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ORIGINAL ARTICLE

Water absorption of fine recycled aggregates: effective determination by a method based on electrical conductivity

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Abstract The high absorption of fine recycled aggregates is indicated as the main difference with respect to fine natural aggregates. This property determines the extra amount of water to be added during mixing to avoid a loss in workability when these aggregates are used for making concrete. Although several methods have been proposed for its determination, none of them has been standardized or has achieved full consensus. In this paper, a method for the determination of absorption based on electrical conductivity is applied. The results from this method and other particular methods proposed in the literature for this type of aggregate are analyzed and compared regarding their representativeness. The outcomes of this study show the suitability of the conductivity method for the effective determination of water absorption of fine recycled concrete aggregate, with relatively low variation and incidence of the operator.

Keywords Fine recycled concrete aggregates · Saturated surface dry · Absorption · Electrical conductivity

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1 Introduction

The use of recycled concrete aggregates (RCA) in new concrete production involves two types of environmental benefits. It reduces the exploitation of non-renewable resources such as natural aggregates (NA), and it decreases the environmental impact generated by the final disposal of construction and demolition waste (CDW). Therefore, it can be considered a byproduct of the demolition process on the basis of this added value. The main difference between RCA and NA is the attached mortar in variable contents in the composition of the former. The attached mortar increases the porosity and water absorption of the aggregate [1–3], and it is thus responsible for a potential reduction in concrete density and durability. Due to these differences, also in the fresh state, concretes produced with RCA may exhibit distinctive behavior from concretes with NA, when RCA retains part of the mixing water and affects workability. This issue can be easily overcome when the water absorption of the aggregate is considered, and the corresponding amount of additional water is included during mixing. For this purpose, it is very important to know the absorption capacity and rate of RCA.

Regarding the suitable use of coarse recycled concrete aggregate (CRCA), several researchers have found that it produces trivial modifications on concrete properties when it is used in partial replacement of NA [4–9]. Consequently, the use of CRCA in the production of structural concrete is now a regular practice in many countries, where its use has been standardized and implemented [10–14].

Conversely, there is no consensus at present regarding the influence of the fine fraction of recycled concretes aggregates (FRCA) on concrete properties. Whereas some researchers have reported similar or slightly lower consistency levels in mixes containing FRCA [15, 16], others have reported over 60% reductions in the slump value, even when FRCA was used in the saturated surface-dry condition (SSD) or when a water reducing admixture was added to prevent detrimental effects on the consistency level [17, 18]. A similar situation has been noted for compressive strength, as concretes made with different replacement ratios of fine natural aggregates (FNA) by FRCA have shown similar or even higher strength levels than reference FNA concretes [18–20]. Contrarily, some researchers have reported decreases in compressive strength of up to 38% when FNA is partially replaced by FRCA [2, 21–24].

Although there is consensus on the fact that the high absorption of FRCA constitutes the main cause for a reduced performance of concrete made with it, the detrimental effect of FRCA could also be due to an unanticipated effect of the increase in the mixing water content intended to compensate the absorption of FRCA [25]. This procedure may eventually lead to an increase in the effective water/cement ratio if an overestimation of the water uptake by the aggregate is made. The accurate determination of this amount of water is therefore crucial for the design of concrete made with FRCA. Therefore, the reliability of the procedure to determine FRCA water absorption is a key aspect to assure the desired consistency and w/c ratio.

Figure 1 presents a wide range of values for the water absorption of FRCA reported in the literature, together with the compressive strength of some of the source concretes (SCs).

It is interesting to notice that the highest values of water absorption (grey bars) in Fig. 1 [19, 21, 26] were obtained by the immersion method [34], whereas the other references use methodologies similar to the one described in ASTM C128 [35]. Another noteworthy observation from Fig. 1 is the lack of correspondence between the water absorption and the compressive strength of the source concrete (SC). It is very likely that other significant factors are affecting this relationship, but a big proportion of the lack of correlation could also be caused by the particular experimental procedure applied to determine FRCA water absorption in each study.

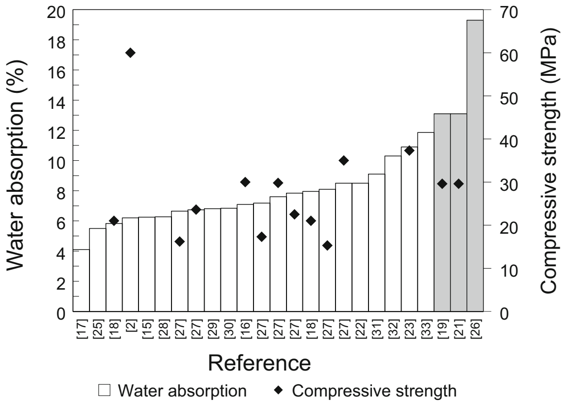

Fig. 1 Water absorption of FRCA by different authors

1.1 Methods to determine the saturated surface dry condition

Different methods to determine the water absorption of RCA have been proposed [34, 36, 37], improved [38–40], and comparatively analyzed [41] in the literature, but only a few are applicable to the fine fraction. A major issue regarding the reliability of each method is its ability to accurately determine the saturated surface dry condition (SSD) of the sample.

