Improving the characteristics of recycled aggregates by using mineral processing equipment: water jig and sensor based sorting

M. Peticila[1], A. S. Young[2,] B. Cazacliu[3], C. H. Sampaio[4], M. M. Veras[5], C. O. Petter[6],

[1]National Company of Road Infrastructure Management - CNAIR, Bucharest, Av. D. Golescu, 38, Sect.1, 010873, Romania (marian_peticila@yahoo.com)
[2,4,6,] Federal University of Rio Grande do Sul - UFRGS, Porto Alegre, Rio Grande do Sul, 90040-060, Brazil
[3]Institut français des sciences et technologies des transports, de l'aménagement et des réseaux - IFSTTAR, Nantes, 44344, France (bogdan.cazacliu@ifsttar.fr)
([4]sampaio@ufrgs.br, [6]cpetter@ufrgs.br, [2]aaronsyoung@gmail.com)
[5]Federal Institute of Education, Science and Technology of Amapá - IFAP, Macapá, Amapá, 66077 530, Brazil (moacir.veras@ufrgs.br)

Keywords: *recycled aggregates, automatic sorting, jig*

Abstract
The construction and demolition waste (CDW) resulting from demolition or from the maintenance of civil engineering projects is a major problem for all countries or regions, regardless of their economic development. Recycled aggregates (RA), obtained from CDW, can be directly used as filling material for landscaping with minimal processing. To increase the economic efficiency of recycling requires selective processing of recycled aggregates for use as raw materials in the manufacture of new materials in civil engineering. This article presents analysis of various trials on the application of mineral processing technology to the processing of recycled aggregates. The major advantage of these technologies consists of high productivity, relatively low cost of equipment and lower energy costs for processing. Two types of laboratory scale equipment similar to industrial equipment were tested. For the ballast material (size range 20 - 40 mm) automatic sorter (AS) type equipment was used, with facilities for analysis by dual energy X-ray transmission (DE-XRT) and charge-coupled device (CCD) sensor in visible spectrum. For RA (size in range 4-20 mm) gravimetric separation in water with "water jig" type equipment was used. It is very important to know as accurately as possible how RA influence in water absorption and density of new concrete when used. If absorptions and densities for each component and their distribution in the mixture of natural aggregates with RA can be known, evaluations can be made. From the values shown as a result of the trials performed, a good predictive model for water absorption and density is observed.

1. Introduction

Construction and demolition waste (CDW) resulting from the demolition or the maintenance of civil engineering projects is a major problem for all countries or regions, regardless of their economic development [4, 7, 16, 35, 37, 40]. According to EU documents, CDW is one of the heaviest and most voluminous waste streams generated in the EU [41]. It accounts for approximately 25% - 30% of all waste generated in the EU and consists of various materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, asbestos and excavated soil, much of which can be recycled [39]. The processing of large quantities of waste generated by demolition is necessary for environmental protection and for sustainable development, in correlation with the preservation of existing natural resources and for offsetting their deficiency locally or nationally [24, 28, 4, 11, 37]. Old masonry material usually has lead-based paint and Portland cement has 5% phosphate additive [15]. The total amount of waste produced annually can be estimated from many different sources, and although amounts vary annually depending on the stage of national or regional economic development, the values are on the order of magnitude of 10^6 - 10^7tons/year [4, 39, 40, 10].

Until relatively recently (beginning in the'70s – '80s), there were no rules imposed on the recycling of CDW materials, particularly in the vicinity of major cities where huge quantities of waste were stored. Part of this waste is very heterogeneous but its predominant components are concrete, brick, plaster, ceramics and degraded asphalt [6, 9, 26, 31]. Given that much of this waste comes from infrastructure works, in the context of sustainable development it is necessary to process the waste considering the entire life cycle of buildings by integrating recycling technologies and adapting effective techniques at all stages of construction, maintenance and demolition and recycling and reconstruction [16, 27, 14, 35]. Thus, the impacts, both social and economic of reducing pollution, saving natural resources, and reducing the carbon footprint of these activities must be considered [3, 12, 24, 40].

Recycling of CDW, in most cases is imposed by environmental legal regulations, probably through indirect subsidies, but there are cases when private companies can develop profitable economic activities in this area. At the EU level, there is the European Framework Directive 2008/98/EC [39], which has a different degree of implementation from each EU country. Also, there are national standards in countries like the Netherlands and Germany, probably due to the degree of economic development, but also because of the limited quality natural aggregate reserves in their own countries [37]. Worldwide, the effects of local or regional administration regulations in the areas with strong urban development are generally very positive, of which good results have been obtained in NY, Taiwan, and Hong-Kong [16, 19, 35].

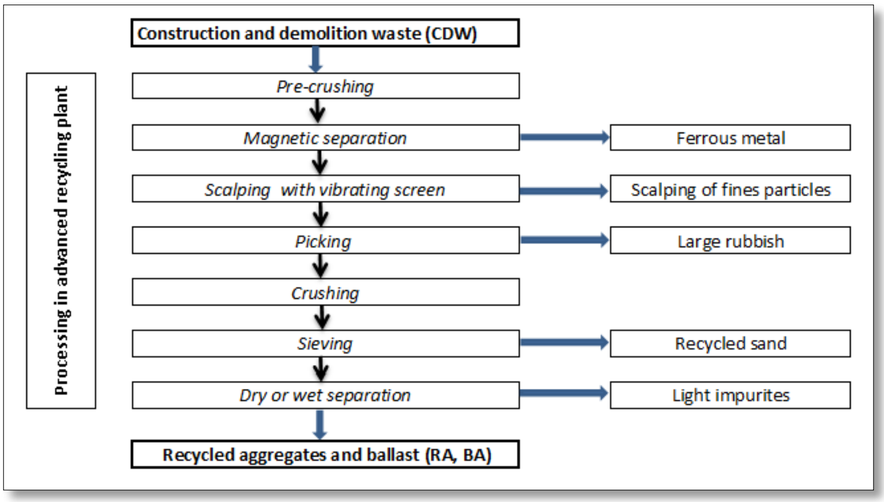


Figure 1.1 – Current advanced process in recycling platforms

Recycled aggregates (RA) and Recycled Ballast (RB) obtained from CDW are inert wastes, which can be directly used as filling material with minimal processing, but in many cases this use becomes more restricted especially if the building location is a long-distance for transport or quality requirements impose rigorous geotechnical specifications [24, 28]. To increase the economic efficiency of recycling deposits requires selective processing of recycled aggregates for use as raw materials in the manufacture of new building materials, concrete and/or road materials. An example for this process is exemplified in Figure 1.1 [14, 21, 23, 32, 36].

Although there are many scientific articles on the possibility of using RA as raw materials (rocks and mortar from waste concrete, bricks and ceramics) for obtaining new concrete, the authors of this study found no detailed information on how to sort the components of RA by automatic sensor based sorting. Also, unknown to the authors of this study were the details for sorting or processing CDW in terms of high productivity.

This article presents analyses of trials that are part of a larger study on the application of mineral processing technology to the processing of recycled aggregates. The major advantage of these technologies consists of high productivity, relatively low equipment cost and low energy costs for processing. In the laboratory “Laboratório de Processamento Mineral” - LAPROM at the Universidade Federal do Rio Grande do Sul, two types of laboratory scale equipment, which were both similar to industrial equipment, were used for testing. For larger inert CDW (ballast in size range 20 - 40 mm) Automatic Sorter (AS) type equipment was used, with facilities for analysis by dual energy X-ray transmission and CCD camera sensor using the visible light spectrum. For smaller sizes of CDW (RA in size range 4-20 mm) gravimetric separation in water was used with “jig” type equipment.

Gravity concentration is defined as the process whereby particles of different sizes, shapes and densities are separated from each other by gravity. It is called gravity concentration because the separation is performed mainly based on density (specific gravity). Jigging is a separation process which consists of repeated expansion and contraction of a vertical bed of particles through a pulsating movement of water. The result is the stratification of the bed. The particles are deposited in layers of increasing density from top to bottom. Jigs were and still are widely used, mainly due to their costs. They have low operating costs, are robust, have high capacity and are easy to operate. Usually, jigs are used to treat ores with a wide particle size range and with large fluctuations in contents [29]. For this reason, jig technology can be used with high economic efficiency for RA treatment [25, 29].

Automatic sorting can be further developed in the future as computing power grows in parallel with falling prices for software and hardware (computer components, DAQ boards, sensors, etc.). Technology also will develop through implementation of machine learning algorithms. In conclusion, automatic sorting in combination with artificial intelligence technologies that enable automatic recognition and adaptation to the heterogeneity of CDW is the next trend for the processing of the material [20].

To obtain an improved mix of the RA with the Sorter, several scenarios are conceivable by passing the mixture successively through the sorter under various settings of CDD and/or DE-XRT. After each pass of the material, it splits into two parts. Given the intended use of the RAs as materials to make concretes, it is of interest to eliminate significant amounts of material in the mixture which is brittle or has high water absorption, and also to increase the natural aggregates content.

This article insists on "water jig" technology and shows that this technology can successful process a blend of recycled aggregates called "concentrate", which contains a high content of natural aggregates. Also, this concentrate will contain crushed brick and concrete mortar with higher densities, and lower porosities and absorption. This concentrate can be used to produce building materials (concrete, bituminous mixtures, etc.) with the performance characteristics demanded by governmental standards. By using water jig, besides advantages in terms of productivity, reduced costs, and equipment reliability [25], there is a major advantage to the use of water in the process, because this leads to cleaner recycled aggregates as a final product.

2. Materials

The feed recycled inert demolition waste used for the study came from a non-governmental organization, located in the borough and named Cristal, in the city of Porto Alegre. The demolition waste was received from small constructions sites from that region, none of which contained plaster. After receiving this material it was comminuted into coarse aggregate to produce concrete block pavers and other small concrete elements (like street curbs). The comminution of the material was carried out by jaw crusher. In this case, approximately 98% of the material contained crushed concrete, natural aggregates, bricks and tiles. The other impurities were: glass, gypsum, scrap metal, etc. (~2%).

The material was sieved and then retained for experimentation in the size range of 4.75 – 37.5 mm (CDW_F). The fine material, inferior to the 4.75 mm size, was not used in this study, considering that such material can be used as material for roads, especially for lower layers of the road structure (for layers stabilized with cement or asphalt concrete). Than the material retained for experimentation was sieved again at 19.1 mm. For tests involving sorter technology, the size range 19.1 – 37.5 mm, named feed ballast (RB_F) was used. For the jig technology tests, the size range of 4.75 – 19.1 mm, named feed recycled aggregate (RA_F) was used. The mass of materials it is shown in Table 2.1 The size range selection was made considering both the estimated efficiency of the two methods, and the optimization of the study in the laboratory with regards to the equipment available.

