



ORIGINAL ARTICLE

# Influence of hydraulic jiggling of construction and demolition waste recycled aggregate on hardened concrete properties

*Influência da jigagem hidráulica de agregados reciclados de resíduos de construção e demolição nas propriedades no estado endurecido dos concretos*

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**Abstract:** Concern with the maintenance of natural resources has increased research about recycled aggregates for concrete production. However, the heterogeneity of recycled aggregates is one of the main constraints for their use in practice, because it can generate variability in concrete properties, hence reducing their final quality. Then, the jiggling has been seen as a promising way of improving recycled aggregate quality. This paper aimed to evaluate its use for better application in concrete. A modified jig was used to sort recycled coarse aggregates. Concrete were produced with water/cement ratio from 0.5 and 100% of recycled coarse aggregate. The recycled aggregate properties upgrade were achieved and the results of compressive strength and modulus of elasticity of recycled concrete made with aggregate which were submitted to jiggling were increased, indicating a potential application in wide scale.

**Keywords:** construction and demolition waste, aggregate, variability and hydraulic jiggling.

**Resumo:** A preocupação com a manutenção dos recursos naturais tem elevado a quantidade de pesquisas sobre agregados reciclados para a produção de concretos. Contudo, a heterogeneidade desses agregados é uma das principais restrições para sua utilização na prática, pois pode gerar variabilidade nas propriedades do concreto, reduzindo assim sua qualidade final. Assim, a jigagem tem sido vista como um instrumento promissor de melhoria dos agregados reciclados. Esse artigo teve como objetivo avaliar o uso da jigagem de agregados reciclados visando sua melhor aplicação em concreto. Um jigge modificado para separar agregados graúdos reciclados foi utilizado. Os concretos foram produzidos com relação água/cimento de 0,5 e com 100% de agregado graúdo reciclado. O incremento das propriedades dos agregados graúdos reciclados foi alcançado e os resultados de resistência à compressão e módulo de elasticidade do concreto produzido com agregados que foram submetidos a jigagem foram mais elevados, indicando ter uma aplicação potencial em larga escala.

**Palavras-chave:** resíduos de construção e demolição, agregados, variabilidade e jigagem hidráulica.

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## INTRODUCTION

In recent decades, the recycling of construction and demolition waste (CDW) has been studied as a sustainable alternative for the minimization of consumption and exploitation of natural resources and also the waste generation in construction sector. The construction industry is considered the world’s largest solid waste generator with an estimated amount of more than 10 billion tons and a growth perspective to coming years [1]–[3] For the Brazilian scenario, it is

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estimated that the production of these residues although variable and correlated with the Human Development Index (HDI) is higher than 70 million tons per year (about 500 kg/inhabitants/year), configuring more than 50% of all urban solid waste in the country [4].

The waste generated by the construction industry is usually disposed in landfills and usually it is dumped in improper area becoming a major environmental problem. On the other hand, studies have been carried out over the last decades aiming at a nobler destination for this waste, such as its use as aggregates in the concrete production. However, CDW have a wide variety of materials, such as bricks, tiles, plaster, concrete and mortar resulting from the use of different construction techniques and systems present in the sector itself which characterizes great variability of aggregates [5], [6]. This variability in the composition and the origin of recycled materials, consequently in the recycled aggregates properties may jeopardize their application, so there is increasing concern about the quality of CDW aggregates which must exhibit high densities and homogeneity for use in structural concretes which [7], [8].

The quality of recycled aggregates from construction and demolition waste is directly related to pores and low resistance of these aggregates [5]. In order to reduce this variability, several processing, separation and classification techniques are applied to improve the materials used, such as: x-ray, infrared, water and air jigging, among others [9]–[12].

