Structural cementitious composites produced with fine recycled aggregate from concrete/ceramics wastes

Compósitos cimentícios estruturais produzidos com agregado reciclado miúdo de resíduos de concreto/cerâmica

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Abstract

This paper aims to evaluate selected properties of structural cementitious composites with fine recycled aggregate as a replacement of natural sand. Mortars were produced with mixed recycled aggregate (sourced from concrete/ceramics wastes) in contents up to 40%, without pre-wetting or additional water. Experimental investigation results were contrasted with updated literature in terms of consistency in fresh state, mechanical strength, porosity, water absorption, and shrinkage. The results showed that despite of 20% reduction in workability, compressive strength is not affected by incorporation of fine recycled aggregate, reaching values above 50 MPa at 28 days. The optimal content around 40% of fine recycled aggregate can keep porosity, water absorption and flexural strength at the same level of the reference sample. Drying and autogenous shrinkages are reduced up to 15% by the presence of fine recycled aggregate, which acts as internal curing agent for mortars with CP V-ARI and same water/cement ratio. Thus, new possibilities for pre-cast concrete and cementitious artefacts industries are indicated.

Keywords: Construction and demolition waste. Mortars. Fine recycled aggregate.

Resumo

Este trabalho tem como objetivo avaliar propriedades selecionadas de compósitos cimentícios estruturais com agregado miúdo reciclado em substituição à areia natural. As argamassas foram produzidas com agregados reciclados mistos (provenientes de resíduos de concreto/cerâmica) em teores de até 40%, sem pré-molhagem ou compensação de água. Os resultados da investigação experimental foram contrastados com a literatura atualizada em termos de consistência no estado fresco, resistência mecânica, porosidade, absorção de água e retração. Os resultados mostraram que apesar da redução de 20% na trabalhabilidade, a resistência à compressão não é afetada pela incorporação do agregado miúdo reciclado, atingindo valores acima de 50 MPa aos 28 dias. O teor ótimo em torno de 40% de agregado miúdo reciclado pode manter a porosidade, absorção de água e resistência à flexão no mesmo nível da amostra de referência. As retrações de secagem e autógenas são reduzidas em até 15% pela presença de agregado miúdo reciclado, que atua como agente de cura interna para argamassas com CP V-ARI e mesma relação água/cimento. Assim, são indicadas novas possibilidades para indústrias de concreto pré-fabricados e artefatos cimentícios.

Palavras-chave: *Resíduo de construção e demolição. Argamassas. Agregado reciclado miúdo.*

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Introduction

Construction industry represents about 3.2% of GDP and employs 5.9% of formal workers in Brazil (CBIC, 2021). However, its high demand for construction materials leads to severe environmental impact caused by exploitation of natural resources and significant generation of solid waste. In 2021, more than 48 tons of construction and demolition wastes (CDW) were collected in Brazilian cities (ABRELPE, 2022). This material, in turn, has a great potential to be incorporated in cementitious composites, which has been widely used as eco-friendly alternative aggregates for concrete and mortar productions (Jiménez *et al*., 2013; Santos; Cabral, 2020; Silva *et al.*, 2015; Gomes *et al.*, 2015; Lima *et al*, 2020). This solution reduces extraction of natural raw materials and gives a rational application for construction and demolition wastes which could be ended up in landfills or natural landscapes.

According to Brazilian standard NBR 15116 (ABNT, 2021), recycled aggregates can be classified in three types, depending on their main composition: concrete residue, cementitious residue (including concrete, mortars, blocks, etc.), and mixed residue (formed by cementitious materials and clay-based ceramics). To better comprehension of the terminology by the international community, the term “concrete/ceramic waste” is adopted in this paper to refer to “mixed residue”. When recycled aggregate is used for production of non-structural concrete, any type and any content can be incorporated. However, for structural applications, only concrete residue is allowed to be used. Moreover, substitution of natural aggregate by recycled aggregate should be limited to 20% (by mass of aggregates) and applied in structures located in low and moderate aggressive environments (ABNT, 2021; CONAMA, 2002).

It is a well-known fact that performance of final product (concrete and mortars) depends on the type of recycled aggregate, methods of recycling process, and protocol of production of new composite materials. Currently, several investigations are focused on utilization of CDW as coarse aggregate for concrete (Zhou; Chen, 2017; Datta *et al.*, 2022; Alberte; Handro, 2021; Kazmierczak *et al.*, 2019; Silva *et al.*, 2015), which can be related to the importance in terms of volume occupied by this fraction in a concrete composition. However, only a few studies are focused on the fine portion of recycled aggregate to be used either in concrete or mortars. This scarcity of research is primarily attributed to challenges associated with reintroducing fine CDW into construction market, including its high-water absorption and potential presence of contaminants (Ulsen *et al*., 2021; Santos; Cabral, 2020). Although the presence of contaminants is more significant in coarse aggregates because their volume, finer particles have high surface area which can also contaminates coarser fraction of recycled aggregate, affecting the fresh and hardened state properties of cementitious composites. In an attempt to mitigate this problem, adopting methods for pre-wetting recycled aggregates or using of extra water to compensate loss of workability by incorporation of fine CDW has been a common practice. Nevertheless, this may lead to negative effects on phyco-mechanical properties of cementitious composites, such as increase of porosity and reduction of strength (Letelier *et al.*, 2021; Morón *et al.*, 2021; Mora-Ortiz *et al.*, 2022; Wu; Wang, 2022).