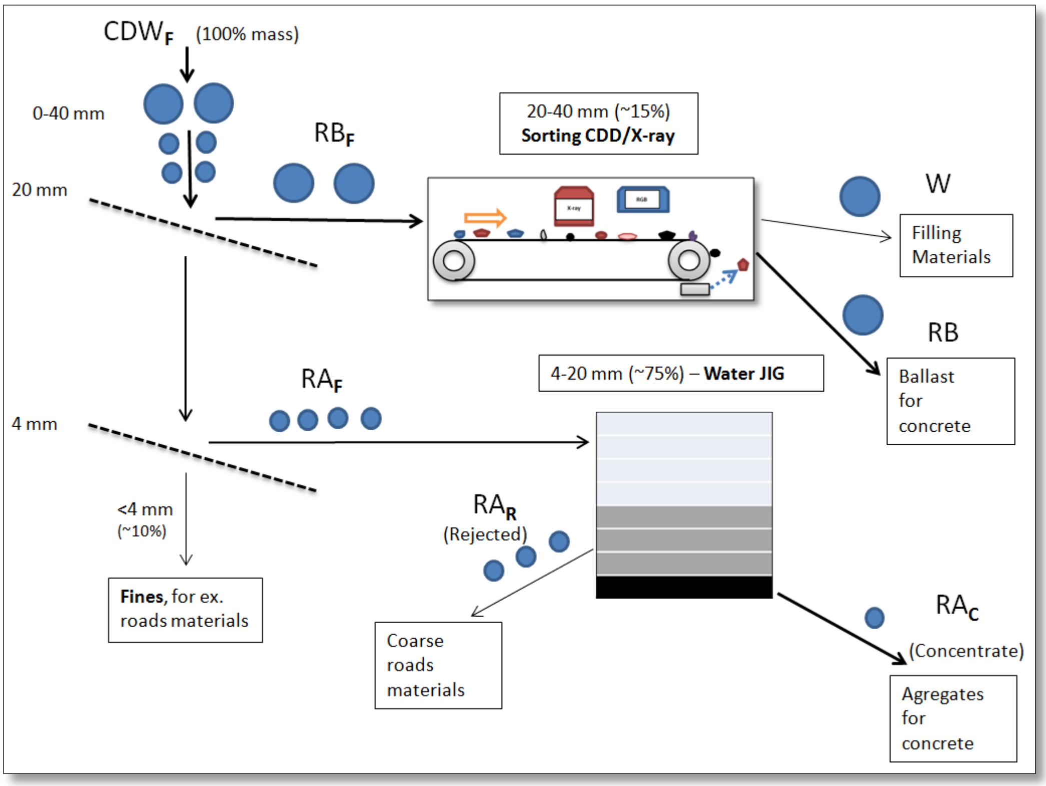


Figure 2.1- Process schematic for inert CDW proposed in our laboratory studies

The distribution of components in the feed was determined by manual sorting. Figure 2.2 represents components of the two granular classes, excluding the mixture's impurities, which account for approximately 1.5% of the total mixture. Total masses of each size range sampled for component identification were above 4 kg. The samples were divided by quartering or splitting until what was considered a good representation of the heterogeneous mixture was taken.

Table 2.1 - Size Distribution for RA

CDW_F Size *<mm>*	Mass *<Kg>*	Mass *<%>*
19.1 – 37.5 (BA_F)	68,3	16%
4.75 – 19.1 (RA_F)	320,0	74%
0 - 4.75	45.4	10%
Total:	433,7	100%

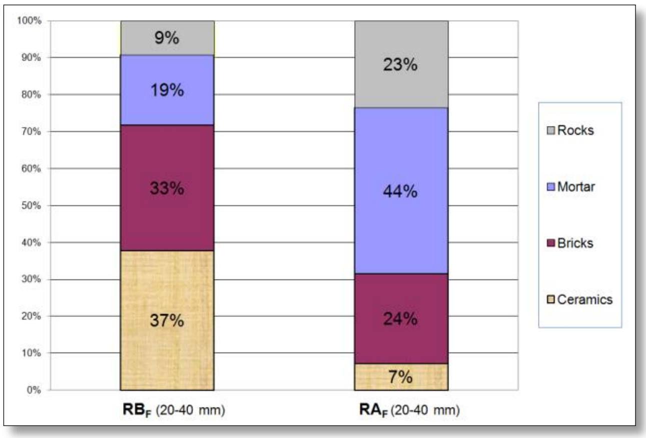


Figure 2.2- Distribution of components in the RA mixture used in study

3. Laboratory methods

3.1 Determination of Particle Size Distribution

The results of the particle size distribution test are provided in graphical form to identify the gradation of the aggregate. The complete procedure for this test is EN 933-1 or ASTM C 136 /AASHTO T 27.

The results are presented in a graph of percent passing versus sieve size. Because coarse RA were targeted, the sieve size scale is linear for the entire graph. To find the percent of aggregate passing through each sieve, first find the percent retained in each sieve.

Sieves with square meshes were used, which had diameters of: 37,5 mm, 19,1 mm, 15,9 mm, 12,7 mm, 9,5 mm, 8,0 mm, 6,35 mm, 4,76 mm, 2,0 mm and 1,0 mm.

3.2 Manual sorting

To identify the components from the RA mix was used the manual sorting, by hand, for the samples of 1-2 kg on average. To ensure representativeness mix, samples were divided by splitting.

Figure 3.1 - The components from the recycled aggregates (RA) after manual sorting

3.3 Sink and float test

The sink and float course is constructed by plotting cumulative yield percent of sinks at specific gravity against the cumulative percent of sinks at the reference specific gravity, also named the NGM-index curve [29]. This curve yields the "efficiency" of the gravimetric separation of the material. In order to evaluate the separation effectiveness for the 4.75 to 19.1 mm size fraction processed by jiging, 3.7 kg of material was tested using the sink and float test.

In order to know the densimetric distribution of particles, tests called sink-float were carried out using mixtures of the following organic liquids: benzene (C_6H_6 – 0,9 g/cm³), tetrachloroethene (C_2Cl_4 – 1,6 g/cm³) and bromoform ($CHBr_3$ - 2.9 g/cm³), at densities in range 2.0 g/cm³ - 2.8 g/cm³ [29].

At first, the particles were immersed in a liquid with density 2.0 and they were divided in two portions: +2.0 g/cm³ (material with density over 2.0 g/cm³) and -2.0 g/cm³ (material with density under 2.0 g/cm³). The material that sinks (density over 2.0 g/cm³) is then immersed in a liquid with density 2.1 g/cm³ and divided in the 2 parts: density over and density under 2.1 g/cm³. The procedure is repeated for all densities described above.

Test and the samples obtained are shown in Figure 3.2.

Figure 3.2 – Sink and float test for the recycled aggregates (RA)

3.4 Automatic sorting with COMEX lab sorter

Automatic sorting is the method of taking individual particles, comparing their measured properties with desired criteria, and then separating the particles, through the use of an external force, into different products based on their measured properties. A COMEX Lab-Sorter MSX-400-VL-XR-3D, shown as Figure 3.4, was used for the study; its working principle and schematic are shown in Figure 3.4.

The sorter can work with two detection systems, one involves the visible light spectrum and the other detection system involves images obtained through DE-XRT. The visible data collected by the CCD camera are represented using Red, Green, and Blue (RGB) colors functioning in a Hue, Saturation, and Luminance (HSL) model. In this model, the sum of all colors yields white. The X-ray data collected by the DE-XRT sensor is a compilation of high and low intensity X-ray images which are captured in grayscale. There is built-in software which superposes these X-ray images, thus reducing the effect of increased X-ray attenuation due to increased sample height. The superposed images are then falsely colored based on a dynamic color model. The color model generated from the DE-XRT is therefore based solely on the readings of the materials in question. The comparisons observed in the X-ray data are relative comparisons and only treat the limited sample base analyzed [33].

Figure 3.3 - The equipment COMEX Lab-Sorter MSX-400-VL-XR-3D

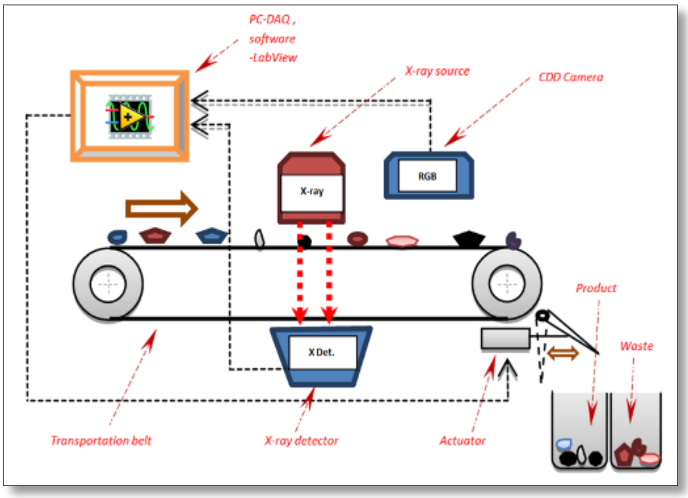


Figure 3.4 - Constructive principle of the AS – COMEX equipment

X-ray online image scanning of the ballast by density is possible using the sorting equipment, because the equipment captures two pictures in grayscale with pixel intensity values correlating to the thicknesses and densities of the samples and referencing these values with known X-ray source intensity values. In combination with the high-resolution image this gives an estimation of the content and properties of the scanned materials. In this way components can be automatically classified into desired categories [32].

Formally speaking, the equipment employs the method of quantitative sorting using DE-XRT imaging as may be found in the literature [17]. This method involves X-ray transmission theory, given by Lambert's law (relation 3.1):

$$I_{det} = I_0 \cdot e^{-\mu(\lambda)\cdot d} \tag{3.1}$$

where:

I_{det} – recorded intensity, and is exponentially dependent on d,

$\mu(\lambda)$ – linear damping coefficient that is a function of the wavelength λ.

I_0 – X-ray source intensity

d – sample thickness

Using Lambert's law, two $\mu(\lambda)$ *values* ($\mu(\lambda)_{high}$ and $\mu(\lambda)_{low}$) as well as d can be determined for any material. By using two distinct I_0 values at two or more different wavelengths the effects of particle height can be negated. This is possible because $\mu(\lambda)$ is a known function which depends on wavelength, density and average elemental composition of the material in question, with the relationship between I_{det} (high) and I_{det} (low) being a function of $\mu(\lambda)_{high}/\mu(\lambda)_{low}$ and d.

