absorption compared with natural aggregates (see Table 3). This high absorption reduces the amount of free water available, resulting in an excessively dry consistency.

3.5. Compressive strength

The compressive strength development over 7, 28, and 90 days for each mix is illustrated in Figure 5. In general, all types of concrete exhibited an increase in compressive strength over time, except for the C100/100-E mix, which demonstrated a localized drop at 28 days. This unexpected behavior may be attributed to the recycled aggregates used in this mix, which have inherent variability and greater water absorption, which impacts concrete strength. It is important to note that the most substantial strength gains occurred between 0 and 7 days, primarily due to the utilization of high early-strength cement. After 28 days, the majority of the samples did not exhibit significant enhancements in strength.

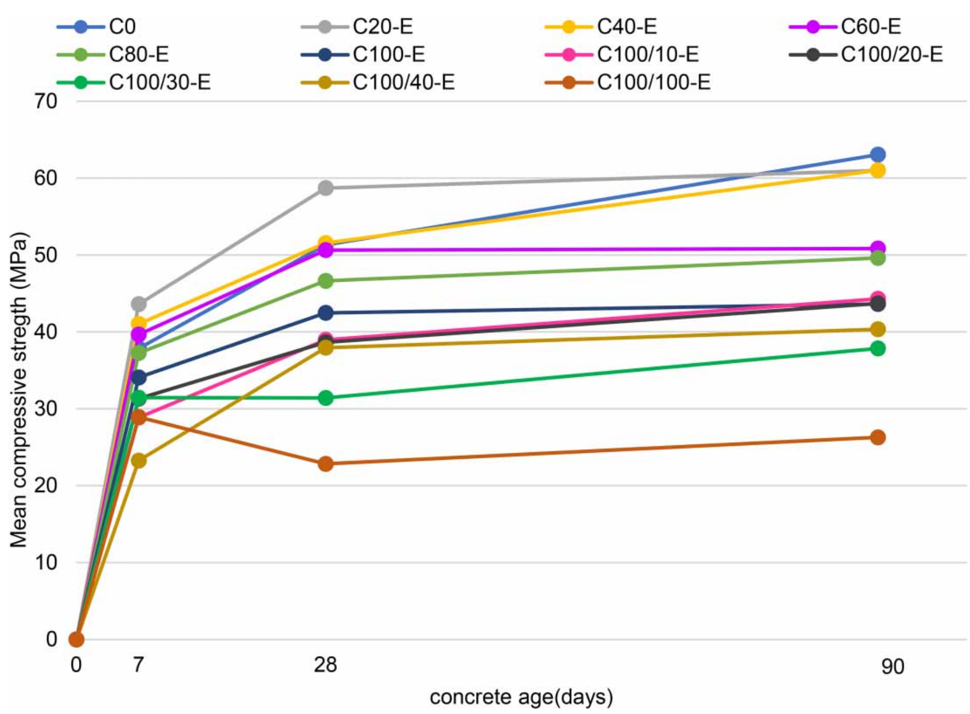


Figure 5 | Mean compressive strength for the C0, CX-E, and C100/Y-E groups at 7, 28, and 90 days.

When compared with the control group (refer to Figure 5), the mean compressive strength of the CX-E mixes exhibited a range of +15.2 to −10.0%, +14.4 to −17.2%, and −3.3 to −30.8% at 7, 28, and 90 days, respectively. On the other hand, the C100/Y-E mixes demonstrated higher variations, ranging from −23.7 to −38.5%, −24.0 to −55.5%, and −29.7 to −57.4% at 7, 28, and 90 days, respectively. A noticeable trend was observed, indicating a decrease in concrete strength with a higher rate of aggregate substitution. However, all CX-E mixes achieved mean compressive strength results ranging between 43 and 61 MPa after 90 days. Among the C100/Y-E mixes, only C100/10-E and C100/20-E exhibited strength values exceeding 43 MPa at the same age.

The role of aggregate and water substitution on concrete strength in the current experiment may be also commented on. It is widely acknowledged in the existing literature that the use of recycled aggregates does not enhance this property due to the formation of a weak and complex interfacial transition zone, as well as its high water absorption, which compromises cement hydration and mechanical performance (Xiao *et al.* 2012; Agrela *et al.* 2013). However, Jiang *et al.* (2019) argue that fine particles can have a positive effect on replacements up to 50%, depending on the composition of the aggregates. In fact, by comparing the results of C100-E and C100/Y-E at 90 days, where the only difference lies in the use of recycled sand, it becomes apparent that fine aggregate replacements up to 20% had a positive effect on compressive strength.