However, this approach is still uncertain and inconclusive, as there is a lack of studies that considers the production of structural composites without any additional water by incorporation of CDW. This becomes even more unclear when the fine portion of mixed recycled aggregate (sourced from concrete/ceramics residues) is used in contents above 20%.

In this context, the present paper aims to evaluate the fresh and hardened state properties of structural cementitious composites produced with fine recycled aggregate derived from concrete/ceramic wastes. They were used as a replacement of natural sand in contents up to 40%, without pre-wetting or additional water. Experimental investigation results were contrasted with updated literature in terms of consistency in fresh state, mechanical strength, porosity, water absorption, and drying and autogenous shrinkages.

Methodology

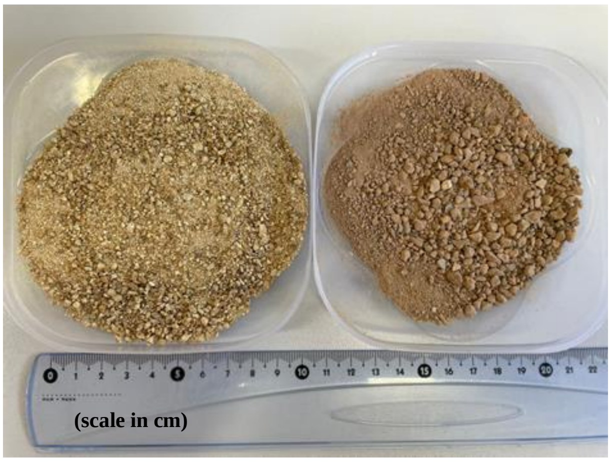
A high early strength Portland cement containing 90-100% in mass of clinker + calcium sulphate (CPV-ARI) was used (Table 1). A superplasticizer PowerFlow 4000 MC (MC Bauchemie) was adopted to obtain mortars with plastic consistency.

Natural quartz sand was commercially obtained and used as conventional fine aggregate. Recycled fine aggregate was supplied by Urban Cleaning Superintendency (SLU) of Belo Horizonte (state of Minas Gerais, Brazil), sourced from grinding of blended construction and demolition wastes (CDW), and characterized according to NBR 15116 (ABNT, 2021). Figure 1 shows both fine aggregates used in this research.

Table 1 **- Characteristics of Portland cement (CP V-ARI) (source: manufacturer)**

Property	Value
Specific mass	2.97 g/cm³
Surface area (Blaine)	4.888 cm²/g
Initial setting time	143 min
Final setting time	179 min
Compressive strength at 7 days	41.2 MPa

Figure 1 **- Fine aggregates used in the experimental program: (a) natural sand, and (b) recycled fine aggregate**



(a) (b)

Table 2 shows composition of fine recycled aggregate, which was basically composed by a blend of fragments derived from cementitious materials (pastes, mortars and concrete), rocks (from concrete´s aggregates) and clay-based ceramics. Figure 2 shows micrographs of typical particles of fine aggregates used in this study, obtained by the optical microscope. It is observed that recycled aggregates display more pores than natural sand (quartz), as indicated by yellow arrows.

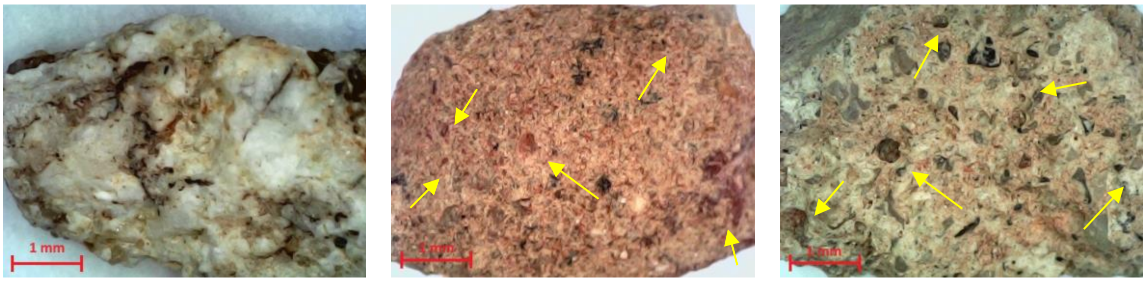
Table 3 shows physical characteristics of natural sand and recycled fine aggregate. Figure 3 shows particle size distribution of both fine aggregates used in this research, and they mostly fit within the optimal zone of limits recommended by NBR 7211 (ABNT, 2009).

Cementitious mortars were produced in the proportion of 1:2 (cement : fine aggregate), by mass. For fine aggregate, natural sand was replaced by fine recycled aggregate in contents of 0% (reference), 20% and 40% (by volume). A water/cement (w/c) ratio of 0.42 was adopted for all mixes, using 1% of superplasticizer additive (Aïtcin, 2015). Both aggregates were used in dry conditions, and recycled sand was not pre-wetting prior mixing, i.e., no additional water was used in the mix to compensate the higher water absorption of recycled aggregate (as seen in Table 3) and eventual loss of workability of mortars. Table 4 shows quantity of materials necessary to produce 1 m³ of mortar.