Using these relationships an approximation of the average atomic number of the observed sample and its thickness d can be determined.

Online analysis of images obtained by either CDD camera or DE-XRT, performed with COMEX software (made with LabView™ software), allows for setting the selection criteria of the two types of components that need to be separated prior to the initiation of the sorting test. The external force used by the sorter to separate the particles for the experiments performed in this study was that of a pneumatic flap.

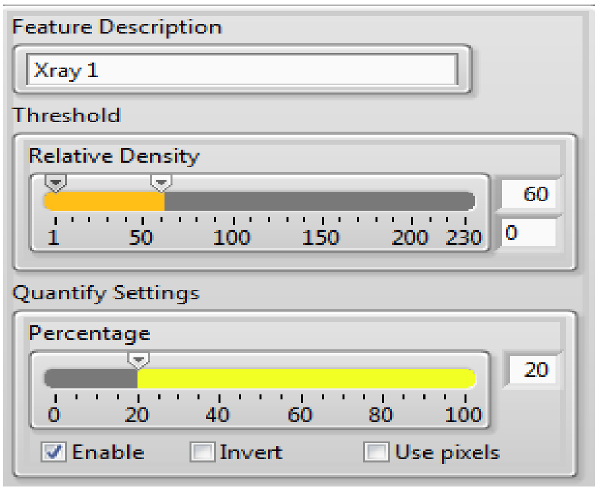


Figure 3.5.a- Settings in the COMEX software to use X-ray to extracting ballast with higher density

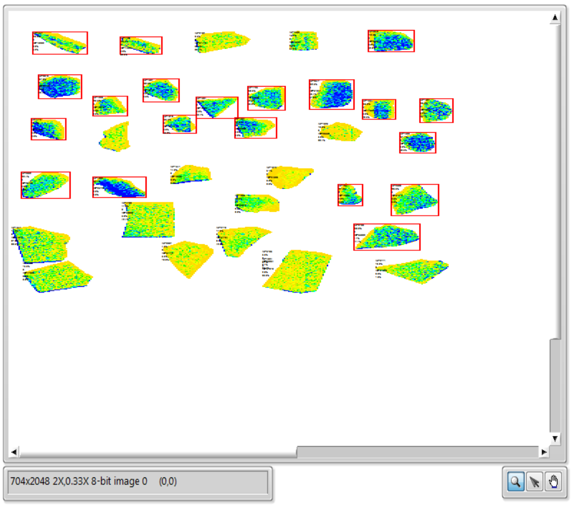


Figure 3.5.b - X-Ray image processed for automatic identification for ballast with low density

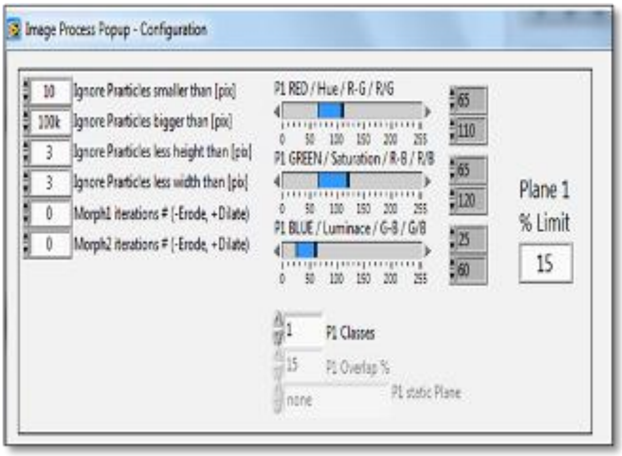


Figure 3.6.a - Settings in the COMEX software to use CCD camera to extracting bricks from the mixture of ballast

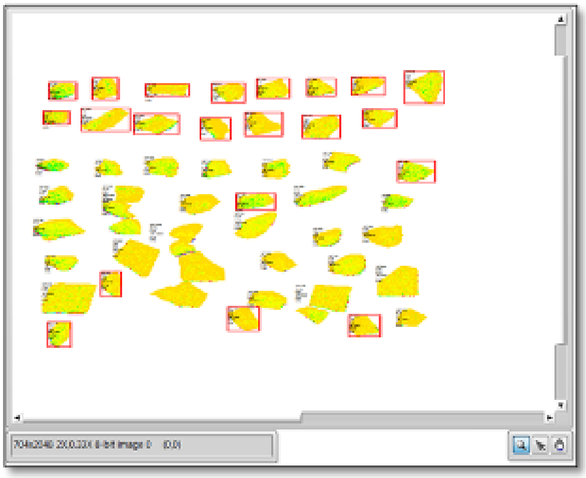


Figure 3.6.b - Automatic identification of bricks in red (first 2 upper rows)

To perform a separation, sample material is placed on sorter belt and fed into the sorter one particle at a time. The sorter analyzes each particle and decides whether to keep or reject the particle. The concentrate produced may be put back into the sorter and the process repeated under a different calibration of the sorter. For statistical studies on the accuracy of the method and settings, repetition of the same material can occur several times. The COMEX sorting software has subroutines for the selections made automatically on the analyzed material, which can be processed either as such or in statistical calculations combined with other tested parameters for product material or waste material.

3.5 Water jig

The device used to perform the tests in this study was a water jig, model "*minijig*"® S 400 - from All Mineral company (Figure 4.4). The jig is composed of a chamber assembled with a multiple layered transparent frame from plexiglass, where RA is placed for trial and stratification. The frames used in the tests were 35cm x 35cm x 5 cm [34]. In the trials, the RA was subjected to the action of two inputs of water flow which enter simultaneously from the bottom chamber. The first water flow is continuous and causes the expansion of the particle bed; the second water flow is discontinuous and is responsible for vibration of the particle. This continuous cycle of expansion and contraction gives a stratification of the particle bed, where heavier RA prevails with in the bottom layer and the lighter RA prevails in the top layers. The water jig yielded two RA mixtures: "concentrated RA" (RA_C), from the bottom layer, and "rejected RA" (RA_R), from the upper 3 layers.

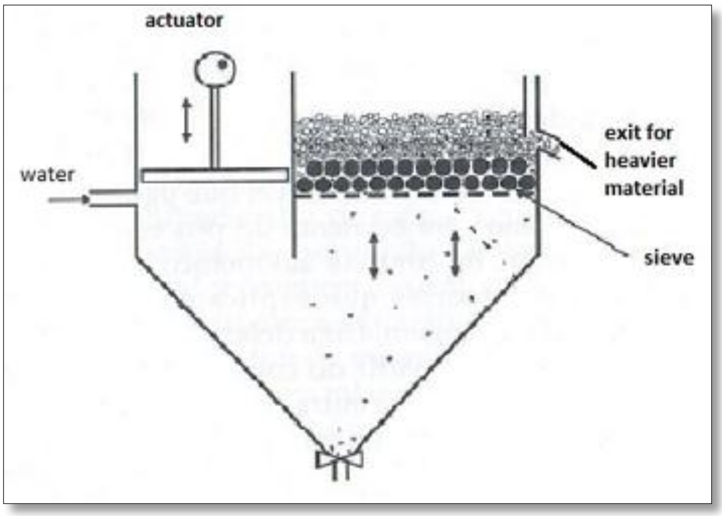


Figure 3.7 – Constructive principle of the "Water jig" [29]

The following operating parameters for the jig were used: frequency (0.5 s^{-1}), amplitude (25 cm) and time of operation (10 minutes). RA was loaded into the jig until it reached the height of 4 layers (frames). A total of 196.45 kg was used, which corresponds to 4 batches.

3.6 Determining the densities with gas pycnometer

To more precisely evaluate the effectiveness of the sorter, and considering that there was no major visual evidence to support differences of the same type of component in both RA mixture obtained, also given the small amounts of material collected and sorted (the limiting amount due to difficulty of manual sorting of the small particles), specific gravity measurements of the mixtures were performed using a gas pycnometer. In this way, an accurate evaluation of the variability of the components within the RA mixtures yielded by the sorter equipment could be performed.

The pycnometer determines the density of solid or powder samples by mesuring the pressure diference when a known quantity of helium under pressure is allowed to flow from a precisely known reference volume into a sample cell containing the solid or powder material.

Knowing ideal gas law ($PV = nRT$), gives the equation 3.2.

$$V_p = V_c - V_R\left[\left({}^{P_1}/_{P_2}\right) - 1\right] < cm^3 > ; \qquad (3.2)$$

where:
V_P – volume of sample $<cm^3>$,
V_C – volume of cell $<cm^3>$,
V_R – reference volume $<cm^3>$,
P_1 – refference pressure,
P_1 – pressure equalization

Having determined the sample volume very precisely, density can be calculated with relation 3.3.

$$D = \frac{M_p}{V_P} < {}^{g}/_{cm^3} > \qquad (3.3)$$

where:
D - density
M_p – mass of test sample $<g>$
V_P – volume of the sample $<cm^3>$

The uncertainty of the determination of gas pycnometer is very low, both for reasons of accuracy of the method and equipment, but also because it is unaffected by porosity or other superficial phenomena, for example when compared to determinations by immersion in liquid (water pycnometer or hydrostatic volume determinations).

Equipments used for density determination were a pycnometer, QuantaChome Multipycnometer® and one analytical balance with precision to within $\pm 0.5 \times 10^{-3}$ g. The cell reference used was "large cell", which allows for the determination of samples with a mass of about 110-130 g. Working pressure (P_1) is above 17 Psi (1.17 Bar).

For a more accurate analysis of the mixture heterogeneity, the uncertainty of the methods used must be considered. To estimate the coefficient of variation for the density determination with pycnometer, individual determinations of sample volume were used as a start. According to the working procedure, for each sample measurement the mean value of 3 individual measurements of the sample was determined by varying the pressure in the cell.

In this way, the standard deviation and coefficient of variation across all measurements for the pycnometer can be determined. A total of the 24 determinations were performed from a total of 72 individual measurements, which generated confident statistical results. Given that the variation of density as measured is within a small range, it can be assumed that the uncertainty of measurement may be made by the average of the coefficient of variation for each determination. In this manner, the value of the coefficient of variation of the method is C_{Vp}=0.10% was obtained. This value confirms the precision of the method applied in determining real density of the granular mixtures.

3.7 Specific Gravity and Water absorption

To demonstrate the possibility of using RA to make new concrete and to show some comparisons between the two materials obtained by jig technology (RA_C and RA_R), tests were performed according to the methods established in civil engineering. Thus, the densities and water absorptions in accordance with European standards EN 1097-6 or US standards ASTM C 127-88 / AASHTO T 85-91 were demonstrated. Although the European Standard EN 1097-6, the Annex H has restrictions for this particle size fraction, the hydrostatic method was implemented, with special attention given to its operation in the laboratory.

