Potential of CO_2 mitigation in concrete containing recycled aggregates

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Abstract: The replacement of natural aggregates with recycled ones is a strategy for developing sustainable concrete formulations, which could decrease landfill disposal of construction waste. However, the increase of recycled aggregates (RA) content in concrete frequently leads to an increase in cement content – which is the heaviest environmental burden of concrete due to CO_2 emissions. This study presents a strategy for a better engineered concrete design approach that could allow using RA without increasing cement content. From a more detailed aggregate characterisation, a known particle packing theory could be applied to optimise the concrete packing of particles, allowing a decrease in cement content. The eco-efficiency of cement use was assessed by Binder Index (BI) – the ratio between binder content (environmental load) and compressive strength (performance indicator). Better-engineered concrete could provide similar efficiency of cement use in packed concrete formulations with 100% low-quality RA compared to ordinary ones with 100% natural aggregates.

Keywords: concrete; aggregate; waste treatment; particle size distribution; mixture proportion.

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1 Introduction

Building construction is the most impacting chain in terms of resource consumption and CO_2 emissions by manufacturing new materials. For that reason, the recycling of old (and even new) buildings has been raising interest in global sustainability, since it can avoid: 1) the use of natural limited new resources for the production of new materials; 2) CO_2 emissions related to these processes; and 3) landfill disposal of high amounts of construction and demolition waste (CDW) (Tam and Tam, 2006).

However, sustainability must include much more than just post-use decisions. Impacts are huge from resources extraction. Cement production processes, for instance, released around 842 kg CO_2/ton clinker by the year of 2014 (CSI WBCSD, 2013), which is by far the most important environmental load of concrete. Despite industrial efforts focused in kilns and processes, this value is decreasing very slowly, as well as the clinker to cement ratio (75.6% in 2010, and 74.5% in 2014) (CSI WBCSD, 2013), which means that other strategies are needed – such as the use of lower cement content for making the same concrete. So, some 'sustainable' concrete solutions – such as the well-known use of any type of wastes replacing natural aggregates – must consider their impact on cement content increase or decrease for being sustainable.

This concept seems to be forgotten or neglected by some of the current concrete waste researchers. It is very common to find in literature many works that do not consider the impact of recycled wastes on the cement consumption of resulting concrete formulations. In the particular case of recycled aggregates (RA) from CDW, they have very specific characteristics that can impact on that relationship. The most important ones are:

1 the high level of variability in terms of source

2 porosity (Angulo et al., 2010).

If their real density is near 2.6 kg/dm^3 (clays, ceramics, rocks present such density due to their mineralogical properties), on the other hand the apparent density – the one that considers the volume of voids – can vary from 1.7 kg/dm^3 (very high porosity) up to 2.6 kg/dm^3 or near (this last one would be reached in case of zero porosity). The difference in terms of porosity and apparent density of RA is not linked to the mineralogical source or construction material source (red ceramics, grey mortars or concretes), but to the production process of the material: well-burned ceramics have low porosity; poor-burned ceramics have higher porosity. In the case of concrete and mortars, porosity is linked to the mixing design – the higher the water content for achieving rheological behaviour, the higher the porosity, and vice-versa. Due to all these factors, RA presents lower quality and higher heterogeneity than natural aggregates (De Brito and Saikia, 2013).

It can be observed that a simple quality control based on the separation of "red" and "grey" is not effective to make more homogeneous RA. This is more complex. There are works in which RA are separated by a density-liquid process, achieving more homogeneous samples (Angulo, 2005); however, these processes are expensive for real use in the scale of a recycling plant. Maybe the fast and accurate measurement of apparent density and porosity, which are the theme of some other literature works (Damineli et al., 2016b; Kropp, 2005; Tam et al., 2008; Tegguer, 2012; Leite, 2001; Schouenborg et al., 2003), could be a simpler way to evaluate the quality of RA.

Once the apparent density is known, it is possible to implement another way to increase sustainability of RA: the design of concrete using particle packing and dispersion technology, which showed to be effective tools for decreasing cement content reaching mixtures with 50% to 75% lower cement content compared to traditional market benchmark (Damineli et al., 2013). The increase in cement efficiency use was measured by the Binder Index (BI), which is the ratio between cement content, in kg/m^3, and the compressive strength, in MPa. Making the correlation between an impact indicator (cement content) and a performance indicator (compressive strength), BI is capable of providing objective comparative information regarding the efficiency. A more detailed discussion on BI and its utility is found in Damineli et al. (2010).