Table 2 - **Composition of recycled fine aggregate (CDW)**

Type of material	Composition (%)
Fragments of cementitious materials	50.26
Fragments of rocks	26.92
Fragments of clay-based ceramics	25.56
Others	0.26

Figure 2 - **Micrographs of particles of fine aggregates obtained by optical microscope: (a) natural sand (quartz), (b) clay-based ceramic, (c) cementitious mortar - Yellow arrows indicate some observed pores**



(a) (b) (c)

Table 3 - **Physical characteristics of fine aggregates**

Property	Natural sand	Recycled fine aggregate (CDW)
Water absorption (%)	1.84	9.99
Powder material content (< 75 µm) (%)	4.49	13.29
Maximum dimension (mm)	2.36	4.75
Fineness modulus	2.31	2.22
Density (dry condition) (g/cm³)	2.08	1.83
Density (saturated condition) (g/cm³)	2.12	2.02

Figure 3 - **Particle size distribution of recycled and natural sands (usable and optimal zone limits defined according to NBR 7211 (ABNT, 2009)**

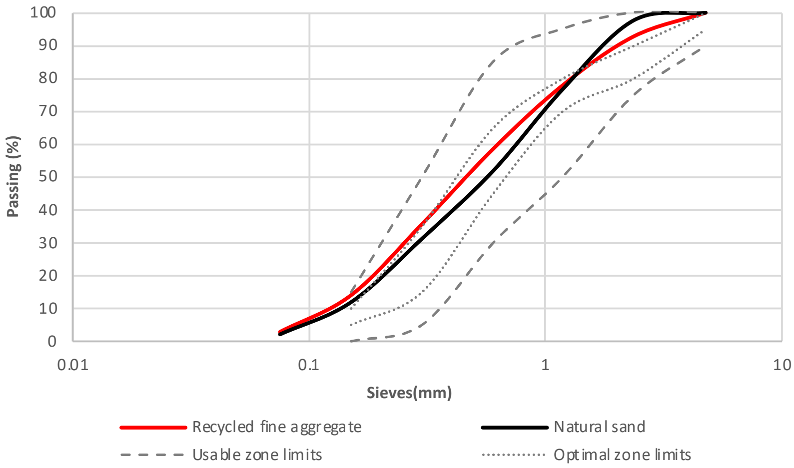


Table 4 - **Quantity of material (in mass) to produce 1m³ of mortar**

Sample	Cement (kg/m³)	Natural sand (kg/m³)	Recycled sand (kg/m³)	Additive (kg/m³)	Water (kg/m³)	Total w/c ratio
CPV - R	579.68	1159.36	0	5.80	243.46	0.42
CPV - 20	579.68	927.48	204.07	5.80	243.46	0.42
CPV - 40	579.68	695.61	408.13	5.80	243.46	0.42

Mixing procedures for cementitious composites were based on Pedro, de Brito and Evangelista (2017) and Bravo *et al.* (2018), according to NBR 7215 (ABNT, 2019) and NBR 15116 (ABNT, 2021). The adopted procedure is in line with Silva Neto *et al.* (2020, 2022). Mixing steps are described below:

(a) all aggregates, i.e., natural sand and recycled fine aggregate (if any), and 2/3 of water were added in the mixing bowl; and

(b) mixing was initiated in low speed for 120 seconds to allow water absorption by aggregates;

(c) Mixer was turned off for 30 seconds to add cement and 1/3 of water with superplasticizer;

(d) Mixing was resumed in low speed for 90 seconds;

(e) Mixer was turned off for 30 seconds to scratch mortar from bowl wall; and

(f) Mixing was resumed in high speed for 180 seconds.

Prismatic and cylindrical specimens were casted using a vibrating table and cured in air under laboratory conditions until the age of test. Consistency of fresh state mortars was evaluated by the flow table test, as recommended by NBR 13276 (ABNT, 2020).

Mechanical properties were assessed by flexural and compressive strength tests at 7, 28 and 91 days, following NBR 13279 (ABNT, 2005b). The test was performed by a Shimadzu Autograph press, model AGS-X, with maximum capacity of 300 KN and loading rate of 0.45 ± 0.15 MPa/s. Three prismatic specimens (4 x 4 x 16 cm^3) for each mortar and each age were subjected to flexural test. The six halves were then subjected to compressive test.

For analysis of physical properties, open porosity and water absorption by immersion test (Archimedes principle) was assessed according to NBR 9778 (ABNT, 2005b). Water absorption by capillary rise was evaluated by measurements at 3, 6, 24, 48 e 72 hours, as specified in NBR 9779 (ABNT, 2005a). All tests were carried out in triplicate using cylindrical specimens (5 cm diameter, 10 cm height) at 28 and 91 days.

Drying shrinkage was tested in non-sealed prismatic samples (2.5 x 2.5 x 30 cm^3) based on NBR 15261 (ABNT, 20205b). The measurements were obtained by using a digital bench dilatometer at 7, 9, 11, 14, 21 and 28 days, followed by weekly measures up to 120 days. For autogenous shrinkage, the same procedure was adopted, but samples were sealed with aluminum foil and paraffin coat to avoid loss of water, according to procedure used by Melo Neto, Cincotto and Repette (2008). All tests were carried out in triplicate.