Steps for the procedure included the following:

1. Saturate the material by immersion in water, 24 h;
2. Use a towel to remove the film of water covering the surface and weigh the saturated surface dry (SSD) mass, after10 minutes;
3. Measure the hydrostatic mass jointly with the water temperature measurement to estimate the real density with Thiesen-Schell-Diesselhorst's relation;
4. Dry the sample until it reaches a constant mass and measure the oven-dry mass (drying above 24 h at 105ºC ± 0.5ºC).

The equation used to calculate densities and water absorption are (in accordance with EN 1097-6):

$$\rho_{App} = \frac{M_3}{M_1 - M_2} \cdot \rho_w < Kg/m^3 > \quad (3.4)$$

$$\rho = \frac{M_3}{M_3 - M_2} \cdot \rho_w < Kg/m^3 > \quad (3.5)$$

$$WA = \frac{M_1 - M_3}{M_3} \cdot 100 \quad < \% > \quad (3.6)$$

where:

M_1 − mass of saturated − surface − dry test sample in air $< g >$
M_2 − mass of saturated test sample in water $< g >$
M_3 − mass of oven − dry test sample in air $< g >$
ρ_w − water density corection with temperature $< Kg/m^3 >$

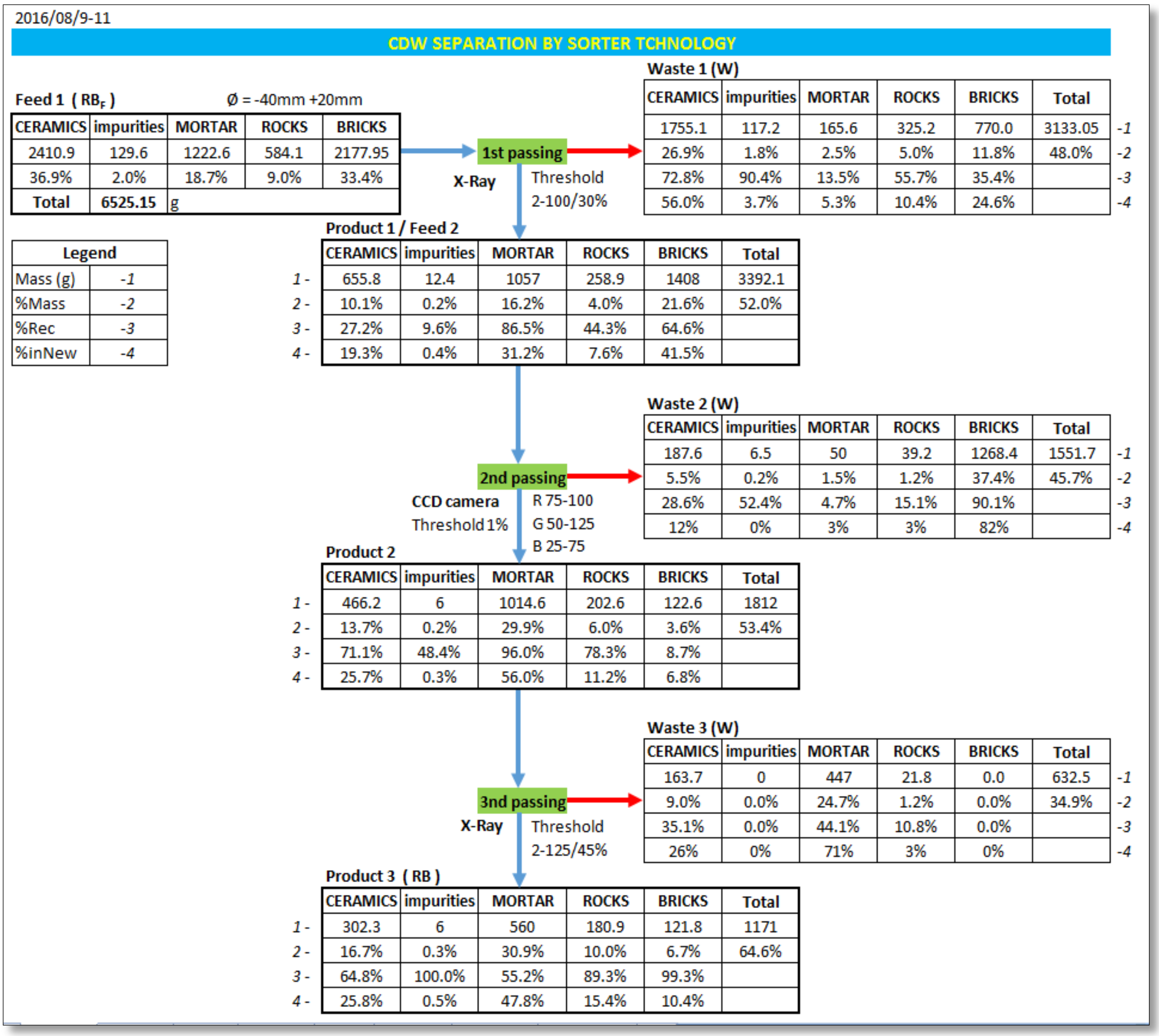
Relation 3.4 give in EN standards „Apparent particle density" and in the ASTM standard give „Bulk Specific Gravity". Relation 3.5 in ASTM standars give „Apparent Specific Gravity". Also, relation 3.6 it's named „Water absorption" in NE standards, and „Absorption" in ASTM standards.

4. Results

4.1 Automatic Sorting

Approximately 7 kg of ballast (RB_F) material was prepared from the bulk sample using a sample divider, also known as a splitter.

In Figure 4.1, a diagram of the separation process for the sorter, along with the mass balance for the various material components of the ballast material sorted is presented. Figure 4.2 presents the partition obtained, in mass distribution as a result of the sorter. It may be observed that in this process the content of natural rocks, in the RB increased from 9.0% to 15.4%.



2016/08/9-11

CDW SEPARATION BY SORTER TCHNOLOGY

Feed 1 (RB_F) Ø = -40mm +20mm

CERAMICS	impurities	MORTAR	ROCKS	BRICKS
2410.9	129.6	1222.6	584.1	2177.95
36.9%	2.0%	18.7%	9.0%	33.4%
Total	6525.15	g		

1st passing — X-Ray — Threshold 2-100/30%

Waste 1 (W)

CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total	
1755.1	117.2	165.6	325.2	770.0	3133.05	-1
26.9%	1.8%	2.5%	5.0%	11.8%	48.0%	-2
72.8%	90.4%	13.5%	55.7%	35.4%		-3
56.0%	3.7%	5.3%	10.4%	24.6%		-4

Legend

Legend	
Mass (g)	-1
%Mass	-2
%Rec	-3
%inNew	-4

Product 1 / Feed 2

	CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total
1 -	655.8	12.4	1057	258.9	1408	3392.1
2 -	10.1%	0.2%	16.2%	4.0%	21.6%	52.0%
3 -	27.2%	9.6%	86.5%	44.3%	64.6%	
4 -	19.3%	0.4%	31.2%	7.6%	41.5%	

2nd passing — CCD camera — Threshold 1% — R 75-100, G 50-125, B 25-75

Waste 2 (W)

CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total	
187.6	6.5	50	39.2	1268.4	1551.7	-1
5.5%	0.2%	1.5%	1.2%	37.4%	45.7%	-2
28.6%	52.4%	4.7%	15.1%	90.1%		-3
12%	0%	3%	3%	82%		-4

Product 2

	CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total
1 -	466.2	6	1014.6	202.6	122.6	1812
2 -	13.7%	0.2%	29.9%	6.0%	3.6%	53.4%
3 -	71.1%	48.4%	96.0%	78.3%	8.7%	
4 -	25.7%	0.3%	56.0%	11.2%	6.8%	

3nd passing — X-Ray — Threshold 2-125/45%

Waste 3 (W)

CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total	
163.7	0	447	21.8	0.0	632.5	-1
9.0%	0.0%	24.7%	1.2%	0.0%	34.9%	-2
35.1%	0.0%	44.1%	10.8%	0.0%		-3
26%	0%	71%	3%	0%		-4

Product 3 (RB)

	CERAMICS	impurities	MORTAR	ROCKS	BRICKS	Total
1 -	302.3	6	560	180.9	121.8	1171
2 -	16.7%	0.3%	30.9%	10.0%	6.7%	64.6%
3 -	64.8%	100.0%	55.2%	89.3%	99.3%	
4 -	25.8%	0.5%	47.8%	15.4%	10.4%	

Figure 4.1 – Calculation and diagram in MS-Excel spread sheet for the separation of the ballast (RB_F), using the Automatic Sorter COMEX with the three step processing.

For the first separation, the DE-XRT sensor was used and it was calibrated based on the variation of densities of the feed material with higher density material being considered product. In this step of the process, the waste material is composed of a high amount of ceramics with 56% of the material being ceramics, and 72.8% of the ceramics of the feed material being rejected at this step.

The product sorted after the first step was fed into the sorter again, this time the material was analyzed with the CCD camera sensor to remove the bricks from the mixture. To obtain waste material with high bricks content a red color from the RGB color scale was used which most closely matched the red brick color for the majority of the bricks (the exact RGB settings are shown in Figure 3.6a). At this step of process the waste contains high brick content, with 82% of the waste being composed of bricks and 90.1% of the bricks in the first product being removed at this step.

For the third sorting step, DE-XRT was used under different settings to maximize the rock (natural aggregates) content in the ballast, due to its higher density. In this last step of the process, the waste contains high amounts of mortar, with 71% of the waste being composed of mortar and 44.1% of the mortar in the second product material being rejected at this step.

The final product, after all three steps, can be named recycled ballast (RB), and it might be possible to study this material for the creation of new concretes, as it represents a concentration of 89.3% of the rock material originally found in the second product material. This final product represents an increase of 71% in the rock concentration from the original feed material. Also, even though there is a higher rock content in the ballast, the other components have higher densities, which can lead to a favorable influence if the recycled ballast is used to produce cement concrete.