Regarding the effect of treated wastewater on concrete strength, there is a divergence of opinions among researchers, enhancing the need for further investigation. Some authors argue that the presence of residual organic compounds has detrimental effects on compressive strength since it could have an effect over cement hydration and as a consequence on setting time and strength (Asadollahfardi *et al.* 2016; Ahmadi *et al.* 2017; Asadollahfardi & Mahdavi 2018; Catanzaro *et al.* 2019; Hassani *et al.* 2020a; Yahyaei *et al.* 2020). On the other hand, there are those who defend that the presence of residual organic solids and microorganisms can fill the voids and create effective interfacial interaction, thereby enhancing its performance (Swami *et al.* 2015; Oliveira *et al.* 2016).

The results depicted in Figure 5 demonstrate a decrease in the average strength of concrete as the level of aggregate substitution increases, aligning with findings from previous studies. All samples (except the control) had the effect of wastewater addition, which means that it is not immediately clear if it had a damaging or beneficial effect. Then, in further research, it might be necessary to investigate the individual and the interaction effect of treated wastewater and recycled aggregate aiming to clarify if the decline caused in compressive strength is associated with the use of only one or with both alternative materials.

Either way, the total effect (individual effects plus their possible interaction) of both parameters is compared with the control group in the current experiments. It is noteworthy to comment that the above-mentioned resistance results are compatible with several concrete applications, although it is essential to ensure its appropriate durability to guarantee safe utilization. This strength behavior is like those observed in several studies that used both wastewater and aggregate substitution: a general trend in mean concrete strength reduction (Elchalakani & Elgaali 2012; Ramírez-Tenjhay *et al.* 2016; Elchalakani *et al.* 2017; Ahmed *et al.* 2021; Raza *et al.* 2021). The mean strength decrease, evidently, varies between those studies, as many aspects (aggregate amount, size and type, wastewater quality, concrete mix design, cement type, and others) might have an influence over concrete's mechanical performance.

Nevertheless, it is important to note that the presented compressive strength results for each mix represent an average derived from five samples, indicating a range of outcomes. Consequently, in order to discern whether the discrepancies observed in the compressive strength results stem from natural variability or significant differences attributed to the various replacements tested, an ANOVA and *post hoc* Dunnet's test were conducted.

The analysis compared the effect of treated wastewater and coarse aggregate (CX-E versus C0) and treated wastewater and coarse and fine aggregate (C100/Y-E versus C0) replacements over compressive strength performance. Regarding the CX-E and C0 comparison, at 7 days, no statistically significant difference between the groups and the control sample was detected. As for 28-day results, coarse aggregate replacements of 20, 80, and 100% induced statistically significant differences, while at 90 days the same tendency was observed for substitutions exceeding 40%.

As for the C100/Y-E and C0 comparisons, the joint influence of drinking water, recycled coarse aggregate, and different ratios of natural fine aggregate were assessed. As anticipated, the presence of fine recycled aggregate and its higher water absorption led to a considerable decrease in compressive strength. After 28 and 90 days, all groups exhibited a statistically significant difference compared with C0, while at 7 days, only the groups C100/20-E and C100/30-E did not follow the same tendency.

3.6. Splitting tensile strength

Figure 6 displays the splitting tensile strength of all concrete mixes at 7 and 28 days. Like the behavior observed in compressive strength, significant strength gains were observed between 0 and 7 days for all concrete types. At 7 days, all mixes demonstrated superior results compared with C0, with improvements ranging from +4.7 to +19.4%, except for C60-E, C100/30-E, and C100/100-E, which exhibited slightly lower values, although after 28 days, all mixes had lower splitting tensile strength than the control. Regarding family CX-E, the decreases varied from −10.8 to −18.0%, and no trend was observed, since C20-E and C100-E had almost the same strength, despite the common knowledge that higher amounts of coarse recycled aggregates cause higher drops in splitting tensile strength (Silva *et al.* 2015). The present authors attributed this variation to the inherent recycled aggregate variability and proposed that the C100-E samples were probably cast with a fraction of aggregate with a high content of more resistant components, such as concrete and unbound aggregates.