Results and discussions

Consistency in the fresh state

Table 5 shows results of consistency (by flow table test) of the fresh state mortars with and without recycled aggregate.

Incorporation of 20% and 40% of fine CDW significantly reduced consistency values of fresh state mortars, in the order of 17% and 20% in relation to the reference sample, respectively. This is due to higher porosity and increased amount of powder material (< 75 μm) in recycled aggregate, as showed in Figure 2 and Table 3. Finer particles with higher surface area increase water demand in mortar production. It is important to note that no pre-wetting of recycled aggregate or additional water was used in mortar production. Although all samples used the same total w/c ratio, the effective w/c ratio is lower for mortars with CDW, which results in lower values of consistency index. However, this difference was not significant when mortars with different contents (20% and 40%) of fine recycled aggregate were compared.

Table 5 - **Flow Table test results**

Sample	Flow values (mm)
CPV - R	175 ± 10
CPV - 20	145 ± 10
CPV - 40	140 ± 10

Therefore, this outcome of reduced workability by CDW incorporation was already expected, as investigated by other authors. Dang *et al*. (2018) and Vaishnav and Trivedi (2022) evaluated consistency of fresh state mortars using recycled aggregates from clay and concrete bricks, respectively. The authors observed an increase of this property as the content of fine CDW was increased up to 100%. This was attributed to greater porosity of recycled aggregate, which absorbs more mixing water and, consequently, reduces workability of mortars. However, the mentioned authors affirms that this effect of reduced workability can be minimized by using higher contents of superplasticizer (to disperse finer particles) or pre-wetting recycled aggregates (to compensate water absorption).

Mechanical strength

Mechanical properties were evaluated through compressive and flexural strength tests. Results of compressive strength up to 91 days are shown in Figure 4.

Incorporation of CDW as fine recycled aggregate had little influence in compressive strength of the composites assessed in the different ages. Overall average changed from around 50 MPa (at 7 days) to 55 MPa (at 91 days). This can be attributed to high early-strength Portland cement used in this experimental program.

Moreover, no significant variations were observed in compressive strength results considering different mortars at the same age. The maximum spread of result was around 6%, 2% and 3%, respectively for 7, 28 and 91 days of curing, all values within the standard deviation. This shows that mortars with and without CDW incorporation have similar behavior, regardless the age of testing. It is valid to remember that all samples were produced with the same total w/c ratio. This means that effective w/c ratio is lower for CDW samples, since they absorb part of mixing water. Thus, even with a higher porosity (observed in Figure 2), recycled aggregate was not able to significantly reduce compressive strength of mortars using same total w/c ratios. A careful analysis of this outcome should be done regarding samples with same consistency, where additional water or pre-wetting process could be considered. In this case, a reduction in compressive strength can be observed (Morón *et al.*, 2021; Wu; Wang; Ma, 2022).

A collection of mechanical strength data from other authors is listed in Table 6. Although most of the analyzed papers show a reduction in compressive strength, the outcome of this present study is aligned with some authors that observed incorporation up to 40% of concrete/ceramic recycled aggregate does not affect this property (Mora-Ortiz *et al*., 2022; Dang *et al*., 2018). Thus, substitution levels and type of aggregates are decisive for keeping similar values of mortars' properties. It is important to highlight that Mora-Ortiz *et al.* (2022) pointed out that mortars with fine CDW (from cementitious mortars and clay bricks) up to 40% showed mechanical performance comparable to reference samples. Dang *et al.* (2018) also supports the occurrence of an optimal substitution level of around 50%.

Figure 4 - **Results of compressive strength at 7, 28 and 91 days**

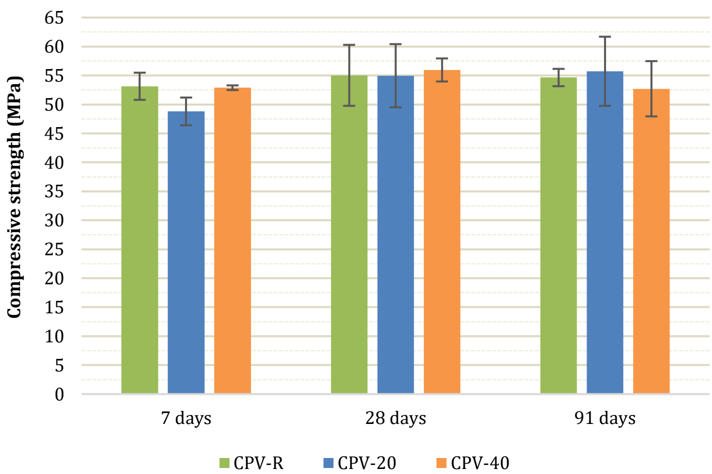


Table 6 - **Compressive and flexural strengths of mortars with fine recycled aggregate**