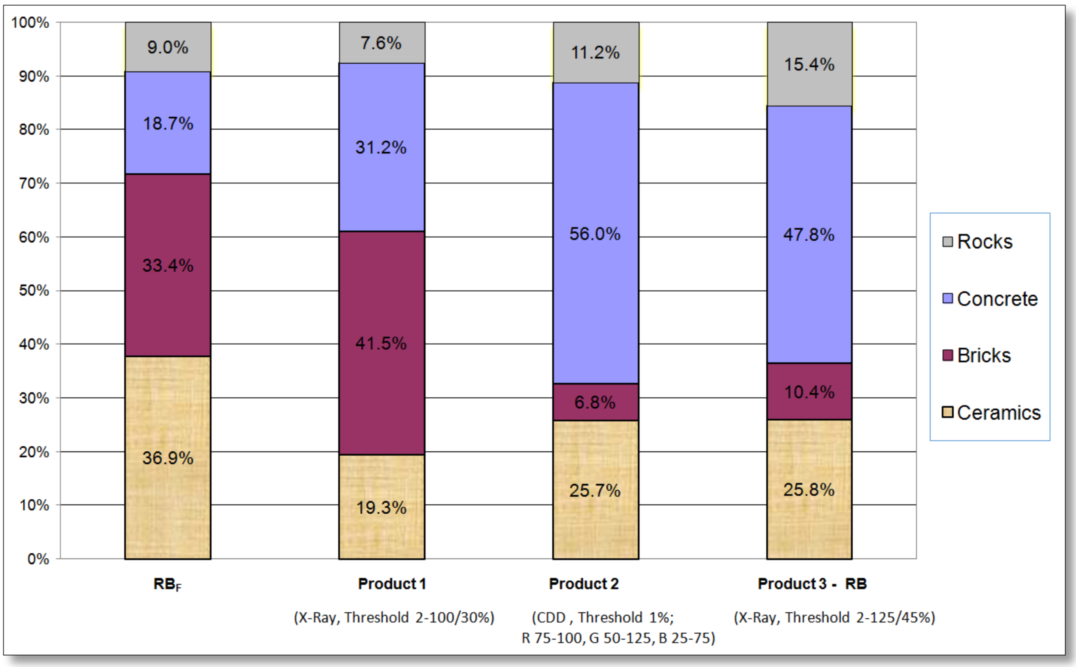


Figure 4.2 - Distribution of the components in ballast, with the three step processing and the settings for AS-COMEX.

4.2 The density distribution for RA_F by the sink and float test

As shown in Table 4.1 it is very clear that a big proportion of the material of the smaller (RA_{4-20}) size range contains bricks in the density range of 2,2 - 2,3 t/m^3 and rocks (natural aggregates from the RA) with density superior to 2,4 t/m^3. As a result, it is expected that a good separation of the RA from the rest of the material will result from crushed concrete aggregates using the jig.

Table 4.1 - Density distribution for RA_F obtained with the "Sink and Float" test

Density	Total Mass		Mass - Bricks		Mass - Mortar		Mass - Ceramics		Mass - Rocks	
<g/cm3>	<g>	<%>	<g>	<%>	<g>	<%>	<g>	<%>	<g>	<%>
< 2.0	101.7	2.74	15.2	0.41	86.5	2.33	0.0	0.00	0.0	0.00
2.0 – 2.1	65.4	1.76	1.0	0.03	64.4	1.74	0.0	0.00	0.0	0.00
2.1 – 2.2	396.2	10.69	11.2	0.30	385.0	10.39	0.0	0.00	0.0	0.00
2.2 – 2.3	1598.1	43.11	625.8	16.88	845.8	22.82	126.5	3.41	0.0	0.00
2.3 – 2.4	600.7	16.20	207.3	5.59	375.0	10.12	18.4	0.50	0.0	0.00
> 2.4	945.0	25.49	259.2	6.99	350.6	9.46	39.0	1.05	296.2	7.99
Total	3707.1	100.00	1119.7	30.20	2107.3	56.84	183.9	4.96	296.2	7.99

With the values in Table 4.1 a floatability curve and the curve of the index NGM were obtained and are displayed in Figure 4.4. Hence, with these values, the effectiveness of the jig separation method was estimated.

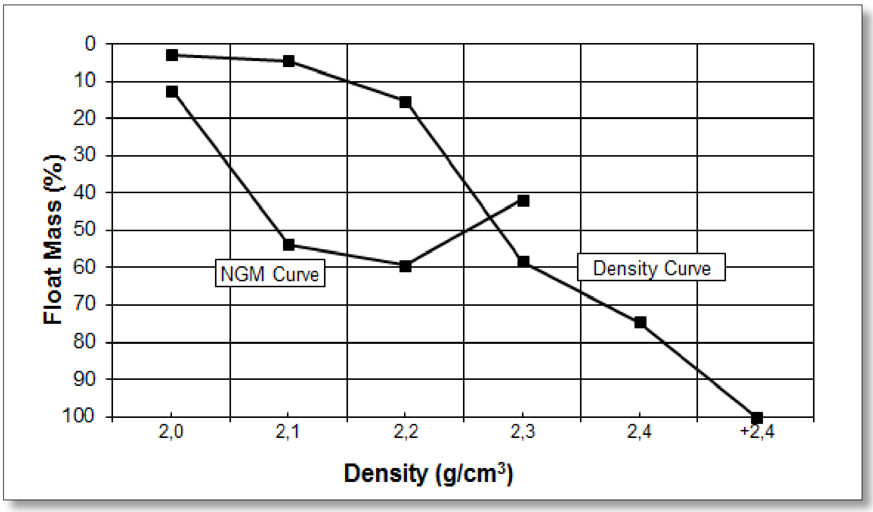


Figure 4.3 - Density distribution and NGM curve for RA_F

4.3 Use of water-jigging for performing component separation

After jigging two material categories were obtained (Figure 4.4):

- Material from the lower layer named „concentrated RA" (RA_C) – mass 57.65 Kg
- Material from the upper layers named „rejected RA" (RA_R) – mass 138.80 Kg

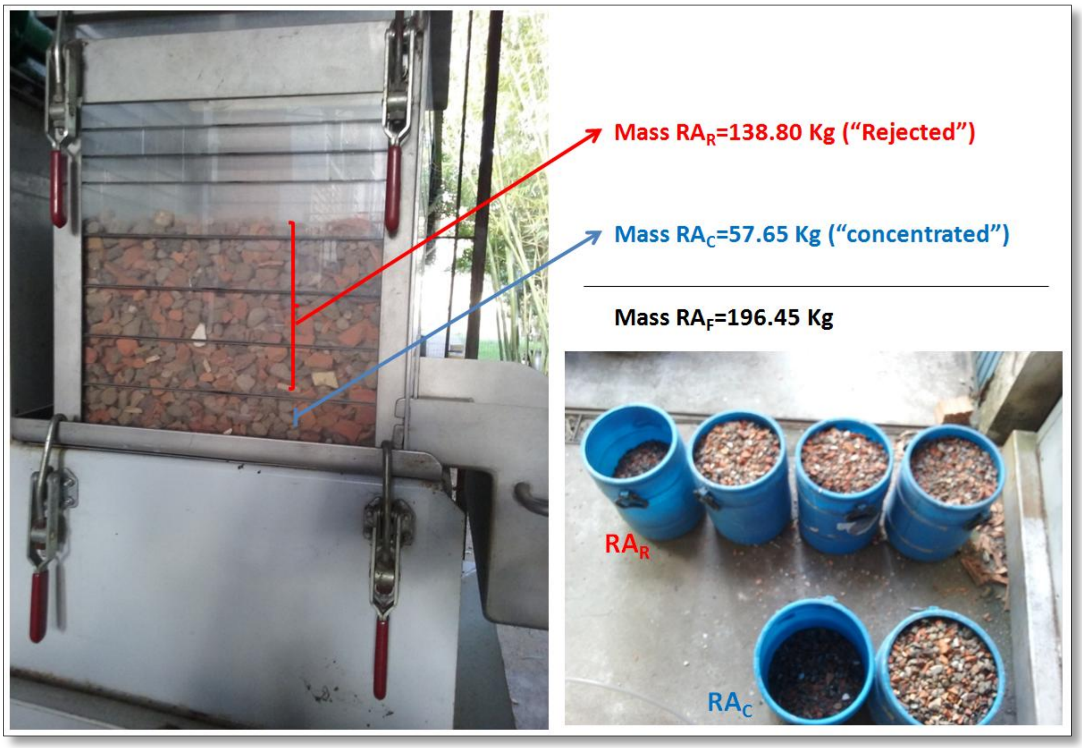


Figure 4.4 Separation of the RA with the Water JIG equipment

4.4 Distribution of the components for RA after separation by water jig

To highlight how the separation in the jig was made, determinations for evaluation regarding the densities, both for the RAs and also for the components of the mixture, were made.

After sampling from the 2 materials, RA_C and RA_R, the material was sorted by hand to be evaluated for the content of each component: bricks, mortar, tiles and rocks. The results are shown in Table 4.2. By re-composition of the two mixtures, with the percentage for components from RA_C and RA_R, conduct to similar distribution for the components with the initial distribution for RA_F, what was showed in Figure 2.2.

As expected, for the first time, it was obvious that the rocks, the components that have the high density, were concentrated due to the jig process.

Table 4.2 - Distribution by components for the RA after separation in the jig equipment for two materials: RA-concentrate (RAC) and RA-reject (RAR)

Components / **RA material**	***Mass sample*** *<kg>*	***Bricks*** *<%>*	***Mortar*** *<%>*	***Ceramics*** *<%>*	***Rocks*** *<%>*	***Other*** *(gyps. Glass, asbest, metals, etc.) <%>*
RA_C	4.100 (100%)	17.4	39.3	6.1	35.6	1.6
RA_R	3.608 (100%)	31.4	50.0	8.3	9.1	1.2

4.5 Particle size distribution for RA_C and RA_R

For each component of RA_C and RA_R were conducted the sieving tests and was obtained the grading curves and these are presented in Figures 4.5 – 4.8, where the curves with label "C" indicate the origin of the components from RA_C, curves with label "R" indicate the origin of the components from RA_R.