The objective of this paper is to preliminary investigate the potential of using packing and particle dispersion tools for decreasing cement content in concrete formulations made from 100% RA. This could compensate for the loss of cement efficiency use brought by higher porosity and heterogeneity of RA, with potential high industrial applications, since concrete formulations with RA would have a higher field of applications and could become economically viable due to the controlled cement content (which is the most expensive component of concrete with RA). In this context, BI has a central hole in the paper analysis: it is used to assess and compare the dosage efficiency for all mixtures, allowing a more direct way to understand the effect of RA on the environmental performance of concrete.

2 Improving design of concrete mixtures

2.1 Packing of particles: general concept and theory used

Mixtures were designed with the aim of assessing the efficiency of cement use in concrete formulations with RA compared to the same mixtures with natural aggregates, using a method of design that does not take into account packing efficiency (Helene and Terzian, 1992) and, in a second step, optimising packing in concrete formulations with RA. This way, it was possible to

1. determine the loss of efficiency in cement use provided by the available low-quality RA
2. assess how much of that efficiency it is possible to recover just by optimising packing but still using the same low-quality aggregates.

The theory of packing of particles is based on the fact that it is possible to produce a system with lower volume of voids between particles (aggregates, cement particles) by using different sizes of particle fractions if smaller ones fill the voids between larger ones. The lower the voids of aggregate skeletons, the lower the paste volume required for filling it and enabling the flow – which starts when paste surpasses the volume of voids. As compressive strength in an ordinary cement-water paste depends mostly on water/cement ratio, a better packing project makes it possible to use lower paste content for the same flow and the same strength, resulting in concrete with the same performance, lower cement content and therefore higher cement use efficiency. The lack of concrete dosage methods is not to take into account measuring voids for that optimisation. In optimised packing, flow is not dependent on paste increase, but on voids volume decrease.

Several particle packing theories are known (as for example De Larrard, 1999 and Yu and Standish, 1991), some based on mathematics to calculate, from a set of known-sized particles, the volume of voids. In this paper, (Funk and Dinger, 1994) it was used to measure the voids and to optimise the design of concrete formulations.

2.2 Dispersion of fine particles

For a system to be efficient, fine particles need to be fully dispersed, since they tend to agglomerate due to their low mass and high surface area, which generates higher attraction forces. Agglomerates:

1. modify the granulometric distribution
2. increase viscosity, since they block the mobility of flow lines
3. generate voids within the agglomerates, increasing water consumption
4. decrease the surface area available for hydration (Oliveira et al., 2000).

To obtain this dispersion with economic criteria, it is necessary to use dispersants that, due to economic reasons, need to have their content optimised at the minimum required level to generate the highest possible flow (Damineli et al., 2016a).

3 Methodology

3.1 Materials

RA used in this work were produced from CDW disposed of in a landfill in the São Carlos area, Brazil. The landfill does not accept mixed wastes – when samples have contaminants such as soil, timber, glass, polymers or others, they are rejected. However, mineral phases with a large heterogeneity still remain, since they can contain concrete, mortar, bricks and some ceramics adhered, from very different sources and qualities (affecting porosity). The wastes are milled and sieved to produce the RA. The final RA does not receive any processing besides sieving (for example, to remove very fine particles, remove adhered ceramics, and remove some other possible contaminant). Three different particle-sized RA produced were collected and used in this work, allowing us to reach the best packing compositions possible by their different combinations according to the theory presented in item 2.1.

A typical CP V Brazilian cement was used. This cement is made of 95–100% clinker + gypsum and 0–5% limestone, ground finer to present high initial strength. It is the purest cement in Brazil (no mineral admixtures such as blast-furnace slag and pozzolans, so variation sources were decreased, allowing a focused analysis only in RA influence).

A typical polycarboxylate dispersant was used.

3.2 *Experimental planning: packing and dispersion for low binder CDW concrete formulations*

Table 2 shows the concrete compositions in volume, since packing optimisation considers space occupation of voids and is designed in volume. For the same reason, apparent density was used for mass converting – it considers the effective volume occupied by particles. Two reference concrete formulations (Ref) were mixed with natural granite aggregates and four concrete formulations using 100% RA (Rec) – both sand and gravel were replaced with recycled ones. The dispersant was fixed at 1% of cement mass for all types of concrete, except Ref-01, which used 0% dispersant for comparison.