Article	Recycled aggregate source	Level of substitution	Compressive strength trend by increasing CDW content	Flexural strength trend by increasing CDW content
Dang *et al*. (2018)	Clay brick	0%, 25%, 50%, 75% and 100%	Decreases at 25% and 75%, but increases at 50%	Increases at 25% and 50%, but decreases at 75%
Jesus *et al*. (2019)	Concrete	0%, 10%, 15% and 20%	Increases	Increases
Jesus *et al*. (2019)	Ceramic/Concrete	0%, 10%, 15% and 20%	Decreases	Decreases
Morón *et al*. (2021)	Ceramic/Concrete	0%, 100%	Decreases	Decreases
Mora-Ortiz *et al*. (2022)	Mortar/clay brick	0%, 10%, 20%, 30%, 40%, 50%, 60%, 80% and 100%	Decreases above 40%	-
Vaishnav and Trivedi (2022)	Concrete	0%, 25%, 50%, 75% and 100%	Decreases	-
Wu, Wnag and Ma (2022)	Concrete	0%, 25%, 50% and 100%	Decreases	Decreases
Fang *et al*. (2021)	Concrete	0%, 50% and 100%	Decreases	-
Sun *et al*. (2021)	Concrete	0%, 100%	Similar	Increases

Among the studies that found a reduction in compressive strength, Vaishnav and Trived (2022) and Wu, Wang and Ma (2022) noted that compressive strength decreases as the content of recycled fine aggregate is increased due to its greater porosity. Following this trend, Jesus *et al.* (2019) and Morón *et al*. (2021) also observed a reduction in this property by using ceramic/concrete aggregates and 100% of replacement of conventional sand, respectively. However, Jesus *et al*. (2019) observed that incorporation of CDW aggregate from only recycled concrete resulted in increased strength. This discrepancy can be justified by particle size of recycled aggregates below 150 μm, providing a filer effect and, consequently, increased compactness and strength of mortars (Jesus *et al*., 2019). Although Fang *et al*. (2021) also found reduction in compressive strength of mortars produced with recycled concrete aggregate (compared to mortars with natural sand), they noted that concrete carbonation of aggregate increases this property (compared to mortars with recycled aggregate without carbonation).

It is valid to mention that the Brazilian standard NBR 15116 (ABNT, 2021) only allows the use of up to 20% of recycled aggregate derived from cementitious composites (concrete and mortars) in structural elements located in low or moderate aggressive environment. However, this paper shows an important contribution to technical community indicating that concrete/ceramics recycled aggregates (i.e., a blend of cementitious and clay-based materials) could be considered up to 40% since the w/c ratio is kept constant. This should be done without pre-wetting of aggregate and without additional water for mixing.

Figure 5 shows results of flexural strength of mortars with and without recycled aggregate up to 91 days.

A slight reduction (around 12%) was noted for mortars with 20% of recycled aggregate. Samples with 0% and 40% had similar behavior, indicating that this content can be considered as an optimal value of substitution, also noted by other authors for concrete/ceramic aggregates (Dang *et al.*, 2018). Moreover, the maximum variation of experimental results was registered in 6%, 9% and 11% for 7, 28 and 91 days, respectively. It seems that the curing time may have certain influence in this property. The drying process of recycled aggregate may have left behind some small pores during hydration process, which led to higher spread of results.

These results corroborate the literature regarding flexural strength (Table 6). Dang *et al*. (2018) showed the difference of values is reduced over the time between the reference mortar and mortars with CDW clay-brick. Furthermore, this property can even be exceeded for CDW mortars, due to pozzolanic and internal curing effects of recycled aggregate. Their high porosity works as an extra water reservoir for prolonged hydration of cementitious reactions. This outcome is aligned with results from Jesus *et al*. (2019) using concrete recycled aggregate. Increased flexural strength was attributed to filer effect, possible presence of anhydrous cement particles in concrete aggregate, and low water/cement ratio used in the mix. Sun *et al*. (2021) also observed an increase in flexural strength due to interaction between the recycled aggregate and expanding agents (optimal content of 9%). On the other hand, Wu; Wang and Ma (2022) observed opposite effects of decreased flexural strength owing to high porosity of recycled aggregate and weakening of interfacial transition zones. Morón *et al*. (2021) also observed this reduction in flexural strength with 100% of replacement.

Therefore, the optimal content of 40% found in this experimental study can be related to the balance between porosity and filler effect from recycled aggregate (for same w/c ratio). The higher porosity of recycled aggregate (as observed in Figure 2) is counteracted by the higher amount of powder material (< 75 µm) (Table 3), leading to similar performance to flexural strength of the reference sample. The content of 20% seems to be not enough to promote this adequate balance, and porosity left by recycled aggregate leads to significant reduction in this property.

Open porosity and water absorption

Results of open porosity and water absorption of mortars evaluated by immersion tests (Archimedes principle) at 28 and 91 days are shown in Figure 6.

Overall, open porosity and consequently water absorption by immersion were increased from 28 to 91 days for all mortars. It is valid to remember that mortars were cured in air under laboratory conditions. Thus, the increase of mortar porosity can be related to drying shrinkage effects which resulted in appearance of microcracks and increased interconnection of pores.