Two widely used methods for the determination of FRCA water absorption are the immersion method [34] and the method specified by ASTM C128 [35]. In the immersion method, a sample of FRCA is placed over a 0.044 mm sieve mesh, which is then immersed in water, while the mass variation is recorded after a gentle agitation at time intervals during the first 24 h. From the data recorded, the absorption-time curve is drawn. The increasing absorption at progressive time periods allows for the estimation of the partial water absorption capacity of the aggregate during the period in which fresh concrete is mixed and manipulated. In theory, accurate correction of the mixing water content without modifications in concrete performance would be possible. However, the unfeasibility of recording the initial submerged weight (the first reading is taken 2 min after submersion because of the time required for the scale to stabilize) is the major limitation of this method. Water absorption is thus calculated as the average between the absorption values relative to the dry sample weight and the submerged sample weights, which implies significant uncertainty for the value obtained as this computation method for water absorption has no theoretical support.

The content of fines in the aggregate is another concern when it comes to the immersion method. These small particles in FRCA can agglomerate and occlude air, thus resulting in inconsistent weight measurements [42]. An improved procedure to solve this issue was suggested by Rodriguez et al. [38]. They used a solution of hexametasulphate to avoid occluded air. However, they still determined the SSD condition and water absorption by a procedure similar to that in ASTM C128 [35].

The ASTM C128 standard establishes the truncated cone method for the determination of the SSD condition of fine aggregates. This method is very suitable for aggregates with spherical particles. However, it becomes less suitable for crushed fine aggregates in which the angular shape, rough surface and content of material finer than 75 µm cause more contact points among particles. Also, according to the standard, a low reproducibility of the test when the aggregate has water absorption capacity higher than 1% is to be expected. Although the standard provides some special recommendations for crushed aggregates, some subjectivity is still involved, and the influence of the operator can have a major impact [43].

Alternatively, Ueno et al. [44] determined the SSD state by a method based on a significant increase in electrical conductivity with the surface moisture content of the aggregate. A standard procedure based on this principle is currently indicated by the Japanese Society of Civil Engineers [45] for fine aggregates in general. In spite of the great number of approaches proposed in the literature for the determination of the water absorption capacity of FRCA, only two studies have considered the application of this particular method for FRCA [43, 46].

The fundamentals of the conductivity method are that conductivity of fine aggregate is a function of its surface moisture content, with an abrupt decrease in the conductivity produced when all surface water is removed from the particles due to the significantly lower electrical transport capacity of the solid particles. Therefore, two very different states are reflected by distinct relationships between the conductivity of the granular material and the moisture content, which can be identified and modeled with two straight lines in a semi-logarithmic plot. The limit between these two states is identified as the SSD condition and determined by the significant shift in the decreasing rate of conductivity as the sample is further dried.

When the surface of the grains is wet, water tends to form liquid bridges at contact points between the grains for the easiest possible nucleation. As surface moisture is reduced, the number of bridges is reduced as well. Eventually, no liquid bridges will be present with enough drying, and electrical conduction will only be allowed by solid-to-solid contact. A significant loss of continuity and the consequent significant decrease in conductivity of the assemblage are then produced. The geometrical characteristics of liquid bridges are determined by the thermodynamic condition of zero difference in pressure between the inside and the outside of the bridge, the wetting condition on particles, and the geometry of the particles. From these hypotheses, the number of bridges is a function of the content of surface moisture and the number of contact points between particles. With a certain packing degree of particles, achieved through a standard compaction procedure, the average number of contacts should scarcely be affected. Consequently, the number of bridges would remain relative to the amount of surface water. A direct connection between surface water and electrical conductivity can thus be derived from this relationship. Then it is suitable for all kind of fine aggregates, including FRCA. In a previous study [43], similar values of water absorption when determined by the ASTM method and the proposed method for rounded siliceous aggregates (for which the ASTM method is considered very suitable) (Fig. 2) give support to the universal application of the conductivity method.