Among these techniques, jigging is a beneficiation process which by applying expansion and contraction pulsatile blows of water or air in a particle bed, it performs the density separation of the mixture material on layers with increasing order of magnitude from top to bottom [13]–[15]. Jigs are widely used equipment in the mining industry due to the ease and low cost operation. They are one of the oldest known processes for concentrating minerals which is based exclusively on the differences in density of the particles [13]. Recently, their use is expanding to other sectors, such as civil construction aiming to reduce variability and to improve the quality of aggregates for concrete production [5], [16], [17]. Sampaio et al. [10] and Ambrós et al. [12] showed the stratification of concrete/brick/gypsum particles in a air jigging system to separate recycled CDW aggregates was efficient. Also, Cazacliu et al. [18] have observed that it is possible to drastically improve the quality of recycled concrete aggregates.

However, as a viable alternative, this research proposes to evaluate the use of the technique of jigging of recycled aggregates aiming at its better application in concrete. Thus, the study was divided into two distinct phases: the characterization of recycled construction and demolition waste aggregate before and after jigging and the evaluation of the hardened properties of concrete produced with recycled aggregates after density separation.

## MATERIALS AND EXPERIMENTAL PROGRAM

### Materials

In this study, a Brazilian Portland cement CPV-ARI according to NBR 16697 [19], which is equivalent to cement Type III specified by ASTM C150/C150M-19a [20], were used for all concrete mixes. It was chosen because it is the purest cement in the local market. Due the minimum of the mineral additions presents on this cement, it is the best used for effectiveness of results of research. The Tables 1 and 2 show the main properties of this cement.

**Table 1.** Chemical characterization of cement CPV-ARI

Oxides	(%)	Oxides	(%)
CaO	77.01	SiO <sub>2</sub>	1.27
SO <sub>3</sub>	5.29	SrO	0.51
MgO	5.14	TiO <sub>2</sub>	0.23
Al <sub>2</sub> O <sub>3</sub>	4.50	Na <sub>2</sub> O	0.20
Fe <sub>2</sub> O <sub>3</sub>	4.15	P <sub>2</sub> O <sub>5</sub>	0.19
K <sub>2</sub> O	1.37	MnO	0.09

A quartz natural river fine aggregate whose particle size distribution is within the usable zone of NBR 7211 [27], with a fineness modulus of 2.16 determined according to NBR NM 248 [28], with specific density of 2.50 g/cm<sup>3</sup> and bulk density of 1.59 g/cm<sup>3</sup> in accordance with NBR NM 52 [29] was used in this study.

**Table 2.** Physical and mechanical characterization of cement CPV-ARI

Tests	CPV- ARI	Units	Standard	limits
Specific density	3.14	g/cm <sup>3</sup>	NBR 16605 [21]	-
Fineness (Blaine)	4628	cm <sup>2</sup> /g	NBR 16372 [22]	≥ 3000
#200	0.3	%	-	≤ 6
#325	1.7	%	-	-
Expansibility	0.0	mm	NBR 11582 [23]	-
Loss on ignition (1000° C)	3.6	%	NBR NM 18 [24]	≤ 4,5
Initial setting time	249	min	NBR 16607 [25]	≥ 60
Final setting time	323	min	NBR 16607 [25]	≤ 600
Compressive strength – day 1	21.1	MPa	NBR 7215 [26]	≥ 14
Compressive strength – day 3	37.6	MPa	NBR 7215 [26]	≥ 24
Compressive strength – day 7	42.5	MPa	NBR 7215 [26]	≥ 34
Compressive strength – day 28	47.9	MPa	NBR 7215 [26]	-

The coarse aggregate used was a recycled aggregate of construction and demolition waste from a landfill located in the city of Porto Alegre/RS, Brazil, which collects rubbles from different constructions, demolitions and refurbishments in the city. For its characterization, the specific density of 2.49 g/cm<sup>3</sup> was based on the method proposed by Leite [30], the bulk density of 1.14 g/cm<sup>3</sup> in accordance with NBR NM 45 [31], fineness modulus of 6.62 according to NBR NM 248 [28] and water absorption of 10.11% proposed by Leite [32]. The water used in this study is provided from the public supply network.