Table 1 Composition of concrete studied

Mix	*Composition (% vol)*							*Disp (% cem mass)*	*Voids aggr*	*Voids total*
	Cem	*S1n*	*G1n*	*S2r*	*G2r*	*G3r*	*Water*			
Ref-01	16.1	38.1	45.7	-	-	-	23.4	0	26.6	22.9
Ref-02	16.1	38.1	45.7	-	-	-	16.0	1	26.6	22.9
Rec-01	18.8	-	-	27.1	-	54.1	13.1	1	26.2	22.3
Rec-02	12.2	-	-	35.1	-	52.7	13.1	1	24.7	21.9
Rec-03	12.2	-	-	35.1	24.0	28.7	12.0	1	15.7	11.4
Rec-04	12.2	-	-	35.1	24.0	28.7	12.0	1	15.7	11.4

Notes: Cem = cement; S1n = Sand 1 (Natural); G1n = Gravel 1 (Natural); S2r = Sand 2 (Recycled); G2r = Gravel 2 (Recycled); G3r = Gravel 3 (Recycled); Voids ag = voids between aggregates.

Concrete formulations of Table 2 were designed with the aim of comparing performance of concrete made from natural aggregates and a non-packing dosage methodology (Helene and Terzian, 1992) against

a concrete with 100% RA using the same non-packing methodology (Rec-01 and Rec-02)

b concrete made from 100% RA using (Funk and Dinger, 1994) packing method (Rec-03 and Rec-04).

Comparing Rec-01 with Rec-02, they result from 1:3 and 1:5 (cement:aggregates) mass proportions, respectively, mortar content = 50% (parameters from Helene and Terzian, 1992). As a comparison, Ref-01 and Ref-02 are 1:5 mass proportion, mortar 50% (same as Rec-02). Additionally, Rec-03, Rec-04, and Rec-05 are a result of packing optimisation on Rec-02, so they take packing into account but are 1:5 cement: aggregate proportions, mortar = 50%. The difference is that Rec-02 used 1% of dispersant and was made under lab conditions; Rec-04 is the same, made under external environmental conditions; and Rec-05was made with no dispersant as it can be seen in Table 2. Voids between aggregates were 26.6% for Ref-01 and Ref-02, following 26.2 and 24.7 for non-packing concretes with RA (Rec-01 and Rec-02). Rec-03, Rec-04, and Rec-05, however, achieved 15.7% voids between aggregates – more than 10% lower void volume. For the overall void calculation, including paste (in this paper, paste is a fixed 100% cement-water, no mineral admixtures such as blast-furnace slag, fly ash, fillers were used), Ref-01 and Ref-02 had 22.9% voids, Rec-01 and Rec-02, 22.3 and 21.9% (the four were similar), while Rec-03, 04 and 05 presented 11.4%. As void calculations are made based on dry material data, the % volume of materials is presented on the basis of 100% total dry materials.

3.3 Procedures and methods

3.3.1 Cement characterisation

Since there are important parameters for the design of concrete based on packing, the specific surface area for the cement was experimentally determined by BET method (Brunauer et al., 1938), and the real density, using a Helium Pycnometer. The chemical composition was also determined by quantitative X-ray fluorescence spectrometer.

3.3.2 RA characterisation

The particle size distributions of 3 different CDW RA were measured by the sieving test. The complete sieve series was used as described in ASTM E11 (American Society of Testing Materials, 2017) (19,000 μm, 16,000 μm, 12,000 μm, 11,200 μm, 9,500 μm, 8,000 μm, 6,300 μm, 5,600 μm, 4,750 μm, 4,000 μm, 3,350 μm, 2,800 μm, 2,360 μm, 2,000 μm, 1,700 μm, 1,400 μm, 1,180 μm, 1,000 μm, 850 μm, 710 μm, 600 μm, 500 μm, 425 μm, 355 μm, 300 μm, 250 μm, 212 μm, 180 μm, 150 μm, 125 μm, 106 μm). Compared to the standard sieving procedure, this series includes three sieves between each size gap. The more accurate particle size determination is due to the fact that this is required for measuring and optimising the packing of aggregates by the chosen method, item 2.1.