A disadvantage of the conductivity method indicated in [44, 45] is that it uses a set up for direct conductivity measurement which might be significantly influenced by the quality of the contact with the terminals. In the case of crushed fine aggregates, the contact between aggregate particles and electrical terminals can be deficient due to the shape and surface texture of particles. As the material next to the boundaries is inevitably less compacted than the bulk, the number of contact points between the granular material and the electrodes might be unwantedly reduced with a direct transmission arrangement. In this

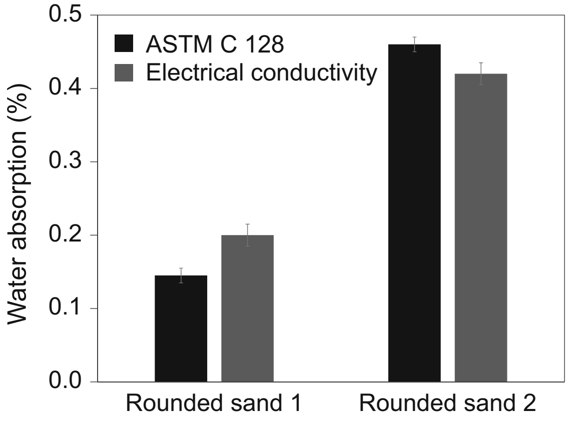

Fig. 2 Water absorption of rounded aggregates determined by the ASTM and electrical methods (adapted from [43])

sense, a possible improvement could be achieved with a four-point arrangement, in which four electrodes instead of two are used. This is why the four-point method is normally applied to determine conductivity in soils and other granular materials [47].

In this study, an approach to determine the SSD condition and water absorption of FRCA through electrical conductivity is presented. The method applied involves a four-point arrangement with the aim of improving electrical contact and reducing the influence of boundaries. The water absorption capacities determined by the conductivity method are contrasted with those obtained in accordance with ASTM C128 [35] and the immersion method [34]. The variability of each method is finally contrasted with each other.

2 Experimental

2.1 Methodology

For the proposed conductivity method, a cell with a U-shaped cross section was used with the aim of avoiding right angles that could cause distortion in the measurements. The container was made of polyvinyl chloride (PVC) of 2 mm thickness. Stainless steel plates of 1.5 mm of thickness at each extreme of the cell were used. Two stainless steel rods of 5 mm of diameter were used as internal electrodes. The dimension of the cell and a schematic diagram of the set are shown in Fig. 3. For the measurements, the potential difference between the inner electrodes (E) was registered while an electrical potential of 12 ± 1 V (AC) was applied between the outer electrodes and the corresponding current passing (I) was registered. Then, a value for the electrical resistance can be computed. For converting this measurement into a conductivity value the cell constant of the device must be calculated. Therefore, the system was calibrated by verifying the electrical current passing through the device when it was filled with a 0.01 M KCl standard solution of known conductivity. This calibration is applied in the form of a geometrical coefficient of the cell. Finally, the resulting conductivity was calculated according to Eq. 1.

$$C = \frac{I/V}{Cs} \tag{1}$$

where C = Conductivity (S/m), I = Electrical current (μA), V = Electrical Potential (V), Cs = Geometrical coefficient of the cell (m).

For each FRCA, a representative sample of approximately 2.5 kg was saturated by immersion in water for 24 h. Then, the sample was placed into the cell in two layers, compacting the first one with 10 hits and the second one with 15 hits. The tamper indicated in ASTM C128 was used for compaction. The filling procedure was completed by making even the surface and removing the exceeding material.

Immediately after the electrical measurement, approximately 200 g of material from inside the cell was sampled and weighed. This sample was dried in an oven at 110 °C ± 5 °C until constant weight. The moisture content of the sample was then calculated by Eq. 2.

$$H(\%) = \frac{Ww - Wd}{Wd} \cdot 100 \tag{2}$$

where H = moisture content (%), Ww = wet weight (g), Wd = dry weight (g).

The procedure was repeated for different moisture contents as the sample was progressively dried according to the procedure described in ASTM C128. For each FRCA, two rounds of progressive determinations for decreasing moisture contents were performed up to an electrical conductivity of about 1μS/cm. After the measurement, the conductivity is plotted versus the moisture content in a semi-logarithmic scale. It is notable that although the procedure is standardized [45] and several used it in soil

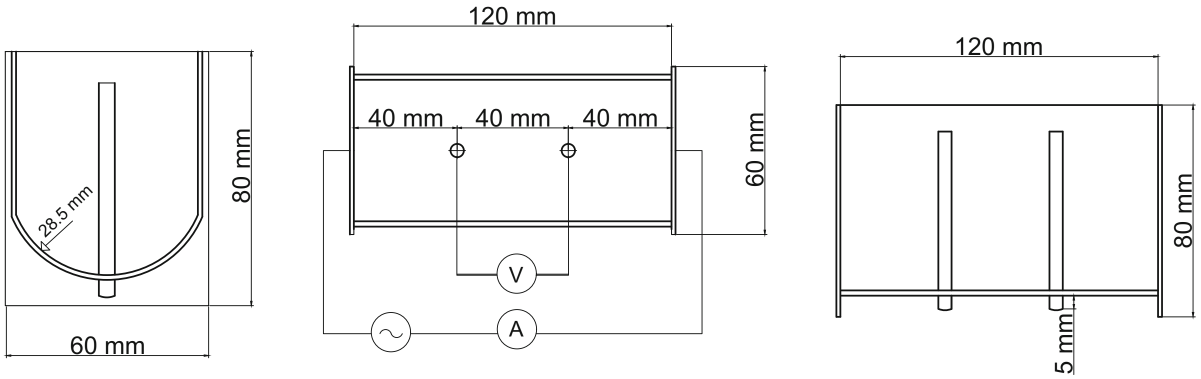

Fig. 3 Scheme of the device used; **a** cross section, **b** side section, **c** plan