## Experimental program

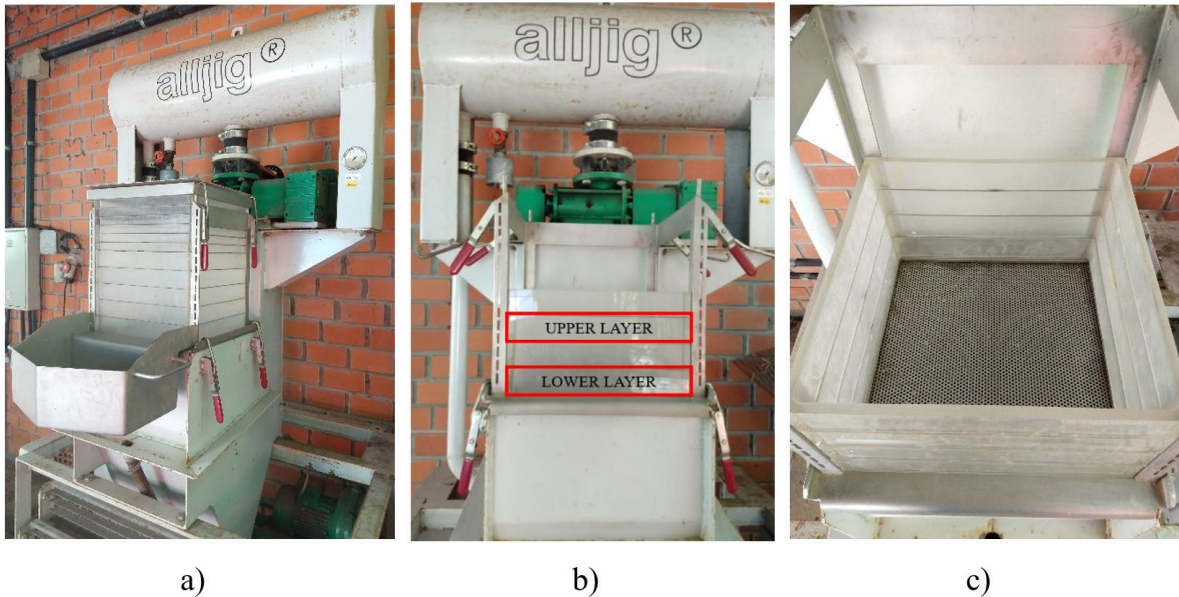
### Preparation of recycled aggregates

The coarse aggregates were collected from landfill in particle size range of 4.8 to 25 mm, regularly available for concrete production. They were washed to remove the large amount of impurities presents on their surface and then dried in an oven at 100°C. The CDW aggregates were sieved with the aid of a mechanical siever using particles in size range between 4.8 mm and 19 mm, because it is within the hydraulic jig operational range. The homogenization and quarrying were performed following the prescription of NBR NM 27 [33], until it was obtained aliquots of 25 kg, in order to all samples were representative and minimize the variability of the concrete produced. The characterization of recycled aggregates subjected to water jiggling will be shown in section 3.1, as it is part of the study results.

### Jiggling process

This research aims to evaluate the influence of the water jiggling process on the main properties of CDW recycled aggregates and its effects on the compressive strength and modulus of elasticity of concrete. Therefore, the sorting of CDW recycled aggregates was carried out in a batch pilot-scale hydraulic jig model AllJig S-400 (Figure 1a) from Allmineral with a capacity of approximately 25 kg per batch and an operating size range of 1 to 19 mm. This equipment is U-shaped with two sections, being one responsible for air pulsation and the other one for a separation chamber with stratification layers (Figure 1b). Both sections are filled with water and through the air injection into a tank containing water, the sample is moved in the separation plates of the other section. A centrifugal blower model SCL 30DH MOR of 1.32 kW which provides an air flow rate of up to 1.1 m<sup>3</sup>/min and generates pressures in the order of 30 kPa is used for air injection into a closed air chamber located on top of the jig. The jiggling chamber is assembled with three acrylic boxes with square section dimensions of 430 x 430 x 50 mm and six smaller boxes with dimensions of 430 x 430 x 25 mm fitted one over the other. The aggregate density separation is achieved as a result of the air flow through the particles bed that are supported on a perforated plate with a diameter equal to 1 mm inside the separation chamber (Figure 1c). During this process, two distinct upward air flows pass simultaneously through the bed, and therefore a continuous flow keeps the bed in a pre-expanded state and a pulsatile flow promotes successive blows of expansion and compression of