Aggregates had also their chemical composition determined by quantitative X-ray fluorescence spectrometer. Some other important parameters for aggregate characterisation, such as water absorption, real density (volume excluding pores) and apparent density (volume including internal pores) were determined by Mercosur standard methods – NM 53 (ABNT, 2009b) or ASTM C127 (American Society of Testing Materials 2007) for coarse aggregates, NM 30 and NM 52 (ABNT, 2009a, 2001) for fine aggregates. The content of materials finer than 75 μm in each aggregate, which can increase water content in concrete mixture, were determined by NM 46 (ABNT, 2003). Non-mineral materials present in each fraction, which are contaminants for RA, were measured by NBR 15116-B (ABNT, 2004). Clay content, which decreases final resistance, was measured according to NBR 7218 (ABNT, 2010).

3.3.3 Optimum dispersant content

In this work, the dispersant content was experimentally determined, for cement with three different water/cement (w/c) ratios, by two flowing tests: mini-slump test (flow in low shear rate, yield stress; and Marsh funnel time flow, an indirect measurement of viscosity, flow in high shear rates). For mini-slump determination, the higher the spreading, the lower the yield stress and the higher the flow; for Marsh funnel, the lower the time the paste surpasses the hole, the lower the viscosity and the higher the flow. The optimum content would be that one where flow reaches the highest potential with the lowest dispersant.

3.3.4 Fresh state – mixing procedure, rheological properties and casting

Before concrete mixing, RA were pre-saturated in water for 24 hours, aiming to avoid the absorption of water from the designed composition during the mixing process. This is a related problem in Poon et al. (2004) that can highly decrease flowability. The consequence is the need to increase water content during the mixing process. Thinking in better ways of increasing quality control in such a low-quality process, pre-saturation is much simpler than compensating water by adding to the mix the amount measured by water absorption test. In these cases, concrete water content is more difficult to be calculated and controlled (Damineli et al., 2016b), and a 24h pre-saturation guarantees that most of the pores will be filled at the moment of mixing.

Concrete formulations were mixed for ten minutes in a simple 120-litre concrete mixer – a low-knowledge process so results could be applied, since it is the most common in practice. Water and dispersant were placed, cement was added for one minute, followed by two minutes of mixing. After, aggregates were placed, from coarsest to finest, one minute between each one for providing higher mixing level, up to reaching the final ten minutes.

Rheological behaviour was measured by the simple slump test (ABNT, 1998). Six 10 × 20 cm cylindrical specimens were cast for measuring compressive strength at seven and 28-day ages (three specimens each age) (ABNT, 2008).

3.3.5 Hardened state – Cure and compressive strength

After 1 day, specimens were uncast and taken to the humidity chamber (temperature 23 ± 2°C, relative humidity ~ 100%) (ABNT, 2008) and kept under moist cure up to the compressive strength test (7 and 28 days).

Surface regularisation of top and bottom was done by grit. Compressive strength was performed at 7 and 28 days by the ABNT (2007) procedures. Tests were carried out with specimens in a wet state.

3.4 Cement use efficiency – binder intensity

In Damineli et al. (2010) two useful tools for assessing the efficiency of cement (and binder in general) use were presented and discussed: the binder intensity (BI) and the CO_2 intensity (CI).

In environmental terms, CO_2 decrease is the main objective. Considering actions on concrete design, this can be done by:

1. replacing clinker with low environmental load mineral admixtures with pozzolanic contribution, such as blast-furnace slag or fly ashes
2. increasing efficiency of binder use in concrete mixtures.

Both can act together and are cumulatively beneficial. As this paper does not discuss binder replacement – paste was fixed as 100% water + cement CPV, which has 95–100% of clinker/gypsum –, the optimisation of the use of binders will be the focus of analysis. In this case, the increase in aggregate packing can decrease paste content maintaining fresh and hardened performance by the mechanisms already discussed. In this combination (binder fixed, packing optimisation), CO_2 footprint is strictly dependent on total binder content – so CI follows BI. Due to that, BI will be the only and satisfactory assessment index adopted.

As a definition, BI is the ratio between the total binder (in this case cement) content, in $kg \cdot m^{-3}$, and the performance (in this case, the 28-day compressive strength, in MPa), equation (1):

$$BI = binder / CS \quad (1)$$

where binder is the total binder content (cement in this paper), in $kg \cdot m^{-3}$; CS is the 28-day compressive strength, in MPa.

This index is expressed in $kg \cdot m^{-3} \cdot MPa^{-1}$ and allows the analysis of the relationship between the total amount of binders (impact) and performance measurement (the most commonly used for concrete is compressive strength). The lower the BI, the lower the binder content required for the same performance and therefore the higher the eco-efficiency.