[44, 47–49], no procedure to separate both branches is made. In this study, the criterion adopted for this purpose was to split data for maximizing the average R^2 value of both branches. Special attention was put for the wet branch to avoid excessively soaked condition of the aggregate as some free water might accumulate at the bottom of the device and affect the measurement. This condition is however quite far from the saturated surface dry condition and easily avoidable by visual inspection.

In addition to the conductivity method, the water absorption capacity of each FRCA was also determined according to ASTM C128 [35] and immersion [34] methods. Each reported value for these methods is the average of three determinations by the same operator. In order to evaluate the reproducibility of the methods, three different operators performed complementary determinations by each of the methods applied for one of the FRCAs.

3 Materials

Five FRCAs were obtained from crushed concretes with different compressive strength levels which were originally made with crushed quartzite (Q) or granite (G) as natural coarse aggregate. For the crushing process, two cycles of jaw crushing were used; the first cycle was applied to source concretes. Particles with a size larger than 20 mm were crushed for the second time. Then, the recycled aggregates were separated in fine and coarse fractions with a 4.75 mm sieve. The FRCAs are identified as RQ or RG, according to the natural aggregate in SC, followed by the corresponding compressive strength level (in MPa). The properties of FRCAs are presented in Table 1. The paste content of recycled aggregate was determined according to the procedure described in ASTM C1084. The pore volume for each aggregate was determined by mercury intrusion porosimetry (max. pressure of 200 MPa). It is interesting to note that the contents of paste are similar for all FRCAs. Then, no difference according the compressive strength level and type of natural aggregate in the SC were noticed in paste content. However, porosities and densities of FRCAs increase and decrease, respectively, as the compressive strength of the SC decreases.

Particle size distributions of all aggregates are similar even though they were obtained from concretes made with different natural coarse aggregates and different compressive strength levels. The similarity is even more significant for aggregates with the same mineralogy as the coarse aggregate in the SC. The most natural explanation is that particle size distribution is firstly influenced by the crushing process and secondly by the properties of waste concrete [1, 12]. The results show that the affinity between the quartzite coarse aggregate and the mortar has greater influence than the compressive strength of the source concrete, but still of secondary order.

4 Results and discussion

The semi-logarithmic plots for the relationships between moisture content and electrical conductivity for the five FRCAs are presented in Fig. 4. The values presented include two independent progressive drying rounds of determinations carried out by the same operator. A good correlation between conductivity and

Table 1 Properties of FRCAs

	RG30	RG35	RG45	RQ25	RQ35
Source concrete					
f′c (MPa)	28.6	35.0	45.1	25.9	34.6
Constituting coarse aggregate	Granite			Quartzite	
Properties of FRCAs					
Density	2.41	2.49	2.48	2.40	2.46
Material finer than 75 μm (%)	7.2	2.7	5.0	6.0	4.5
Paste content (%)	30	33	31	28	27
Volume of pores (mm^3/g)	56.6	n/d	22.9	64.2	30.7
Particle size distribution					
Material passing sieve (%)					
9525 μm	100	100	100	100	100
4750 μm	99	97	99	99	97
2360 μm	74	66	73	67	66
1180 μm	53	45	53	44	45
600 μm	34	31	37	28	31
300 μm	16	17	19	14	17
150 μm	7	8	9	5	8

moisture content is observed for the five aggregates evaluated ($R^2 > 0.81$). This is a consequence of the electrical conductivity being much more influenced by the surface moisture content than by the aggregate shape. For each aggregate, two different zones are defined by fitting straight lines to the experimental results. The intersection between both fitting lines indicates the limit for the presence or absence of surface moisture on the particles, so these two zones reflect surface wet and surface dry conditions. Consequently, the intersection point is used to define the SSD condition, with the corresponding moisture content being the absorption capacity of the sample [43]. Notably, the relative change in the slope from the dry branch to the wet branch depends on the characteristics of each aggregate. In this sense, features of FRCA such as content of fines, bulk density and particle shape determine the number of contact points among particles, and they might be the reason for a more or less significant change in conductivity when moisture disappears from the surface of particles.

In order to compare the water absorption capacities obtained from the conductivity, ASTM C128 and immersion methods, three samples of each FRCA were tested by a single operator to obtain average values from each method, which are presented in Table 2. A high dispersion among values can be noted especially for the immersion method.