the bed, segregating particles of different densities due to the vertical movement of the particles in reply to the combined action of the drag force (upward movement) and the gravity force (downward movement).



**Figure 1.** a) hydraulic jig b) stratification layer; c) perforated plate  $\phi$  1 mm

For jiggling, an amount of 25 kg of aggregates was defined in accordance with the maximum capacity of the equipment. These were added inside the jig and the separation chamber was filled with water so that the sample remained submerged and then the pulsation mechanism was activated. Some jiggling control parameters were previously defined, such as: jiggling time of 2 min, pulse frequency of 80 RPM (revolutions per minute) and bed expansion of 5 cm. The jig was fed through the full volume of three vertical layers of 5 cm and two smaller layer of 2.5 cm. At the end of each test, the boxes containing the stratified material were removed separately by a collector attached to the top of the jig, so that the horizontal drag of the boxes deposited all its contents inside each layer. For this research, only the denser aggregate disposed in lower layer and the less dense aggregate belonging to upper layer were used (Figure 1b).

### Concrete production and test methods

Previously the concrete production, the coarse recycled aggregates have passed through the pre-saturation stage, in order these materials do not absorb the mixing water. Due to the high water absorption potential of these aggregates, the water in the mixture would be absorbed by them and would influence the performance and the concrete properties, and therefore, this research stage is essential. The pre-saturation rate of the coarse recycled aggregate was set at 80%, the same used by Cordeiro [34] and recommended by NBR 15116 [35]. For this procedure, the aggregates were submerged for 24 hours in order to achieve total saturation, so that subsequently they were dried until they got the condition of 80% saturation, measured through the loss of mass. The aggregate was saturated inside and its surface kept dry, allowing a better adherence with the mortar. Afterward, concretes were prepared following the methodology used by Malysz [36] with water/binder ratio of 0.50 and the mixture proportioning was defined by using weight proportioning in the ratio of 1:4 for the components cement: aggregates. A liquid superplasticizer admixture with a rate of 0.26% in relation to the mass of cement, pH of 6.58, density equal to  $1.061 \text{ g/cm}^3$  and solid percentage of 31.58% was added in the mixture. Three groups of concrete were prepared: (a) concrete with recycled aggregates submitted to jiggling process and disposed in lower layer; (b) concrete with CDW aggregates submitted to jiggling and disposed in upper layer; and (c) a control concrete with aggregates that are not submitted to jiggling.

The concretes were molded in cylinders  $\phi 100 \text{ mm} \times 200 \text{ mm}$  and filled in two stage; in the first stage, a layer of concrete was poured into the mold and compacted on a shaking table for 15 seconds; after that in second stage, more concrete was added until the mold was full and compacted on shaking table for 15 seconds. After 24 hours, the samples

were demolded and cured in a climate chamber (relative humidity > 95% and temperature of  $(23 \pm 2)$  °C) until the ages set by experiments.

In order to evaluate the compressive strength, the concretes were ruptured at 28 days according to NBR 5739 [37]. A hydraulic testing machine, model DL20000, with a compression load rate of  $0.45 \pm 0.15$  MPa/s was used to rupture the samples. The modulus of elasticity test of the concrete was also performed at 28 days, as prescribed by NBR 8522 [38].