4 Results and discussion

4.1 Materials characterisation

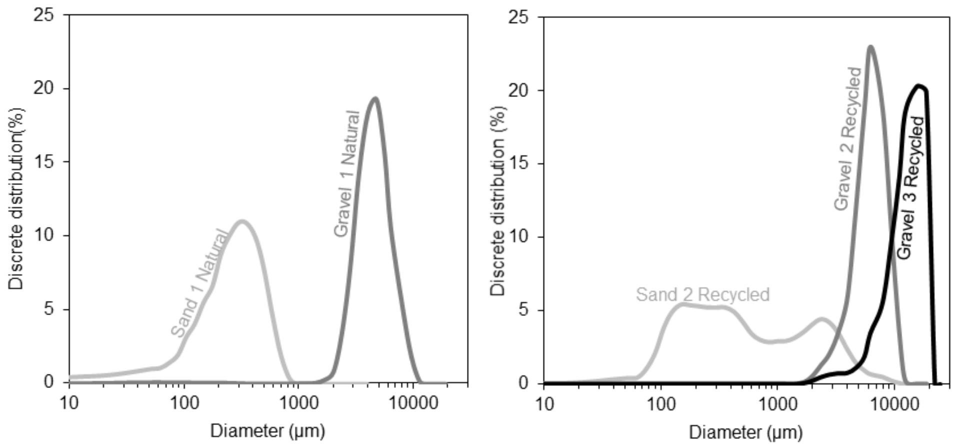
Cement had BET specific surface area = 1.72 m^2/g, and real density measured by He pycnometer = 3.01 kg/dm^3. Chemical composition is presented in Table 2.

Table 2 Chemical composition of the cement used (%)

CaO	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*MgO*	*SO_3*	*Other*	*Loss on ignition*
62.67	19.30	4.34	3.36	0.59	5.85	1.12	2.77

Natural and recycled aggregates had their particle size distribution determined in order to compose packing studies. The results are presented in Figure 1.

Figure 1 Particle size distributions of aggregates used in the concrete formulations



(a) (b)

Note: Natural in full lines, recycled in dashed lines.

Table 3 summarises water absorption, real density and apparent density of natural and recycled aggregates, measured by NM 53 (gravel); NM 30 / NM 52 (fine) (ABNT, 2009a, 2009b, 2007, 2001). It is noted that RA are very low-quality, since they have very high-water absorption and low apparent density. Results of apparent density, in special, are useful for designing concrete mixtures by volume using packing theory.

Table 3 Water absorption, real density and apparent density of aggregates

	Water absorption (%)	*Real density (kg/dm³)*	*Apparent density (kg/dm³)*	*Fines < 75 μm (%)*	*Non-mineral (%)*
Sand 1 (nat)	0.3	2.82	2.81	0.12	0.00
Sand 2 (rec)	19.5	2.63	2.06	14.40	0.15
Gravel 1 (nat)	0.4	2.71	2.71	0.05	0.00
Gravel 2 (rec)	19.0	2.62	2.05	8.65	1.35
Gravel 3 (rec)	19.2	2.61	2.06	6.50	1.95

Tests were performed in triplicate and, for RA, water absorption and apparent density range are presented.

Table 4 Clay content of three RA studied, divided by particle size intervals determined by NBR 7218

	Clay content (%)		
Particle size interval (mm)	*Sand 2 (rec)*	*Gravel 2 (rec)*	*Gravel 3 (rec)*
19.0–9.5	-	2.30	3.06
9.5–4.8	-	9.54	11.04
4.8–1.2	1.77	10.65	12.01

Note: Percentages are relative to the total mass in each sieve interval (not to the total mass).

Table 4 shows clay content of RA present in each particle size intervals, determined by NBR 7218 (ABNT, 2010) standard test method

Table 5 Chemical composition of aggregates used (%)