However, at 91 days, the behavior of CPV-R and CPV-40 are similar, as observed in flexural strength results (Figure 5). The optimal content around 40% of fine recycled aggregate is able to keep porosity at the same level of the reference sample due to higher amount of fine particles (below 75 µm, as seen in Table 3), compensating higher porosity left by CDW. Thus, mortars with lower porosity (compared to CPV-20) lead to higher flexural strength.

Figure 5 - **Results of flexural strength at 7, 28 and 91 days**

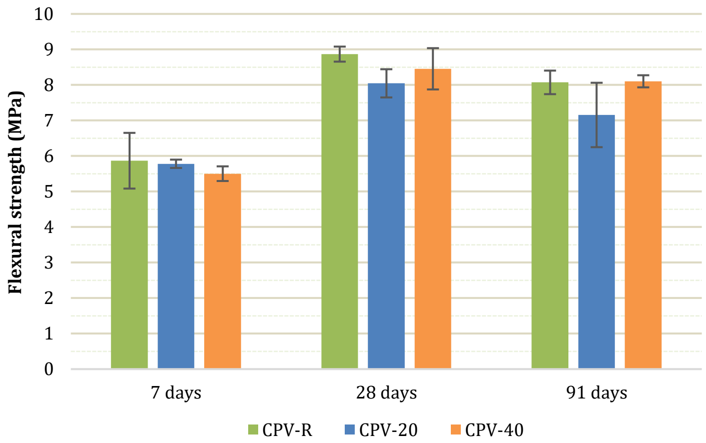


Figure 6 - **Results of open porosity (a) and water absorption by immersion (b) (Archimedes principle)**

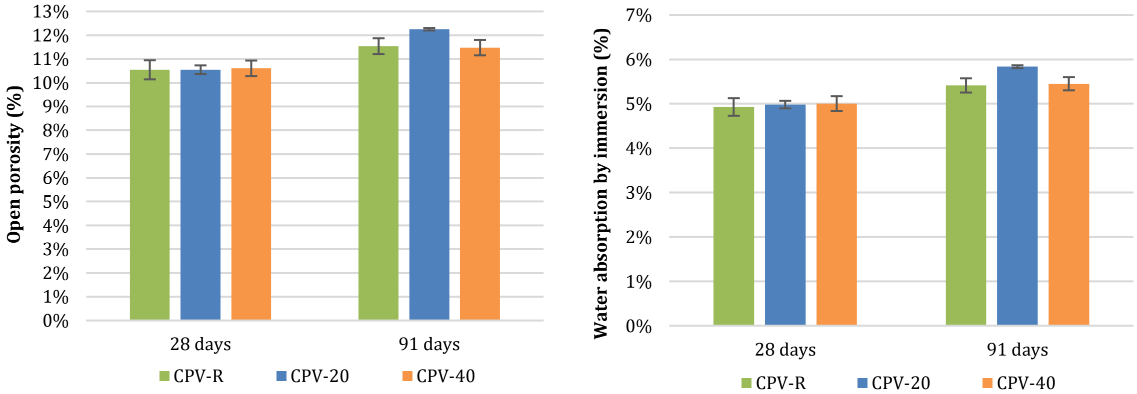


Figure 7 shows results of water absorption by capillary rise at 28 and 91 days. The amount of water absorbed were measured up to 72 hours.

As observed by water immersion tests, the amount of water absorbed from 28 to 91 days were reduced due to higher open porosities of samples. The opener capillary pores, the lower is capillary pressure to rise water in the sample. Moreover, there is another equivalence between CPV-R and CPV-40 samples at 91 days.

Samples with 40% of CDW has a faster water absorption in the first hours (up to 6 hours) due to its increased amount of finer particles (powder material) and higher microporosity given by the recycled aggregate. After that, this samples seems to keep the same absorption pattern than the reference sample. This indicates that the level of tortuosity between both samples are similar, showing that the filler effect by fine recycled aggregate is able to compensate the higher porosity left by the same aggregate, when w/c ratio is kept constant.

The tendency towards increased mortar porosity by incorporation of pre-wetting recycled aggregate (or additional water in the mix) is well documented in most of the papers, as listed in Table 7.

In general, it seems there is a consensus that the higher content of recycled aggregate the higher water absorption of mortars (Marón *et al*., 2021; Letelier *et al*., 2021; Mora-Ortiz *et al*., 2022; Wu; Wnag; Ma, 2022), when additional water is used to compensate CDW porosity. Higher porosity of recycled aggregates can be originated from two ways: original composition of the aggregate mixture (mainly attributed to primary water/cement ratio of previous concrete), and manufacturing process of recycling material (mainly due to crushing and griding of recycled matrix) (Letelier *et al*., 2021; Jesus *et al*., 2019).

Jesus *et al*. (2019) did not used any additional water in samples with CDW. On the contrary to most of other studies, the amount of water was even reduced in mortars by the presence of up to 20% of recycled aggregate. The authors attributed this reduction to filler effect. The fine particles of recycled aggregate filled empty voids between larger particles of sand, decreasing water demand in the mix.