## RESULTS AND DISCUSSIONS

### Recycled aggregates properties

Construction and demolition waste is residue generated from refurbishment, excavation or demolition and usually includes inert materials (concrete, ceramics, bricks, tiles, etc.) with lower amounts of other components such as wood, glass, gypsum, bituminous mixtures, among others [39]. The main obstacle to the use of recycled aggregate of construction and demolition in concrete is the great heterogeneity of its composition, since the construction sector includes several types of systems, avoiding the development of precise models to control and predict the properties of recycled aggregates [40]. Figure 2 shows the stratification results, in percentage of mass in each layer analyzed, of the composition of recycled aggregates before and after they are submitted to jiggling. Concrete aggregates, mortars, ceramic materials and residues present in lower layer and upper layer of the equipment were quantified in relation to the total mass of CDW aggregates.

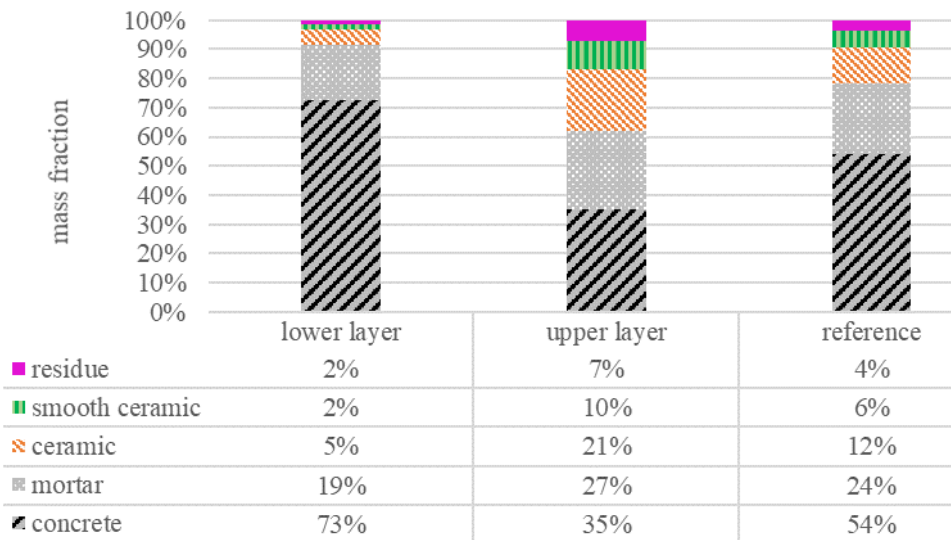


Figure 2. CDW aggregates composition of each layer

It is noted that CDW aggregate components separation took place when were subjected to the jiggling process, with a greater fraction of higher density aggregates present in the lower layer and the less density aggregates disposed in the upper layer, following a trend line of the results and proving the jiggling efficiency, in accordance with described by Sampaio and Tavares [13]. At first, it is possible to observe that the most part of concrete aggregate tended to concentrate in lower layer (73% mass) due the higher density in relation to other materials. The amount of ceramic aggregate before jiggling was 18% and after the sort operation it was set at only 7%. On the other hand, the mortar has an intermediate density then the jiggling process was less efficient, but no least important, reducing from 24% to 19% in lower layer. These results corroborate those found by Sampaio et al. [10] and Ambrós et al. [41] although they differ from those found by Corrêa [42] Malysz [36] and Mondini [43] who did not consider the CDW separation satisfactory in pneumatic jig, because they found different density materials in all stratification layers of jig. In fact, this study shows the hydraulic jiggling efficiency to separate CDW particles, indicating as an alternative to obtain nobler aggregates for concrete production.