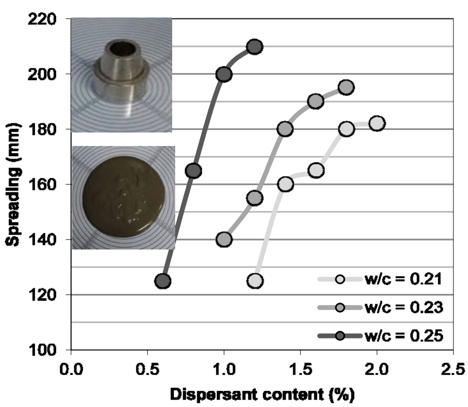
	CaO	*SiO_2*	*Al_2O_3*	*Fe_2O_3*	*Na_2O*	*MgO*	*K_2O*	*TiO_2*	*SO_3*	*Other*
Sand 1 (nat)	0.00	99.28	0.45	0.21	0.00	0.01	0.00	0.00	0.00	0.05
Sand2 (rec)	12.41	59.85	15.45	4.26	3.85	1.31	2.01	0.32	0.30	0.24
Gravel1 (nat)	4.35	65.62	14.75	6.34	2.45	2.02	3.01	0.62	0.20	0.64
Gravel2 (rec)	15.11	56.44	14.92	5.02	4.15	1.11	1.82	0.42	0.28	0.73
Gravel3 (rec)	16.01	55.77	14.83	5.12	4.22	0.98	1.65	0.38	0.52	0.52

Table 5 presents the chemical composition of aggregates used in the study.

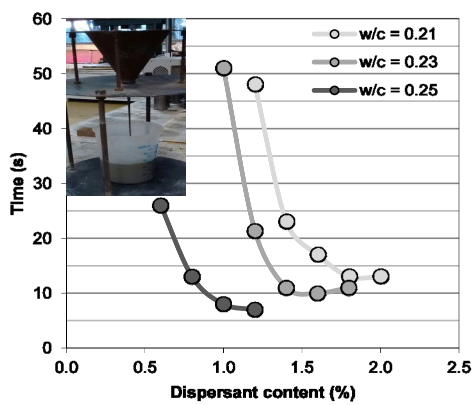
4.2 Optimum dispersant content

Optimum dispersant content was determined for some different w/c ratios (0.21; 0.23; 0.25). It can be seen in Figure 2 that dispersant content varies for different w/c; in general, 1% of dispersant (of cement mass) is the minimum possible to be used for a good dispersion (it can provide flow to pastes with w/c > 0.25, which are the case of the concrete formulations in this study). The use of low dispersant content also complies with the economic aspects required for low-quality concrete. Due to those considerations, 1% was the amount used in this work.

Figure 2 Dispersant content determination for the cement by, (a) mini-slump test (yield stress) (b) Marsh funnel time flow (see online version for colours)



(a)



(b)

4.3 Discussion

Starting from the principle that all concrete formulations were standardised using 1% of dispersant content (except Ref-01 and Rec-05), by mass of cement, Ref-02 required 160 l/m^3 of water for reaching a 210 mm slump, as shown in Table 6. Using the same water content, Rec-01 could not be mixed – very fluid, even segregating. This is possible since pre-saturated CDW recycled aggregates release some trapped pores of water in the mix during the first mixing stages. So, water content needed to be reduced to 131 l/m^3 (plus the water from pre-saturation) for reaching the same slump flow level (200 mm).

Table 6 Rheological behaviour (slump flow), hardened parameters (compressive strength) and cement efficiency index (BI) of studied concrete formulations

Mix	*Voids aggr*	*Voids total*	*Cement (kg/m^3)*	*Water (l/m^3)*	*w/c*	*Slump*	*CS7*	*CS28*	*BI7*	*BI28*
Ref-01	26.6	22.9	367.3	234	0.65	120	29.1	32.0	12.6	11.5
Ref-02	26.6	22.9	402.7	160	0.41	210	40.3	43.4	10.0	9.3
Rec-01	26.2	22.3	484.6	131	0.27	200	32.1	35.3	15.1	13.7
Rec-02	24.7	21.9	314.4	131	0.42	30	23.9	26.3	13.2	12.0
Rec-03	15.7	11.4	318.3	120	0.38	90	27.5	31.3	11.6	10.2
Rec-04	15.7	11.4	318.3	120	0.38	50	25.3	30.0	12.6	10.6

As expected from literature experience, Rec-01, designed with disregard to packing and using 100% recycled aggregates, achieved a low efficiency in the use of cement: BI (28-day) was 13.7 kg.m^{-3}.MPa^{-1}. Comparing to reference concrete formulations, it is a higher value even than Ref-01 (no dispersant), which demonstrates that the indiscriminate use of recycled aggregates without control of their quality or of concrete design, in fact, increases the cement content required for the same performance. The comparable loss of efficiency is around 45% (increase in BI compared to Ref-02). This suggests that a non-controlled low-quality concrete made from RA can release almost 1.5 times the CO_2 from cement compared to a concrete made from natural aggregates, in similar conditions of design (same slump class, same 1% dispersant content, same design method). This is a significant increase in environmental (and even economic) impact, which has much higher (un)sustainable implications than the known and widespread ponderation that the landfill disposal saving can justify the cement increase.