Figure 7 - **Results of water absorption by capillary rise at 28 and 91 days**

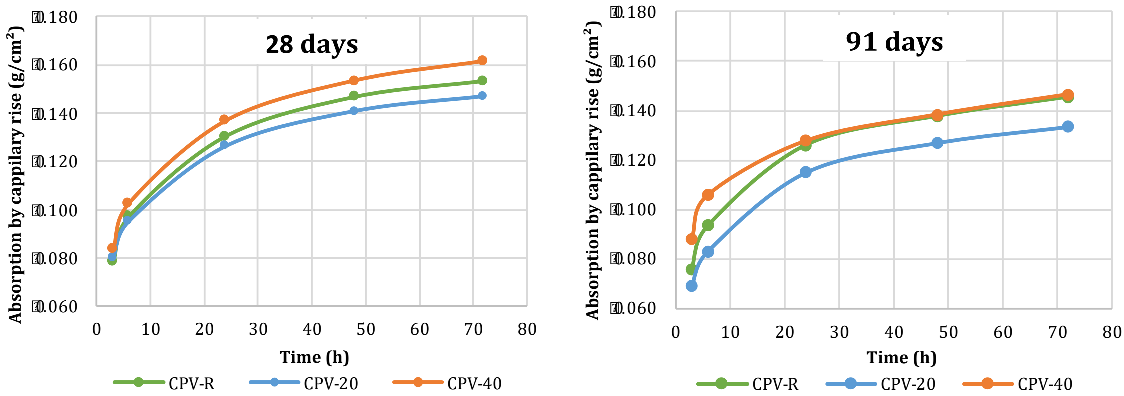


Table 7 - **Water absorption of mortars with fine recycled aggregate**

Article	Recycled aggregate source	Level of substitution	Additional water to compensate CDW absorption	Water absorption trend by increasing CDW content
Jesus *et al*. (2019)	Ceramic/Concrete	0%, 10%, 15% and 20%	No	Decreases
Letelier *et al*. (2021)	Concrete	0%, 15% and 30%	Yes	Increases
Morón *et al*., 2021)	Ceramic/Concrete	0%, 100%	Yes	Increases
Mora-Ortiz *et al*. (2022)	Mortar/clay brick	0%, 10%, 20%, 30%, 40%, 50%, 60%, 80% and 100%	Yes	Increases
Wu, Wang and Ma (2022)	Concrete	0%, 25%, 50% and 100%	Yes	Increases

Therefore, the same amount of water used for mortar production with 40% of recycled aggregate is crucial to keep porosity and mechanical strength at the same level of the reference sample.

Drying and autogenous shrinkages

The evolution of linear shrinkages, triggered by drying and autogenous processes, up to 120 days is shown in Figure 8.

Overall, all samples showed a fast and sharp drying shrinkage in the first 14 days (Figure 8a). This happens because most of capillary water evaporates to the environment, suffering reduction in bulk volume. After that, evaporation rate is reduced until a constancy of linear length, observed after 91 days. Incorporation of fine recycled aggregate also had a relevant impact on this property: the higher replacement level, the lower shrinkage. At 120 days, the highest values were recorded for CPV-R sample (1355 μm/m), followed by CPV-20 sample (1273 μm/m), and then CPV-40 (1165 μm/m). This represents reduction in the order of 6% and 14% for levels of aggregate substitution of 20% and 40%, respectively.

This tendency of reduced drying shrinkage in mortars with CDW level contradicts the observations presented in the literature, as shown in Table 8. There are different reasons for that based on the total amount of water and type of cement used in the mix.

Morón *et al*. (2021) and Wu, Wang and Ma (2022) attributed this increased shrinkage to greater drying of free water, since both studies have considered extra water in mortar preparation due to increased absorption of aggregates. On the other hand, Jesus *et al*. (2019) produced CDW mortars with less water (lower w/c ratio) compared to the reference sample. This reflected in increased cementitious content and increased capillary stress, as the recycled aggregate were obtained from primary cementitious mortars.

Figure 8 - **Results of shrinkage up to 120 days: (a) drying shrinkage and (b) autogenous shrinkage**