Figure 3 shows the results of the characterization of all recycled aggregates used in the research. It can be seen that the specific density of CDW coarse aggregate was 2.53 g/cm<sup>3</sup> in lower jig layer, 2.46 g/cm<sup>3</sup> in upper layer and 2.49 g/cm<sup>3</sup> for those aggregates that did not go through the jiggling process. As shown in the results of CDW composition, the greater presence of concrete aggregate and lower amount of ceramic materials in lower layer can be a positive factor in increasing the specific density of aggregates. Due the mixed aggregates present on upper layer resulted in a less specific density in relation to aggregates that were not jiggling submitted. Thus, it can be concluded that the jiggling procedure has an influence on the specific density of CDW aggregate. In contrast to the specific density, the jiggling process did not have as much influence on the bulk density, with a slight decrease in value for the aggregates who were jiggling submitted. However, it cannot be assumed that it is influenced by gravimetric improvement process.

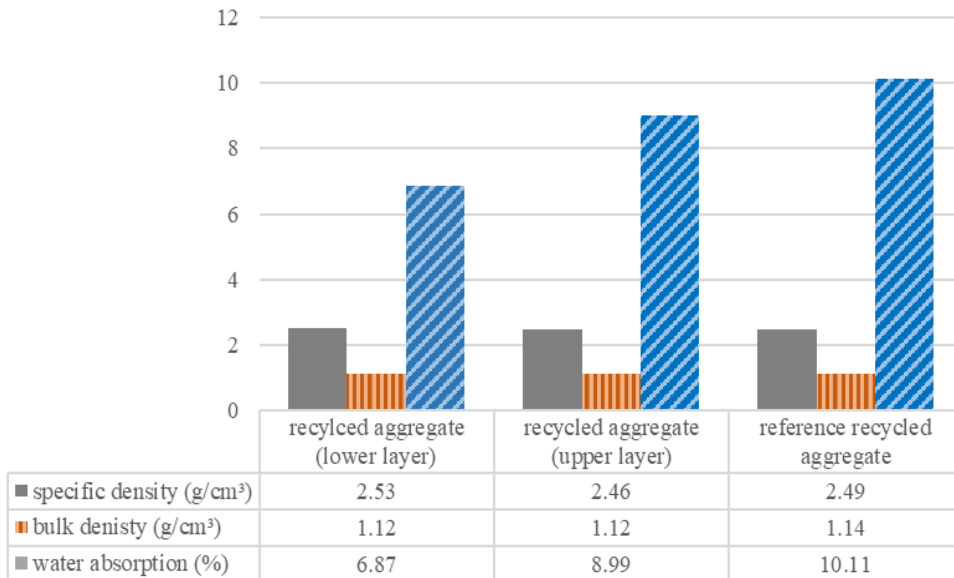


Figure 3. Characterization of CDW recycled aggregates

Recycled aggregates have a higher porosity when compared to natural aggregates, which results in a greater capacity to absorb water and may affect some concrete properties in the fresh and hardened state [34]. Therefore, the determination of the water absorption rate of CDW aggregates is necessary in order to avoid future problems for concrete. Figure 4 shows the results of water absorption rate of the CDW aggregates that were submitted to jiggling process and compares it with those that did not go through jiggling.