All methods provide different values for absorption capacity. Therefore, the influence of the test method is significant.

Table 2 shows that the ASTM method tends to result in the lowest water absorption capacities, which are about a half and a third of the values obtained with the conductivity and immersion methods. This significant difference shows the necessary over-drying to achieve the collapse of the cone in the ASTM method (considered by the standard as the SSD condition), due to the shape, angularity and content of fines in FRCAs. In other words, the shifting point in the ASTM method is not solely defined by the presence of moisture on the surface of particles but also by the friction between particles, which is quite significant for the case of FRCAs (for which the cones remain stable at lower moisture contents than those corresponding to SSD condition due to the friction among particles). To illustrate this situation, the relationship between the conductivity and the shape of the cone formed during the ASTM test for different moisture contents for RQ25 is presented as an example in Fig. 5. This clearly shows that the shape described as shifting point in the ASTM standard could only be obtained for moisture values corresponding to a conductivity value near 1μS/cm in the conductivity method. This situation replicates in all FRCAs. A significant over-drying of the sample to achieve the indicated cone shape in

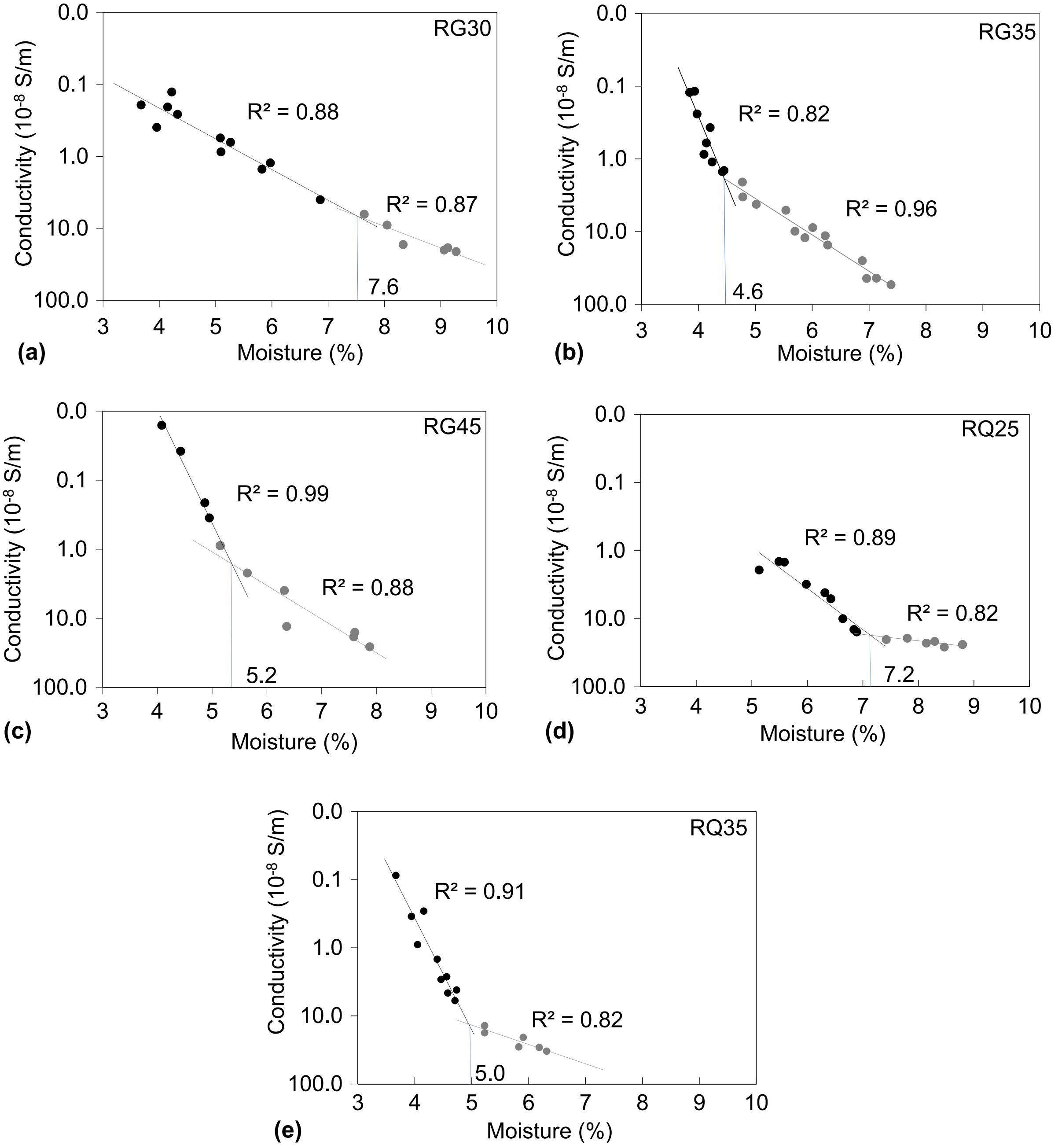

Fig. 4 Moisture content versus conductivity and determination of SSD condition for FRCAs