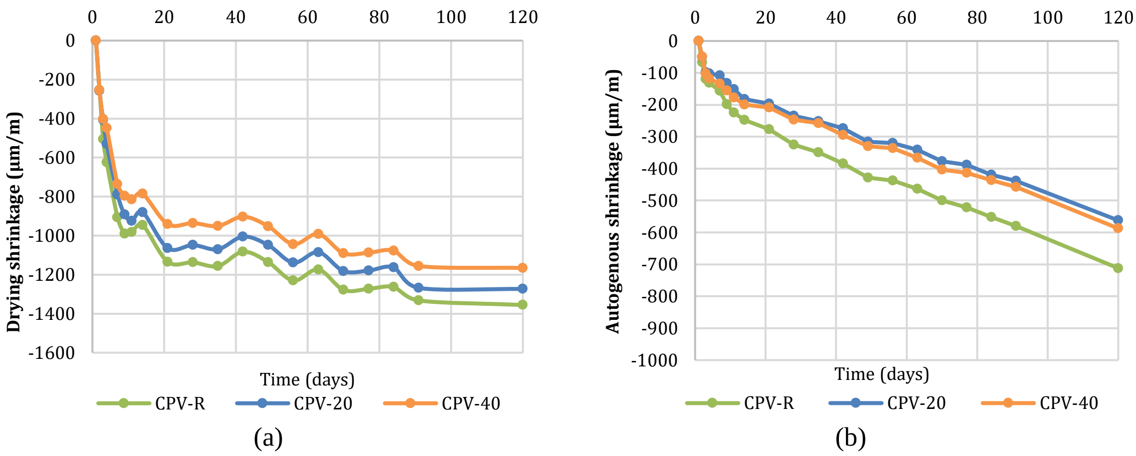


Table 8 - **Drying shrinkage of mortars with fine recycled aggregate**

Article	Recycled aggregate source	Level of substitution	Total amount of water in the mix compared to the reference mortar	Type of cement used	Shrinkage trend by increasing CDW content
Jesus *et al.* (2019)	Concrete	0%, 20%	Reduced	CEM II/ B-L 32.5 N	Increases
Jesus *et al.* (2019)	Ceramic/Concrete	0%, 15%	Reduced	CEM II/ B-L 32.5 N	Increases
Morón *et al.* (2021)	Ceramic/Concrete	0%, 100%	Increased	CEM IV/B 32.5 N	Increases
Wu, Wang and Ma (2022)	Concrete	0%, 25%, 50% and 100%	Increased	Cement with pozzolanic material	Increases

This observation from Jesus *et al*. (2019) indicates that the type of cementitious system interferes in drying shrinkage results. In fact, all analyzed papers used blended cements, i.e., binders obtained from a mix of clinker and supplementary cementitious materials. This system leads to slower and prolonged hydration process (Scrivener; Juilland; Monteiro, 2015), letting water more susceptible to be lost to the environment. The higher evaporation rate, the lower dimensional stability, the greater susceptibility to cracking by shrinkage.

In fact, the present study shows experimental results of drying shrinkage by using mortars with high early-age strength Portland cement (CP V ARI) and same w/c ratio. For the reference sample (without CDW), a rapid cementitious reaction happens and leave available capillary water free to evaporate. When fine recycled aggregate (in dry condition) is added during the mixing (at the same w/c ratio), the porous material absorbs water and keeps it for longer. This water trapped in the porous aggregate is more difficult to be dried than those in capillary pores of mortars. Thus, mortars with recycled aggregate displays reduced drying shrinkage at the same w/c ratio compared to a reference sample. It is important to stress the limitation of the study in using CP V ARI, and an extensive analysis for other types of cement, including blended systems, should be carefully carried out.

Moreover, the positive effect of water retention by recycled aggregate also reflects in reduced autogenous shrinkage (as seen in Figure 8b). In fact, incorporation of CDW resulted in a reduction of approximately 15% of autogenous shrinkage at 120 days. The wetting porous aggregate works as water reservoir for more prolonged cementitious reactions, decreasing the effects of self-desiccation processes (Almeida; Klemm, 2018). In this sense, recycled aggregate acts as an internal curing agent for mortars with high early-age strength Portland cement. Moreover, the porous aggregate provides more room to deposition of hydration products, reducing the effects of chemical shrinkage (Scrivener; Juilland; Monteiro, 2015). For the reference sample, in turn, there is no porous aggregate to retain water, which results in faster hydration process and increased autogenous shrinkage. This observation gives insights for evaluations of other cementitious systems, where fine recycled aggregate could aid prolonged hydration reactions, especially for cements with supplementary cementitious materials.

Together with filler effect, this phenomenon of favoring hydration by fine recycled aggregate (especially at 40% content) may also contribute to keep flexural strength, open porosity and water absorption (by capillary rise and immersion) at the same level of the reference mortar (without CDW), as seen in Figures 5, 6 e 7.

Conclusion

By carrying out this experimental study, it was possible to evaluate selected properties of cementitious composites with fine recycled aggregates sourced from concrete/ceramic wastes in replacement of natural sand. The main outcomes were:

(a) cementitious mortars can be produced with no additional water and no pre-wetting of fine recycled aggregate. For this case, a reduction up to 20% in workability is observed for mortars with 40% of substitution;

(b) incorporation up to 40% of fine recycled aggregate does not affect compressive strength of structural composites, reaching values above 50 MPa at 28 days. For this, rapid early-strength Portland cement and no pre-wetting of recycled aggregate was considered;

(c) the optimal content around 40% of fine recycled aggregate is able to keep porosity, water absorption and flexural strength at the same level of the reference sample (with same water/cement ratio). This is due to higher amount of finer particles (below 75 μm) which compensates higher porosity of recycled aggregates; and

(d) drying and autogenous shrinkages are reduced up to 15% by the presence of 40% fine recycled aggregate. It acts as an internal curing agent for mortars with high early-strength Portland cement and same water/cement ratio. This effect has potential to be explored to other cementitious systems, especially those with prolonged hydration reactions.

Therefore, this paper shows promising indications in using 40% of the fine portion of recycled concrete/ceramic aggregates for production of structural cementitious composites (concrete and mortars). For this level of substitution to natural sand, composites should be produced without additional water (including no pre-wetting of recycled aggregate) and a rapid early-strength Portland cement. Other limitations of this study that should be carefully evaluated are related to durability, type of cement and chemical admixtures, and source of construction and demolition wastes. However, this outcome opens new possibilities for pre-cast concrete and cementitious artefacts industries to use more sustainable aggregates in structural elements.

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