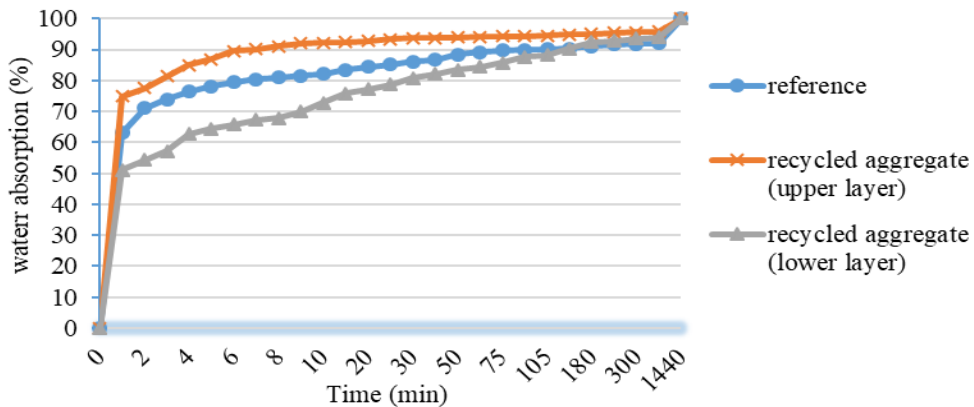


Figure 4. Water absorption rate of recycled aggregates

Figure 4 shows that recycled RCD aggregates absorb a large amount of water in the first minute, up to 54% for aggregate in lower layer, 63% for aggregate in upper layer and 74% for aggregates that were not jigging, due the high porosity of its structure. With the results obtained, it was found that jigging process provided an improvement in CDW aggregates properties in terms of water absorption. For that, a decrease of 32.04% in water absorption of aggregate on lower layer and 11.07% for aggregate on upper layer was noted when comparison is made with those that did not go through jigging. The aggregates of lower layer are basically constituted of concrete aggregate with a higher specific density, which is less porous than ceramic aggregate which may be a determining factor in this result.

### Compressive Strength of recycled concrete

The compressive strength of all recycled concrete is shown in Figure 5. The average, standard deviation and coefficient of variation were obtained by six samples at 28 days of age. It was observed that the compressive strength of concrete made with aggregates set in lower layer of jig showed a slight increase of 13.17% compared to reference concrete. When the comparison is with aggregates from both stratification layers was carried out, the results obtained were those expected, which those concrete made with aggregates from lower layer showed an increase in compressive strength compared to concrete made with aggregates from upper layer.

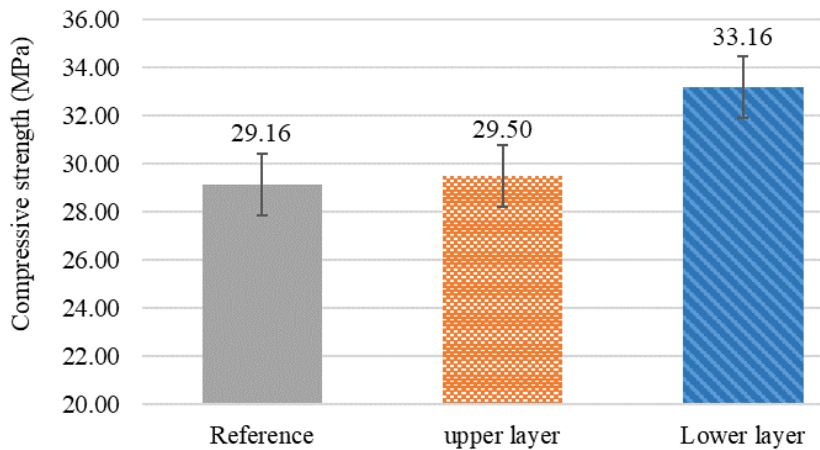


Figure 5. Compressive strength of recycled concrete at 28 days

Table 3 shows the analysis of variance (ANOVA) applied to the study in order to verify the influence of the stratification layer in results of this research. According to this analysis of variance and taking a significance level of 5% as a decision criterion, it was observed that the stratification layers of jig were not statistically significant influence on the compressive strength of concretes.

Table 3. Analysis of variance (ANOVA) - compressive strength of recycled concrete

Source of variation	SQ	gl	MQ	F	P	Sig.
stratification layers	1407.825	2	703.9126	2.403571	13%	non
residue	4100.057	14	292.8612			
Total	5507.882	16				

SQ: Quadratic sum; GL: Degrees of freedom (n-1); SQF: quadratic average; F: test F (calculated Value); P: Significance level; If  $p < 5\%$  = significant impact;  $p > 5\%$  = non-significant

### Modulus of elasticity of recycled concrete

Concrete is a heterogeneous material, so the factors that determine its elastic performance are the volumetric fraction, the density and the modulus of elasticity of their components as well as the characteristics of the interface transition zone of concrete. The modulus of elasticity of concrete is influenced by the porosity of their components, being the density

inversely proportional to the porosity, this is an important factor in determining the elastic performance of concrete. According to some researchers, the coarse aggregate has a significant effect on the modulus of elasticity of concrete [44]–[46]. Ho et al. [47] emphasized that the more porous aggregates in mixture results in a lower modulus of elasticity values for concrete. The results of the modulus of elasticity test for concrete are present in Figure 6. The average, standard deviation and coefficient of variation were obtained by testing four samples at 28 days of age.