When cement content is decreased in concrete made from RA by the most common action for the design method used – decreasing cement: aggregates proportion from 1:3 to 1:5, in mass –, the scenario did not change: concrete Rec-02, which uses same 1:5 proportion compared to Ref-02, same dispersant content and also does not take packing into account, reached BI of 12.0 kg.m^{-3}.MPa^{-1}, a near 30% less efficiency than Ref-02, and even considering a very low-fluid mix (slump 30 mm). Increasing slump to 200 mm would make this scenario even worse. Due to the very similar design parameters, it can be roughly concluded that by replacing 100% of natural aggregates with low-quality (average market) recycled ones, the use of cement can increase by somewhat near 30–50%.

On the other hand, when packing theory is used for engineering the design of concrete made from RA, an increase in cement efficiency use is achieved. Rec-03 concrete was designed starting from Rec-02 (see Table 2) but inserting a new sized aggregate (G2r). The volume of G2r was determined by the calculation of the packing of aggregates by ABNT (2009a) method as described. As a result, a concrete with more than 10% lower void content was designed.

Rec-03 mix achieved a BI of 10.2 $kg.m^{-3}.MPa^{-1}$. This is a good value compared to Ref-02 (BI = 9.3 $kg.m^{-3}.MPa^{-1}$). It can be noted that the packing allows Rec-03 to achieve slump of 90 mm, a higher value than Rec-02 (slump 30 mm) even using lower water content – Rec-03 required 120 l/m^3 for the 80 mm slump, while Rec-02 required 131 l/m^3 more water for the 30 mm slump. Both used the same dispersant content (1% by cement mass). Difference was achieved due to the decreasing of voids (increasing packing of particles) in Rec-03. As a result in terms of efficiency, the lower water content increased compressive strength, decreasing BI to 10.2 $kg.m^{-3}.MPa^{-1}$, almost 20% less than Rec-02. Compared to Ref-02, the BI was less than 10% higher (Ref-02 BI = 9.3 $kg.m^{-3}.MPa^{-1}$; Rec-03 BI = 10.2 $kg.m^{-3}.MPa^{-1,}$ a 0.9 $kg.m^{-3}.MPa^{-1}$ difference). In practice, this means that by using packing knowledge, it is possible to compensate for a big part of the loss of efficiency brought by a very low-quality CDW RA, even when 100% of natural aggregates were replaced by recycled ones, both coarse and fine, and even using the aggregates as they come from the market, without any processing, such as some particle size separation (could make particle sizes that could be packed better available, increasing the packing efficiency), fine washing, density separation, or even changing the surface characteristics (Tsujino et al., 2007). Or, compared to Ref-01, Rec-03 with 100% RA presented higher efficiency in the use of cement than a natural concrete that did not use packing or dispersion (Ref-01 was 0% dispersant) with similar slump.

If on the one hand the dispersant content used was the same 1% of cement mass for Ref-02 and Rec-03, on the other hand the total amount of dispersant was lower in Rec-03 since it has a much lower cement consumption (~90 kg/m^3 lower). This means that it is more economic. If the same dispersant content were used, in total mass, this probably would help to disperse the higher amount of fine particles present in Recycled Sand when compared to Natural Sand (clear in Figure 1), fine particles that were neglected on dispersant dosage (based on cement mass), making slump and efficiency even closer for the same cost.

It is important to highlight that no filler or other supplementary cementitious material (SCM) was used for replacing cement. This is another strategy that could make BI even better in this case, certainly making even concrete with RA surpass the efficiency of reference natural concrete designed with usual methods. The use of a very inefficient mixing method (concrete mixer) is also another way to increase efficiency if desirable. As a last consideration, the range of RA was very limited – in terms of low-quality and porous heterogeneous material but, for the use of packing theory, mainly in terms of the very few particle-size distributions available. If more size distributions were available, a much higher packing, with lower void volume between aggregates could be engineered. When a wide range of particle-sized distribution materials is available, the volume of voids ~5% can be achieved, a lower value than the ~11% possible using the limited RA of this work.