ASTM is therefore derived, as the corresponding conductivity is showing not only the absence of surface moisture but also the absence of bulk moisture. A consequent underestimation of the water absorption capacity with the ASTM method for FRCAs is consequently derived. A similar observation has been previously reported for other types of crushed fine aggregates [43]. Then, the limitations of the ASTM method are not restricted to FRCAs but valid for all fine crushed aggregates.

On the contrary, Table 2 shows that the values obtained with the immersion method are nearly twice as high as the absorption capacities obtained by the conductivity method. The procedure for obtaining the

Table 2 Water absorption capacities by different methods (%)

Aggregate	Method used for water absorption determination (%)		
	ASTM C128	Immersion	Electrical conductivity
RG30	5.08 ± 0.5	11.8 ± 3.3	7.6 ± 0.3
RG35	3.8 ± 0.1	6.4 ± 0.7	4.6 ± 0.1
RG45	3.1 ± 0.3	8.7 ± 0.7	5.2 ± 0.2
RQ25	3.6 ± 0.1	11.6 ± 2.6	7.2 ± 0.2
RQ35	2.8 ± 0.2	7.6 ± 0.5	5.0 ± 0.1

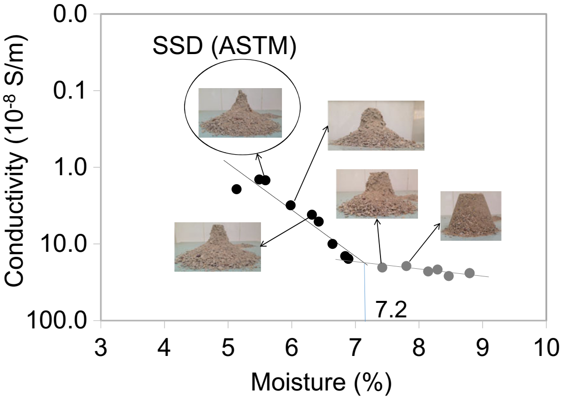

Fig. 5 Relationship between electrical conductivity and the shape of the ASTM cone test

water absorption capacity with the immersion method (average of submerged and dry sample computations) lacks theoretical support, which brings some doubts regarding its accuracy. The results then reflect those in the literature (Fig. 1, where the highest absorption capacities included in the plot were all obtained with the immersion method), which indicate a likely overestimation of the absorption capacity. In order to prove this hypothesis, water absorption of river siliceous sand was determined by the three studied methods. The values obtained were 0.46, 0.42 and 4.2% for ASTM, electrical conductivity and immersion methods, respectively. The ASTM method is widely accepted as an accurate procedure for this type of aggregates (as the slope of the stable cone caused by internal friction of particles does not depart from the slope of the testing cone). The values obtained by the ASTM and conductivity methods are very similar, supporting the suitability of both methods in this case. Conversely, the value obtained with the immersion method is several times higher than the values obtained by the other two methods, making it evident that the immersion method significantly overestimates water absorption capacity even for the case of rounded fine aggregates. This outcome contrasts with the appropriate absorption values reported in the literature for coarse recycled aggregate tested by the immersion method.

In practice, the overestimation of the absorption capacity with the immersion method implies a higher content of free water in the mixtures that certainly increases the w/c ratio and, as a result, the properties of concrete in the fresh and hardened state.

Table 2 also shows a contrast between methods regarding their variability. The standard deviation for the ASTM method is higher than the one indicated in the standard as a reference (for aggregates with water absorption higher than 1% the standard does not indicate standard deviation). For the immersion method, standard deviations for RQ25 and RG30 are huge, while for the conductivity method this indicator shows significantly lower values and variation than those for the other two methods.

Additionally, for evaluating the reproducibility (dispersion for different operators, d2 s according to ASTM C670) of each method, the water absorption capacity of RG35 was determined by three different operators. Figure 6 shows the average values obtained by each operator for each method. Standard deviations are 1.21, 0.06 and 0.61, whereas the variation coefficients are 0.24, 0.01 and 0.008, for ASTM, electrical conductivity and immersion methods, respectively. The variation coefficient for the ASTM method is 1740 and 291 times higher than those obtained in electrical conductivity and immersion methods, respectively. Again, the electrical conductivity method shows much lower variability than the other two methods.