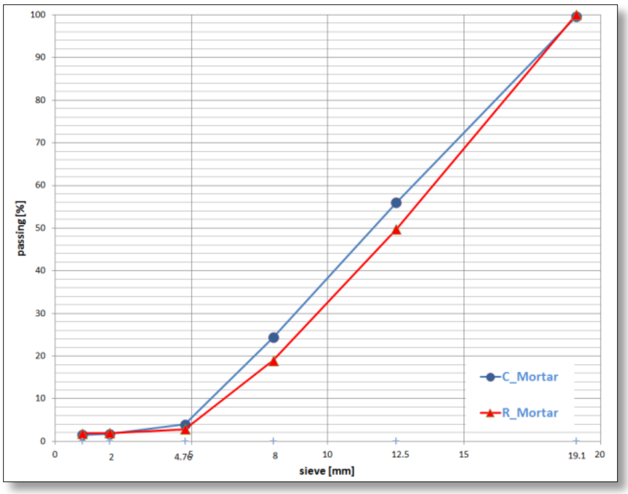


Figure 4.5 – Grading for mortar

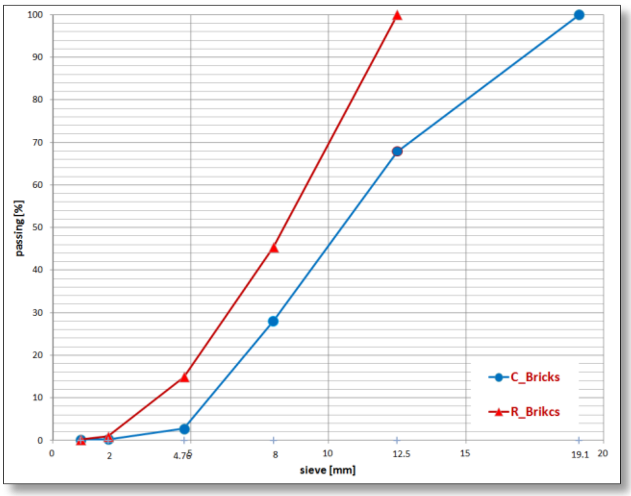


Figure 4.6 – Grading for bricks

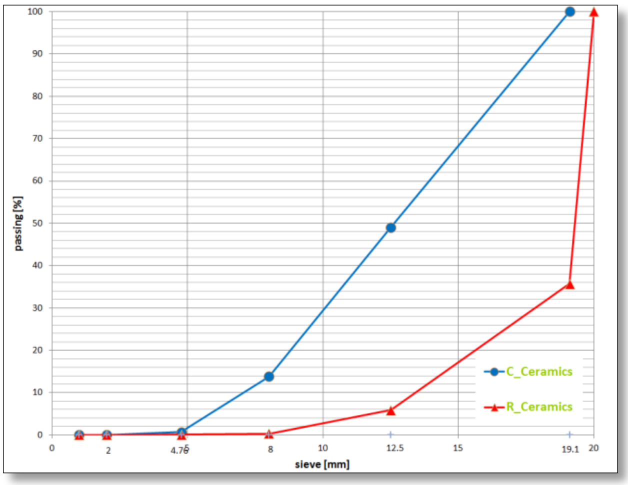


Figure 4.7 – Grading for ceramics

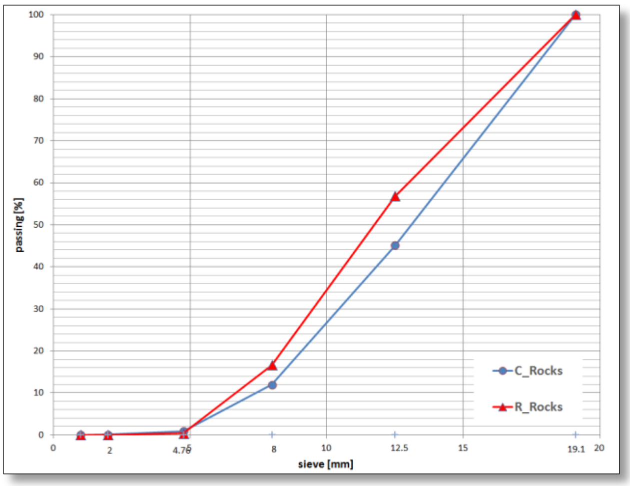


Figure 4.8 – Grading for rocks

4.7. Evaluation of the densities for "concentrated RA" (RA_C) and "rejected RA" (RA_R) by picnometry

To gain a better understanding of the homogeneity of the RA mixture, we made the evaluations for uncertainty of the method and homogeneity of materials and it's presented in Table 4.4. Also, was made determinations for the specific mass for all components within the RA mixture were determined and are presented in Table 4.5

Table 4.4 - Density and statistical analysis for the components of the RA

Material / **Statistical data for density (D)**	**Mortar**	**Bricks**	**Tiles**	**Rocks**
Number of tests	24	6	4	2
Minimum value *<g/cm^3>*	2.508	2.603	2.599	2.698
Maximum value *<g/cm^3>*	2.610	2.649	2.664	2.727
Average value *<g/cm^3>*	2.562	2.627	2.619	2.712
Standard deviation *<g/cm^3>*	0.025	0.016	0.030	-
Coefficient of variation - C_V<%>	0.85	0.44	1.25	-

Table 4.5 - Density and statistical analysis for the mortar from the RA

Statistical data for density (D) \ Mortar	Mortar from RA_C	Mortar from RA_R
Total mass for the all samples <g>	1344,2	1460,1
Number of tests	11	13
Mass percentage for the sample measured	83%	87%
Minimum value <g/cm^3>	2,542	2,508
Maximum value <g/cm^3>	2,610	2,574
Average value <g/cm^3>	2,576	2,549
Standard deviation<g/cm^3>	0,020	0,022

4.8. Evaluation of the specific mass for "concentrated RA" (RA_C) and "rejected RA" (RA_R) by hydrostatic method

Since the intended end use of the RA is to produce concrete, water absorption (WA) and densities for the concentrates were determined rigorously using the standard method (EN 1097-6 and ASTM C 127-88). To highlight more features of RA_C compared to RA_R, comparative measurements were made, beginning with the characterization of their respective components (Table 4.6).

Table 4.6 – Water absortions and densities for RA and for the components

RA/components \ Measurements	WA <%>	ρ_{App} <kg/m^3>	ρ <kg/m^3>
RA_C	8.4%	2156	2640
Mortar	11.0%	1933	2459
Briks	18.0%	1768	2603
Tiles	9.7%	1989	2471
Rocks	1.6%	2631	2748

In addition, considering that the concrete will need to meet imposed specifications. it is necessary follow one specific grading curve. For this the RA granular fractions also need to be corrected by dividing the RA-concentrates into intermediate sorts: 0-4.75 mm. 4.75- 6.35mm, 6.35 - 8mm, 8 - 9.5mm. 9.5-12.5mm, 12.5 - 15.9 and 15.9-19.1mm (Table 4.7).

Table 4.7-Water absortion and densityes for the aggregate size

Measurements \ Sort of RA_C	15,9-19,1 mm	19,1-12,7 mm	12,7-9.5 mm	9,5-8 mm	8-6,35 mm	6,35-4,75 mm
WA<%>	8,7%	10,3%	10,7%	11,6%	12,0%	12,2%
ρ_{App} <kg/m^3>	2123	2027	2025	2009	1980	1990
ρ<kg/m^3>	2606	2569	2592	2623	2599	2631

Because the mortar content is very high in RA, to highlight its influence in the mix of the RA, several attempts were made, to view granularity influence and its presented in Table 4.8.

Table 4.8- Densities and absorption for the each component (size 4-20mm and 8-20 mm)

Measurements \ Mortar from:	"concentrated RA" (4-20 mm RA_C and 8-20 mm $RA_{C.8-20}$)		"rejected RA" (4-20 mm RA_R and 8-20 mm $RA_{R.8-20}$)	
	RA_C	**$RA_{C.8-20}$**	**RA_R**	**$RA_{R.8-20}$**
WA<%>	11.00%	10.60%	13.20%	11.40%
ρ_{App} <kg/m^3>	1933	1942	1828	1895
ρ <kg/m^3>	2459	2448	2414	2424

5. Discussions

5.1 Improved RA characteristics using JIG technology

Jig-type equipment works well if components from the RAs are approximately spherical in shape (rounded aggregates. irregular or partly rounded aggregates. angular aggregates) as can be illustrated with the grading size curves for the separation of rocks and mortar, in Figures 4.5 and 4.8) [21]. Flaky or elongated shapes are common for bricks and plate shapes are common for tiles, corresponding to the grading size curves, in Figures 4.6 and 4.7. Given that the major share (approx. 75%) of the rocks and mortar grading curves are obtained. the theory which predicts that jig separation by density difference is not dependent on the material used, can be confirmed, as shown in the Figure 5.1.

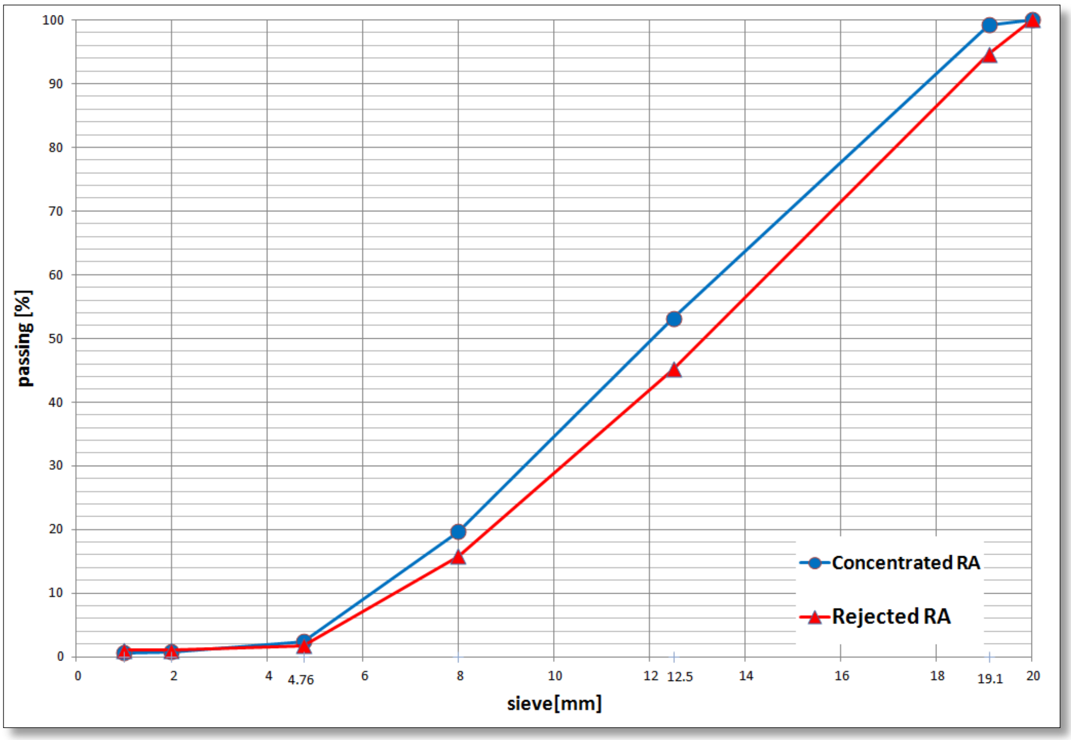


Figure 5.1 - Grading for RA after jiging (for RA_C - *concentrated* and RA_{R4} - *rejected*)

Another observation is that initially only the size range of 4-20 mm was used in the jig. However, after processing components in the size range inferior to 4 mm (fine aggregates and silt) were observed, especially for mortar and bricks. Overall given that approx. ~1.5% of the total mass segregated in the RA is less than 4 mm. this influence on this process was considered negligible for this study.