Rec-04 concrete was mixed as the same Rec-03, changing only time of RA pre-saturation – only ten minutes instead of 24 hours. Mixing was also carried out purposely in an external non-controlled environment, on a sunny 27-29ºC day, low air humidity (< 40%), so mix would lose water quickly and easily to the environment. This was done for assessing the ability of the proposed technology to be successful if used in real practice by local workers, which is the real purpose of such a low-quality aggregate.

Results were encouraging. Rec-04 achieved BI = 10.6 $kg.m^{-3}.MPa^{-1}$ (very similar to the Rec-03 BI = 10.2 $kg.m^{-3}.MPa^{-1}$), despite observing a significant loss of 40 mm in slump. This showed that low control of dosage, as well as high temperature, low air humidity, and non-controlled environmental conditions, affects the efficiency but not in such a significant way. Benefits of a packing dosage method are valid even in those conditions.

Rec-05, the last one, shows that, with the use of recycled aggregates (100%) and no dispersant, maintaining the slump class (the same 120 mm as Ref-01), the efficiency of cement use (BI) is decreased in concrete with RA; however, the packing is capable of maintaining a good efficiency with increases from 11.5 to 16.2 $kg.m^{-3}.MPa^{-1,}$ comparing Ref-01 and Rec-05, both with no dispersants and the last one with packing design. Comparing Rec-05 (packed but no dispersant) with Rec-01 (dispersant but not packed), it is possible to see that the difference in BI is low (from 13.7 to 16.2 $kg.m^{-3}.MPa^{-1}$), showing that both packing and dispersion are important for decreasing BI. If packing is used, an economy in the dispersant content is possible, a very important matter since dispersant is by far the most expensive component of concrete.

CI, the CO_2 index, is an indicator which depends on a combination of

1 total binder content

2 the weighed emissions considered for the different binders.

As an example, clinker, which is a binder, can be considered as releasing 842 kg CO_2/ton (CSI WBCSD, 2013), or even the real factory measured emissions if data were available. Blast-furnace slag can be considered to produce zero emissions (if it is considered a waste), or incorporate a part of steel CO_2 releases, according to the life cycle analysis. In the case of this study, all binders used were the same cement with very high clinker content (~90% clinker, 5% gypsum, 5% limestone). Due to that, CI follows the same trends described in the previous analysis, since the BI increase or decrease in each case makes a proportional CI increase or decrease. It is possible to calculate CI using a quick estimate:

$$CI = BI * 0.9 * 0.842$$

where 0.9 is the clinker content of the cement used; 0.842 is an average emission of kg CO_2/kg of clinker (CSI WBCSD, 2013).

5 Conclusions

The use of CDW as recycled aggregates in concrete is a very usual way found in literature for decreasing landfill disposals and increasing building construction sustainability, since there is a huge amount of these wastes generated every day. However, despite all efforts, most researchers do not consider the increase in cement content that this strategy usually produces in concrete mixing. This is a gap in recycling technology if it aims at being sustainable and economically feasible.

This paper explored the potential of increasing the efficiency of concrete made from RA using a particle packing tool and dispersion of particles. If packing is purposely increased, the volume of voids between aggregates decreases and lower paste content is required for achieving the same rheological and hardened performance.

Results showed that the use of the dispersion and packing of aggregates in concrete made from RA is useful for compensating the loss of efficiency in cement use brought by the lower quality of these materials compared to natural ones, which was proved by the similar BI achieved for both non-packed concrete with natural aggregates (traditional technology) and packed ones with RA. In some cases, concrete formulations with RA had even lower BI (or higher efficiency) – cement is used with more efficiency to glue aggregates despite just filling a high empty void volume. This can have important industrial applications: with similar cement content, concrete with RA can become economically viable; and, with the same performance, they can increase the field of application of RA. The potential is even higher if the experimental settings used in this research were considered: RA used were low-quality ones (high water absorption, low density, not processed by particle or density separation, surface treatment, fine washing) and replaced all the natural ones, from fine to coarse. Furthermore, BI reached were similar to the practiced on the market (~10 $kg.m^{-3}.MPa^{-1}$) using a simple concrete mixer and simple mixing process.

Results can contribute to increasing the use of RA in concrete, considering the efficiency of cement use, which is usually neglected, and can decrease the environmental loads of such materials. This also depends on, rather than quality or processing of RA, better designing concrete methodologies. The difficulty is to control and calculate the packing of aggregates in real market practice. This needs to be addressed by software or by aggregate suppliers – which can mean a change in supplier's processing lines. If benefits of the packing of particles were disseminated, these changes certainly would be implemented with success in the chain, making it more sustainable.

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