In comparison with the control, the C100/Y-E mixes exhibited varying effects on splitting tensile strength at 28 days. Fine aggregate replacements ranging from 10 to 40% resulted in relatively lower reductions in strength (−4.0 to −16.2%), while a complete replacement of fine aggregate caused a significant decrease of −40.2%. Notably, no distinct trend was observed for higher proportions of fine recycled aggregate in this group. It is worth mentioning that C100/10-E and C100/40-E showed better results than C100-E. These findings align with the reports of previous studies (Gonzalez-Corominas & Etxeberria 2014; Bravo *et al.* 2015; Etxeberria & Vegas 2015; Etxeberria & Gonzalez-Corominas 2018; Plaza *et al.* 2021), which suggest that fine aggregate replacements up to 50% may lead to either increases or slight reductions in splitting tensile strength. This behavior is likely attributed to pozzolanic reactions, and the internal curing effect facilitated by ceramic waste, which contribute to a more efficient transition zone (Gonzalez-Corominas & Etxeberria 2014; Etxeberria & Vegas 2015). However, higher proportions of very fine recycled aggregate can compromise the cohesion between cement paste and aggregates, necessitate more water to maintain workability, and result in a more porous and less resistant concrete (Bravo *et al.* 2015) as observed in the C100/100-E mix.

Notwithstanding, the splitting tensile results for each mix are an average of five samples, so there is a range of data. ANOVA and Dunnett's test results comparing CX-E and C100/Y-E families with control C0 showed that, at 7 days, neither mix was statistically different from C0, while at 28 days only C80-E, C100/20-E, and C100/100-E were.

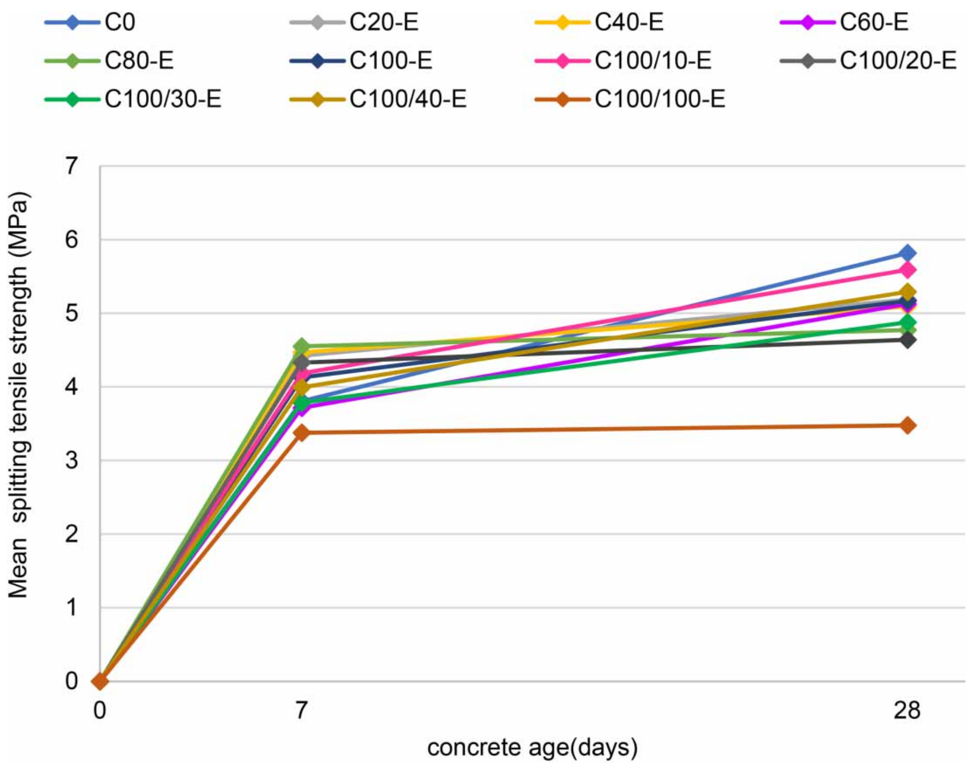


Figure 6 | Mean splitting tensile strength for the C0, CX-E, and C100/Y-E groups at 7, 28, and 90 days.

3.7. Water absorption and air-void ratio

Figure 7 presents the results of water absorption and air-void ratio for all mixes. In the CX-E family, it is evident that the incorporation of treated wastewater and increased coarse aggregate replacement resulted in notable increases that in a certain extent can be tolerated. The water absorption and air-void ratio showed varying increments ranging from +4.7 to +19.8% and +3.4 to +11.9%, respectively. In the C100/Y-E mixes, the presence of recycled fine aggregate led to even higher increases: +21.7 to +70.8% for water absorption and +12.1 to +49.5% for air-void ratio. The ANOVA and Dunnett's test results indicate that while CX-E mixes demonstrated statistically significant differences in water absorption and air-void ratio for replacements exceeding 40%, all C100/Y-E mixes exhibited statistically significant differences for both properties.