When the mean absorption capacities obtained by the three operators are compared, a significant difference arises between the immersion method and the other two methods. Similar mean values were obtained

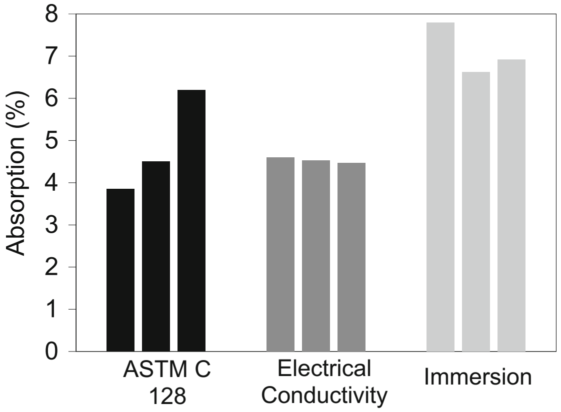

Fig. 6 Variation of water absorption capacity for ASTM C128, electrical conductivity and immersion methods when performed by three different operators

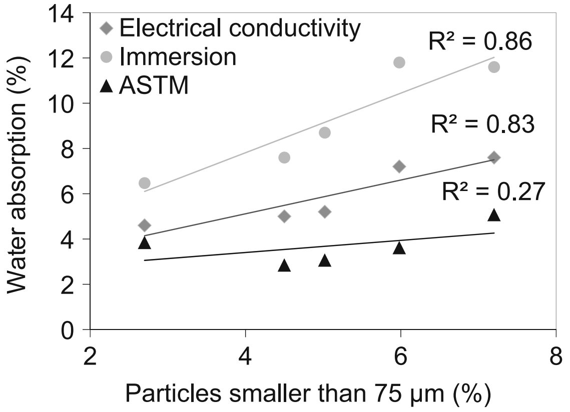

Fig. 7 Relationships between contents of particles finer than 75 μm and water absorption capacities

by the electrical conductivity and ASTM methods. Therefore, the difference between these last two methods reported in Table 2 for a single operator seems to be caused by the subjectivity in the determination of the SSD condition through the cone test. In support of this, the high standard deviation obtained for the ASTM method (Fig. 6) suggests low reproducibility when applied to FRCA, making it unsuitable for accurately determining its water absorption.

Considering the wide range of values obtained by the three methods applied, it is likely that the range of absorption capacities of FRCAs reported in the literature is not a direct and only consequence of the porosity and paste content in FRCAs, but it is also connected to the limitations and representativeness of each of the applied methods. Moreover, the limited reproducibility of some of them (especially the ASTM method when applied to crushed aggregates) contributes to a deficient comparative analysis of the literature. In this sense, the conductivity method showed to be very promising as the most reproducible among the three analyzed methods.

For analyzing the consistency of results, a contrast between the obtained absorption capacities and other aggregate properties is presented below. These properties include the content of fines, paste content and intrudable porosity.

Figure 7 shows the relationship between the content of material finer than 75 μm and the water absorption capacity determined according to the three analyzed methods. The trend of the results from the three methods shows increased absorption with the content of fines, independently of the aggregate type contained in the source concrete. In this regard, but the immersion and conductivity methods are more consistent than the ASTM method (as shown by R^2 values). The influence of the operator on the ASTM method is likely to increase with the increase in the content of fines and to compensate its effect, causing the weak correlation observed between both parameters. A natural increase in water absorption with the content of fines is to be expected due to the higher paste content that fines usually have in comparison with the coarser fraction of particles in the aggregate [50–52]. The more significant affectation by the content of fines for the immersion method could be a reflection of its stronger dependency on the content of fines in relation with deficiencies of the procedure. On the contrary, the slope for the ASTM method can be explained by its tendency to underestimate the absorption capacity of small particle sizes and to slightly overestimate this for medium particle sizes [49].

Figure 8 presents the relationships between (a) the paste content and the water absorption capacity, and (b) the intrudable volume of pores and the water absorption capacity. No relation between the paste content determined from acid solubility and water absorption capacity can be defined for any of the three methods. This is probably due to the fact that paste content is determined by weight, but the pore properties of the attached mortar are determined by volume. A certain content in weight of hydration products means a larger relative volume of paste with a lower compressive strength of the source concrete (as