5.2 Comparation for methods for Density determination

Determination with the pycnometer is an analytical method for determining the density that allows very accurate identification for all density variations of a given mixture. The large number of measurements presented was imposed because. In terms of density variation on each component of RA analyzed, heterogeneity was low.

It is also of interest to compare the two methods of determining density; this is shown in Table 5.1. Comparative results are presented for each method, by pycnometer and by hydrostatic weighing. In the case of this study, in the analysis of two mortar mixtures, although variations were small, it can be stated with certainty that the average density of mortar from RAC is superior to the average in RAR (Table4.4).

Table 5.1 - Comparative results for density by method for RA components

Materials (components) / Mhethod for density	Mortar	Bricks	Tiles	Rocks
Pycnometer (D) <g/cm^3>	2.561	2.625	2.619	2.712
Oven-dried particle density (EN) Specific Weight Hydrostatic (ASTM) **(ρ)** <kg/m^3>	2459	2603	2471	2748

5.3 Variation of the components in function of size range

Starting with the granular curves, which differ for each component (Figures 4.5 - 4.8), and because the content per total mixture of the concentrated RA is known, the content of components in each granular sub-class can be estimated. In the case of this study the following size ranges were obtained from the intermediate sorts of RA_C: 0-4.75 mm, 4.75-6.35 mm, 6.35-8 mm, 8-9.5 mm, 9.5-12.5 mm, 12.5- 15, 9 mm and 15.9-20 mm.

As the sieves 6.35 mm. 9.5 mm and 15.9 mm. were not used in practice, the corresponding values were interpolated by linear fit, considering nearest values. Thereby, the values thus obtained for grading curves enabled estimation of the contents of the 4 components (mortar, bricks, ceramics and rocks) on each class (sort). This distribution is shown in Figure. 5.2.

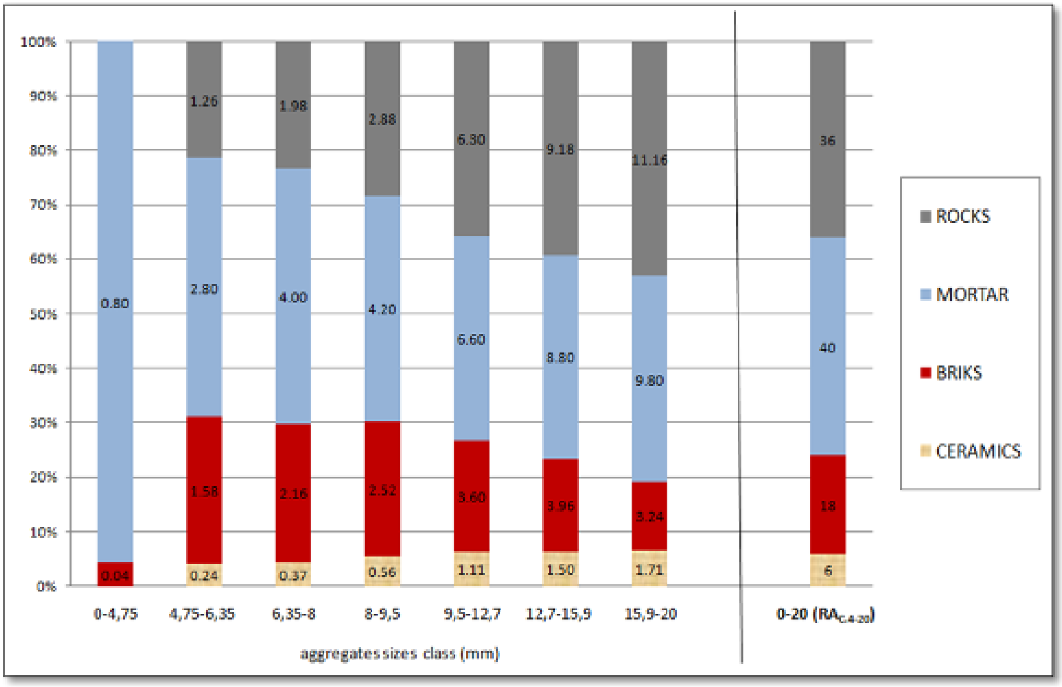


Figure 5.2- Distribution of the components in function of the size class for “Concentrated RA” (RA_C)

It is very important to know as accurately as possible how RA influences the absorption of water used in the production of new concrete. If the absorption for each component and their distribution in the mixture of natural aggregates with RA is known, it is possible to make evaluations. Evaluations of this type are beneficial, both to verify laboratory results, but also to make comparisons with published values in literature [1, 15, 22].

For the RA experimental values of 2156 kg/m^3 and 8.4% were determined for density and water absorption, respectively (Table 4.6).

To check or estimate the influence of the mixture composition, estimates based on experimental determinations for the components and for size classes can be made.

The calculations for density and water absorption from one mixture can be performed using equations 5.1 and 5.2, where the math sum is for the *n* components:

$$\rho_{est.} = \frac{1}{\sum_{i=1}^{n}(\frac{p_i}{100}/\rho_i)} \quad (5.1)$$

$$WA_{est.} = \rho \cdot \sum_{i=1}^{n} \frac{p_i}{100} \cdot \frac{1}{\rho_i} \cdot WA_i \quad (5.2)$$

where:

$p_i -$ mass percentage of the component i

$\rho_i -$ density of the component i

$WA_i - water$ absorption of the component i

$\rho -$ the density of the mixture(estimated or experimentally determined)

Applying equations 5.1 and 5.2 gives the results that are presented in Table 5.2. Thus presenting both the model to estimate the density and water absorption for a mixture of RA, and a verification of the values obtained in the laboratory for the “concentrated RA” (RA_C) and for the separate sorts. These results may be seen in the distribution component of Figure 5.2. which transposed percentage per each sort on rows 1-4 in Table 5.2. The estimated values for density and water absorption are given on lines 6 and 8 values and can be compared with those measured in the lab (shown also in the rows 5 and 7).

From the values shown in Table 5.2, a very good predictive model is shown for water absorption With regards to the density there is only good prediction for RA_C (concentrated). But the correlation between calculated density and experimental density for the sorts can be considered acceptable for estimating the density of a mixture of RA or of the natural aggregates from the RA. However, in the mixing design for concrete water content is a much more important factor to be predicted. Water absorption of the aggregates has strong influence on the water-cement ratio. For this reason the absorption is a factor more sensitive, compared of the influence of the density for quality of the concretes.

Table 5.2 - Estimation for density and water absortionfor the RA size sort, knowing the characteristics of the components

No.	RA / Materials char.	RA_C (4.75-19.1 mm)	15.9-19.1 mm	12.7-15.9 mm	9.5-12.7 mm	8-9.5 mm	6.35-8 mm	4.75-6.35 mm
1.	**Mortar content** ρ=1933 kg/m^3 *WA=11.0%*	40%	38%	38%	37%	41%	47%	48%
2.	**Bricks content** ρ=1768 kg/m^3 *WA=18.0%*	18%	13%	17%	20%	25%	25%	27%
3.	**Ceramics content** ρ=1989 kg/m^3 *WA=9.7%*	6%	7%	6%	6%	6%	4%	4%
4.	**Rocks content** ρ=2631 kg/m^3 *WA=1.6%*	36%	43%	39%	36%	28%	23%	21%
Experimental measured / data estimated								
5.	ρ <kg/m^3> (measured)	2156	2123	2027	2025	2009	1980	1990
6.	$\rho_{est.}$ <kg/m^3> (estimated)	2138	2158	2124	2096	2043	2012	1999
7.	**WA**<%> (measured)	9.4	8.7	10.3	10.7	11.6	12.0	12.2
8.	$WA_{est.}$<%> (estimated)	9.7	8.6	9.5	10.2	11.5	12.1	12.4

5.4 Particle size distribution for the concentrated RA (RA_C)

Particle size distribution for the RA_C studied was very close to the usual grading envelope for normal concrete, according with ASTM C33 - Standard Specification for Concrete Aggregates, or Aggregates for Concrete - EN 1260. In Figure 5.3 the particle size distribution for RA_C and the limits for normal concrete are shown, with ASTM references. The next stage of the research focuses on the characterization of the concrete produced with RA improved with jig technologies (RA_C), or with ballast after sorting (RB).

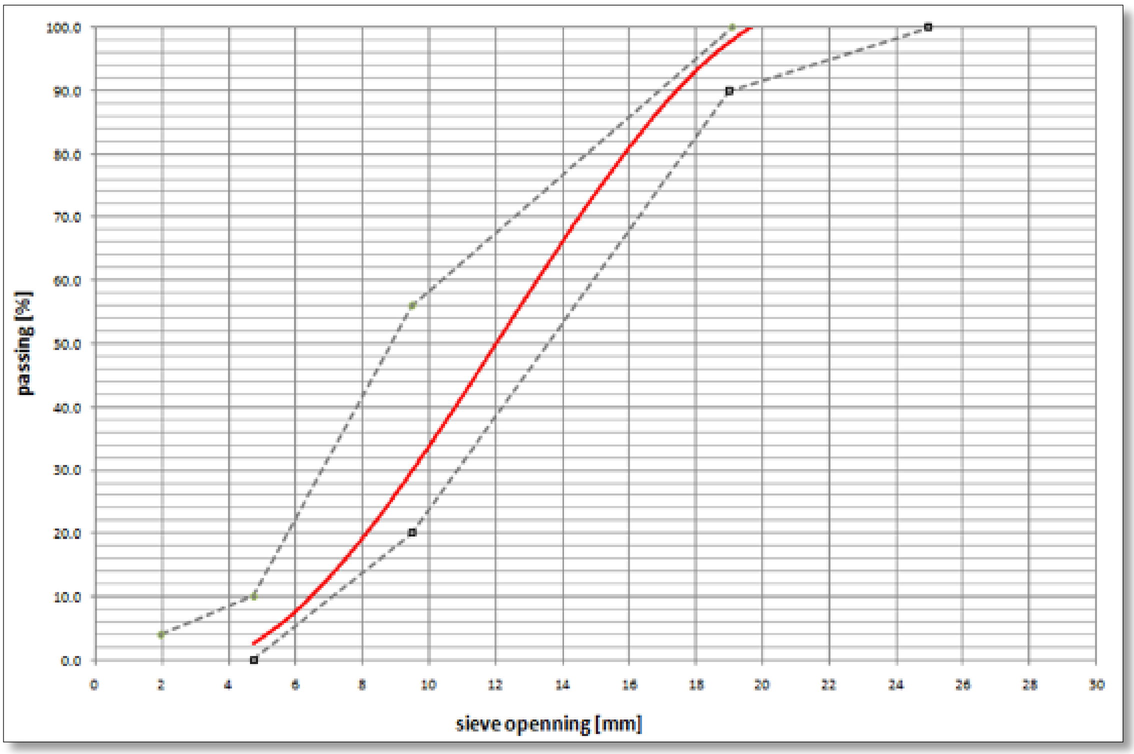


Figure 5.3 - Grading for RA_C and the ASTM C33 limits for concrete

6. Conclusion

The jig and Automatic Sorting technologies can be used to achieve a mixture of recycled aggregates (RA) with enhanced properties for use as raw materials for the manufacture of the new building materials, especially concrete. According to the standard EN 206, RA can be added to concrete up to 20% mass. The material obtained by these processes which are presented in this paper (RAC) contains a higher percentage of natural aggregates or mortar with higher density. Therefore, when using in a mixture of the "RA-Concentrate", the negative influence of density values and influence of water absorption can be diminished. Also, the negative influence at brittle components in the mixture of the RA can be reduced.