The results clearly demonstrate that the detrimental effects on water absorption and air-void ratio were more pronounced with higher proportions of recycled aggregates, with the C100/100-E mix exhibiting the poorest performance. This outcome aligns with the understanding that the physical properties of concrete are closely linked to the physical properties of the aggregates used. However, the influence of water quality on the air-void ratio and water absorption remains a topic of debate.

Some studies such as Ghrair & Al-Mashaqbeh (2016), Asadollahfardi & Mahdavi (2018), Brandão *et al.* (2019) and Gulamussen *et al.* (2021) reported lower air voids and water absorption in concretes incorporating treated wastewater. However, it is widely believed that impurities in wastewater can absorb water, subsequently affecting the formation of crystals and gels and resulting in a porous structure. This viewpoint is supported by studies conducted by Hassani *et al.* (2020a, 2020b), Raza *et al.* (2020, 2021), and Seyyedalipour *et al.* (2015).

Therefore, it is crucial to ascertain whether the observed decreases in water absorption and air-void ratio are from the combined effect of using alternative materials, as suggested by Elchalakani & Elgaali (2012), or if the effects of wastewater are variable and not substantial, with the reductions primarily associated with the utilization of recycled aggregates, as proposed by Raza *et al.* (2021). Further investigation is needed to shed light on this matter.

3.8. Density

The dry, saturated, and true density values for each mix are presented in Figure 8. It is well established that the density of concrete is directly influenced by the densities of its aggregates. Therefore, when natural aggregates are replaced with recycled aggregates having lower specific mass, it is expected that the resulting concrete will have reduced density, as observed in studies conducted by Martínez-Lage *et al.* (2012), Mas *et al.* (2012), Medina *et al.* (2015) and Cantero *et al.* (2019). Regarding

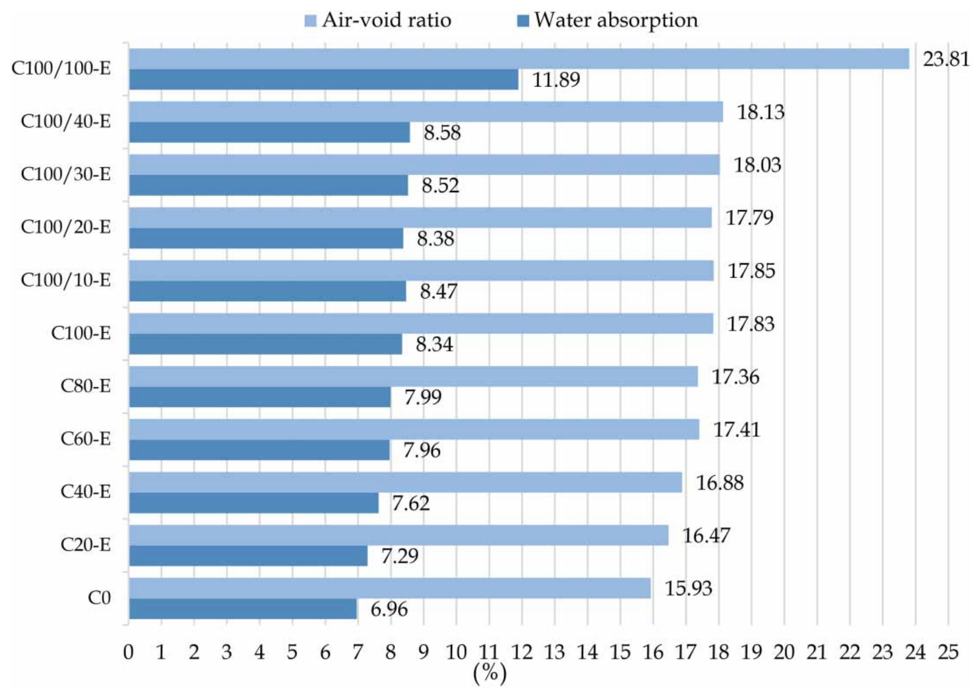


Figure 7 | Mean water absorption and air-void ratio of the C0, CX-E, and C100/Y-E groups.