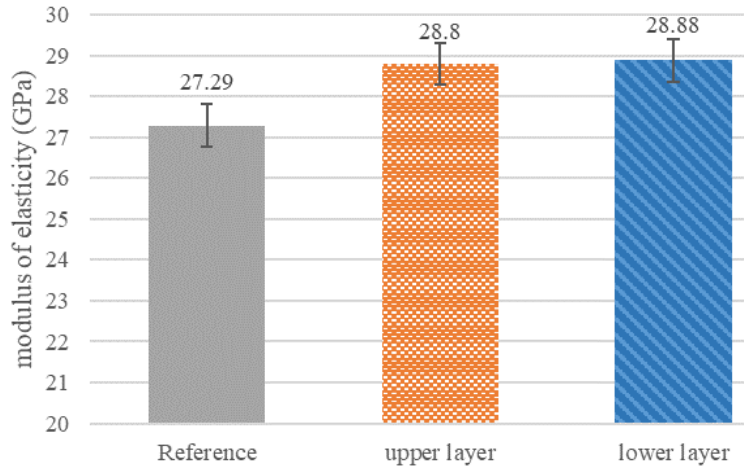


Figure 6. Modulus of elasticity of concrete at 28 days

The results shown a slight increase of 5.82% in value of the modulus of elasticity of concrete made with aggregates on lower layer compared to reference concrete. However, for concrete with less dense aggregates whose arrangement took place in upper layer of the equipment an increase of 5.53% in value of modulus of elasticity compared to reference concrete can be observed.

Table 4 shows the analysis of variance applied to the study in order to verify the influence of the stratification layer in the results of the modulus of elasticity of concrete. According to this analysis of variance and taking a significance level of 5% as a decision criterion, it was observed that the stratification layers of the jig were statistically significant influence on the modulus of elasticity of the concrete.

Table 4. Analysis of variance (ANOVA) – modulus of elasticity of the concrete

Source of variation	SQ	gl	MQ	F	P	Sig.
stratification layers	4.856022222	2	2.428011	7.527939	2.3138%	yes
residue	1.9352000000	6	0.322533			
Total	6.791222222	8				

SQ: Quadratic sum; GL: Degrees of freedom (n-1); SQF: quadratic average; F: test F (calculated Value); P: Significance level; If p < 5% = significant impact; p > 5% = non-significant

Although the stratification layer effects on the modulus of elasticity was considered statistically significant by Fisher’s test, a comparative average analysis was done and it was observed that the modulus of elasticity of concrete are equal to each other.

## CONCLUSIONS

This research presents the processing of CDW recycled coarse aggregates through hydraulic jiggling aiming reduce the inherent variability of this material and to favor its use in concrete and in order to improve its properties in the hardened state. The main conclusions of the study are presented below:

- hydraulic jiggling proved to be an efficient technique for processing recycled aggregates, as the particles were separated by density in different stratification layers of jig. In general, the separation of the CDW components is



noticeable, in which higher density aggregates were accommodated on lower layer and less dense ones on upper layer, following a trend line of the results;

- after jiggling, an improvement in specific density values and water absorption rates was obtained due the high presence of concrete aggregate in the lower layer which has a higher specific density and it is less porous than ceramic aggregates;
- the concrete produced with CDW recycled coarse aggregates that were submitted to jiggling process showed increased values of compressive strength and modulus of elasticity compared to the reference concrete.

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