The most important conclusion from this paper is the correct estimation of the characteristics of a mix of RA, knowing the variation of these components when the material is divided by size range.

The using the aggregates sorts by size it's necessary to manufacture quality building materials using the specific grading envelope. Estimates can be made beginning from the global content for the components of the mixture and grading for each component (bricks. rocks, concrete, ceramics, etc.). Thus, by knowing the characteristics for each component (water absorption, density, mechanical strength, etc.), estimation about the influences these components have on every concentration can be made for each component and it can be determined which concentration can be used in a mixture with natural aggregates what can be used for concrete fabrication.

In concrete plants within the EU countries, for the natural aggregates it is applied the standard EN 12620 - Aggregates for Concrete [42], which defines also the aggregates sizes used in the manufacture of the concrete. In this way calculations must be made considering that the size ranges for adding RA in concrete with this standard are: 0-4 mm, 4-8 mm, 8-16mm and 16-22.4 mm.

This study will continue in this regard, either by using the various proportions of these RA granular sorts with their components, or by conducting tests to make additional separations using jig technology for these granular classes or with automatically sorting.

References:

1. M. P. Adams, T. Fu, A. G. Cabrera, M. Morales, J. H. Ideker, O. B. Isgor - **Cracking susceptibility of concrete made with coarse recycled concrete aggregates:** Construction and Building Materials 102 (2016) 802–810
2. Aliabdo A. A., Abd-Elmoaty M. , H. H. Hassan - **Utilization of crushed clay brick in concrete industry**: Alexandria Engineering Journal Volume 53, Issue 1, March 2014
3. S. C. Angulo, P. M. Carrijo, A. D. Figueiredo, A. P. Chaves, V. M. John -**On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete:** Materials and Structures (2010) 43:519–528
4. A. Arisha, A. Gabr, S. El-Badawy, S. Shwally - **Using Blends of Construction & Demolition Waste Materials and Recycled Clay Masonry Brick in Pavement:** Procedia Engineering · December 2016
5. S. Arora, S.P. Singh - **Analysis of flexural fatigue failure of concrete made with 100% Coarse Recycled Concrete Aggregates:** Construction and Building Materials 102 (2016) 782–791
6. A. Barbudo a, F. Agrela, J. Ayuso, J.R. Jiménez a, C.S. Poon - **Statistical analysis of recycled aggregates derived from different sources for sub-base applications:** Construction and Building Materials 28 (2012) 129–138
7. F. Bektas - **Alkali reactivity of crushed clay brick aggregate:** Construction and Building Materials 52 (2014) 79–85
8. J. A. Bogas, J. de Brito, J. M. Figueiredo - **Mechanical characterization of concrete produced with recycled lightweight expanded clay aggregate concrete:** Journal of Cleaner Production 89 (2015) 187e195
9. M. Bravo a, J. de Brito, J. Pontes, L. Evangelista - **Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants:** Journal of Cleaner Production 99 (2015) 59e74
10. P. Broere **- The Recycling of Construction & Demolition Waste:** ISCOWA – Erland Recycling Services
11. Diagne, M., Tinjum, J. M., & Nokkaew, K. - **The effects of recycled clay brick content on the engineering properties, weathering durability, and resilient modulus of recycled concrete aggregate:** Transportation Geotechnics · January 2015
12. Gomes PC, Ulsen C, Pereira FA, Quattrone M, Angulo SC **- Comminution and sizing processes of concrete block waste as recycled aggregates:** Waste Management 45 (2015) 171–179
13. Gomez-Soberon J - **Porosity of recycled concrete with substitution of recycled concrete aggregate—an experimental study:** Cement and Concrete Research, August 2002, **1301–1311**
14. L. Hu, J. Hao, L. Wang - **Laboratory evaluation of cement treated aggregate containing crushed clay brick:** Journal of Traffic and Transportation Engineering, 2014, 1 (5) : 371-382
15. J. Hua, K. Wangb, J.A. Gaunt b - **Behavior and mix design development of concrete made with recycled aggregate from deconstructed lead-contaminated masonry materials:** Construction and Building Materials 40 (2013) 1184–1192
16. W.-L. Huang, D.-H. Lin, N.-B. Chang, K.-S. Lin - **Recycling of construction and demolition waste via a mechanical sorting process:** Resources, Conservation and Recycling 37 (2002) 23/37

17. de Jong, T.P.R., Dalmijn, W.L., 2003. - **Dual energy X-ray transmission imaging: applications in metal processing:** *Proc. TMS MeetingMarch*, pp.2-6.
18. O. Keles, R. E. Garcıa, K. J. Bowman - **Deviations from Weibull statistics in brittle porous materials:** Acta Materialia 61 (2013) 7207–7215
19. Khalaf, F. and DeVenny, A. - **Recycling of Demolished Masonry Rubble as Coarse Aggregate in Concrete: Review: PhD Degree,** Napier University, 1999
20. Kuritcyn, K Anding, E Linß and S M Latyev **- Increasing the Safety in Recycling of Construction and Demolition Waste by Using Supervised Machine Learning:** IOP Publishing , Journal of Physics: Conference Series **588** (2015) 012035
21. F.C. Leite 1 , R.S. Motta , K. L. Vasconcelos, L. Bernucci , **Laboratory evaluation of recycled construction and demolition waste for pavements:** Construction and Building Materials 25 (2011) 2972–2979
22. Medina, C., Zhu, W., Howind, T., Sanchez de Rojas, M.I., Frías, M., 2014. **Influence of mixed recycled aggregate on the physical e mechanical properties of recycled concrete:** Journal of Cleaner Production 68 (2014) 216e225
23. F. Moghadas Njead, A. R. Ararhoosh, G.H. Hamedi - **The effects of using Recycled Concrete on fatigue behavior of hot mix asphalt:** Journal of Cicil Engineering And Managament, online 2013, Volume 19**.**
24. A. Ossa., J.L. García, E. Botero - **Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry:** Journal of Cleaner Production 135 (2016) 379e386
25. R. S. Paranhos, B. Cazacliu, C. H. Sampaio, C.O. Petter , R. O. Neto , F. Huchet - **A sorting method to value recycled concrete:** Journal of Cleaner Production 112 (2016) 2249e2258
26. J V. Puthussery, R. K. , A. Garg - **Evaluation of recycled concrete aggregates for their suitability in construction activities: An experimental study:** Waste Management (2016)
27. M. Quattrone, B. Cazacliu, S.C. Angulo, E. Hamard, A. Cothenet b- **Measuring the water absorption of recycled aggregates, what is the best practice for concrete production?:** Construction and Building Materials 123 (2016) 690–703
28. G. Rodríguez , C. Medina , F.J. Alegre, E. Asensio , M.I. Sanchez de Rojas - **Assessment of Construction and Demolition Waste plant management in Spain: in pursuit of sustainability and eco-efficiency:** Journal of Cleaner Production 90 (2015) 16e24
29. C.H. Sampaio, W. Ambrós, L. F. R.Miranda - **Improve the quality of recycled aggregate concrete by sorting in air jig:** Conference Paper · August 2015
30. Sampaio C.H., Tavares L.M.M. (2005). **Beneficiamento Gravimétrico: Uma introdução aos processos de concentração mineral e reciclagem de materiais por densidade:** ed. Editora UFRGS - Brazil
31. R.V. Silva, J. de Brito, R.K. Dhir - **Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production:** Construction and Building Materials 65 (2014) 201–217
32. L. Weisheng, Y. Hongping - **Off-site sorting of construction waste: What can we learn from Hong Kong? :** Resources, Conservation and Recycling 69 (2012) 100– 108
33. A. Young, M. Veras, C. Petter, C. H. Sampaio**- Separation of Construction and Demolition Waste by CCD Camera:** Anais do 58-o Congresso Brasiliero do Concreto, Oct. 2016
34. **Product Information**- Allmineral - **alljig**®
35. Gruzen Samton LLP with City Green Inc. - **Demolition Waste Manual** - City of New York, Department of Design & Construction by, May 2003 - *www.nyc.gov/html/ddc/downloads/pdf/waste.pdf*
36. **Guidelines for Selective Demolition and On Site Sorting** - (July 2004) Public Fill Committee Civil Engineering and Development Department – The Guverment of the Hong Kong, Enviromental Protection Departamentdg - *http://www.cedd.gov.hk/eng/services/recycling/doc/sel_dem.pdf*
37. **Reciclarea deşeurilor şi reutilizarea acestora în sectorul construcţiilor,** Conference Paper · May 2013 Conference: Ştiinţa modernă şi energia, Cluj-Napoca, - *www.cncs-uefiscdi.ro*
38. DIN 4226-100: 2002-02 **Aggregates for concrete and mortar** - Part 100: Recycled aggregates.
39. **Construction and Demolition Waste (CDW) -** *http://ec.europa.eu/environment/waste/construction_demolition.htm*
40. World Business Council for Sustainable Development **- The Cement Sustainability Initiative – Recycling Concrete**
41. Standard ASTM C33 / C33M - **Standard Specification for Concrete**
42. Standard EN 12620:2013 - **Aggregates for concrete**