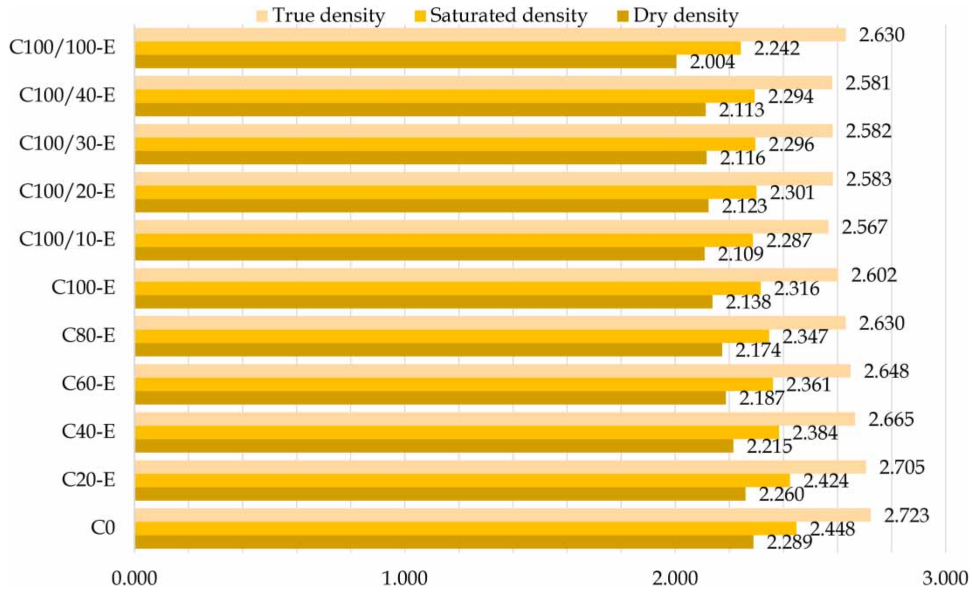


Figure 8 | Mean dry, saturated, and real density of the C0, CX-E, and C100/Y-E groups, values in g/cm^3.

the use of treated wastewater, although the presence of residual solids may slightly enhance the density of wastewater compared with drinking water, the literature consistently indicates that even for poorly treated wastewater, the variation in density is negligible (Almeida & Tonetti 2022).

When comparing the CX-E and C100/Y-E families with the C0 reference, it is evident that the combined use of treated wastewater and mixed recycled aggregates, both coarse and fine, had a detrimental effect on the density property. The observed decreases ranged from −1.3 to −12.5%, with the highest reductions observed in the case of complete replacement of natural materials. Similarly, the saturated density showed variations in the range of −1.0 to −8.4%, while the true density exhibited variations from −0.7 to −5.7%. Despite those results, depending on the concrete's usage, the density reduction might not be considered a disadvantage. The ANOVA and Dunnett's test results indicate that only the C20-E mix did not show statistically significant differences in dry, saturated, and true density when compared with the C0 reference.

4. CONCLUSION

This research is significant because it addresses a gap in the existing literature about the use of both recycled aggregates and treated wastewater in concrete manufacturing. In summary, concrete with acceptable physical and mechanical properties was produced while using recycled aggregates from CDW and treated wastewater from a municipal sewage treatment plant as a source of water. As expected, the characterization of MRA revealed inferior properties compared with natural aggregates, while the quality of treated wastewater aligns with standard requirements for concrete manufacturing.

Our analysis also revealed that the use of treated wastewater caused a slight effect over the initial and final setting times. Concrete's consistency was negatively impacted by the replacement of natural aggregates, although only the C100/100-E mix displayed a significantly dry consistency, leading to difficulties during the casting process. Reflecting on the data presented, it becomes clear that the replacement of natural materials with recycled ones had a detrimental effect on concrete's mechanical properties. Compressive strength decreased with the substitution of drinking water and increasing amounts of coarse MRA and after 90 days, only the C20-E and C40-E mixes did not show statistically significant differences compared with the control (C0). In addition, at 90 days of age, the inclusion of small amounts of fine recycled aggregate (up to 20%) had a positive effect on this property. Regardless, the mean compressive strength results ranged between 26 and 63 MPa, and except for C100/100-E, all samples achieved compressive strength over 35 MPa, which enables the use of this type of concrete for several applications.

The mean splitting tensile strength at 7 days for the CX-E and C100/Y-E families exceeded that of the control sample. However, after 28 days, all samples exhibited lower results, with only the C80-E, C100/20-E, and C100/100-E mixes showing statistically significant differences. As for physical properties: water absorption, air-void ratio, and density experienced poorer outcomes when natural aggregates and drinking water were replaced with alternative materials.

The importance of this study lies in its potential to pave the way for a more conscious civil construction industry, as evidenced by the positive results achieved and the potential for conserving natural resources for more essential purposes. To further promote the use of concrete made with alternative materials, future research should focus on evaluating the durability properties and concrete-steel interaction to ensure the safety of using recycled materials concrete for structural purposes. In addition, it is important to understand the opinions of both the industry and consumers regarding this practice. Finally, it is important to highlight that all tests were conducted for research purposes and activities with different purposes should comply with current regional laws and standards.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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