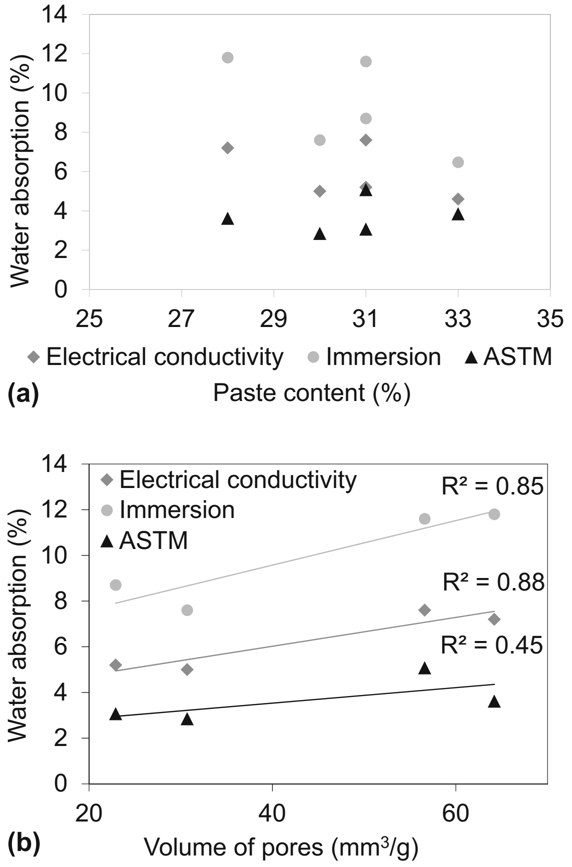

Fig. 8 Relationship between water absorption and **a** paste content, **b** volume of pores

the corresponding paste is more porous). Thus, the similar contents in weight in all recycled aggregates reported in Table 1 correspond to more different relative volumes (and absorption capacity) according to the compressive strength level of the source concrete.

The water absorption capacities determined by the immersion and conductivity methods correlate well with the intruded volume of the aggregates. The lack of adjustment in ASTM method could be explained again by the significant influence exercised by the operator.

The wide range of reported results shows that the water absorption capacity of FRCA is dependent on the method used for its determination. In consequence, the estimation of the amount of water to be added to the mixture for compensating the water uptake by the FRCA will vary based on the determination technique for water absorption capacity. Different levels of success should therefore be expected. In practical terms, the unreliable characterization of the aggregate implies an uncertain amount of free water in the fresh mix and, consequently, there will be an undetermined effective water/cement ratio. Then, a consistent comparison with reference concrete made with natural aggregates is not possible. Detrimental effects reported by some authors regarding the effect of FRCA on concrete properties might be mainly a consequence of an involuntary increase in the w/c ratio due to the inaccurate estimation of the water absorption capacity of FRCAs. In this sense, the immersion method seems to be quite unsuitable for determining the water absorption capacity of FRCAs, and its application would lead to an involuntary increase in the water/cement ratio of concrete containing FRCA. Conversely, the ASTM method seems to be the less repeatable among the three analyzed methods, when testing FRCAs.

From the comparison among the three evaluated methods, the conductivity method demonstrated the lowest variability and highest reproducibility. Moreover, a good correlation between water absorption capacity from the conductivity method and intrudable porosity was found. The experimental evidence is also supported by a theoretical explanation for the relationship between conductivity and surface moisture (including the case of non-angular aggregates, such as river siliceous sand). Therefore, there is a rational basis for considering that the ASTM and immersion methods tend to underestimate and overestimate water absorption capacity, respectively, whereas the conductivity method looks more reliable.

5 Conclusions

The electrical conductivity method was applied for the effective determination of saturated surface-dry (SSD) condition of five fine recycled concrete aggregates (FRCA). Water absorption capacities were computed from the results of this procedure. The outcome of this method is compared with the values obtained by the ASTM C128 and immersion methods. From the analysis, the following conclusions are drawn:

- Results from the electrical conductivity method showed a consistent relationship with the presumed surface moisture content determined by gravimetry. More importantly, this method showed better reproducibility than the ASTM C128 and immersion methods.

- The cone test method applied to the determination of the SSD condition of FRCA shows considerable subjectivity. The features of FRCA, being a crushed aggregate, cause the ASTM C128 method to have significantly poor reproducibility and, more remarkably, a consistent underestimation of the water absorption capacity.
- The immersion method showed the highest values of water absorption for the five FRCAs evaluated in comparison with the other two methods. The values of absorption were two and four times higher than the values obtained by the conductivity and ASTM C128 methods, respectively. The main cause for this outcome seems to be the considerable dependency of the quantified value on the content of fines in the sample. Thus, this method seems more appropriate for coarse aggregates and fine aggregates with a low content of fines.
- It is very likely that the range of absorption capacities reported in the literature for FRCA is not a direct and only consequence of the porosity and amount of the attached mortar in the aggregate, being highly influenced by the procedure and reproducibility of applied method for its determination.
- Water absorption increases with the content of particles smaller than 75 μm. This is related to the increased paste content in this range of particle size in comparison with coarser particles. The influence of the content of fines reflected on the results of the immersion and electrical conductivity methods. On the contrary, a poor correlation was found for the ASTM method, which can be linked to the influence of the operator on the procedure (which seems to exceed the impact of the content of fines in some cases).
- Water absorption capacities were validated by the experimental results of intrudable porosity. However, no correlation could be established with the paste content. Then, it is derived that the quality of attached paste could influence water absorption of FRA more than the paste content.

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