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Control of effective water in recycled aggregate concrete using power curves of the mixer

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Highlights

- ❖ Assessment of water migration during mixing of recycled aggregates concrete
- ❖ Highlighting the difference between theoretical effective water and the real one and, the overestimation of effective water according to standards
- ❖ Investigation of influence of the history and level of initial moisture of recycled aggregates on the water migration kinetics during recycled concrete mixing
- ❖ Monitoring of concrete mixing using power curves of the mixer and, the stabilization of effective water during the mixing

Abstract

Composed of several components (natural aggregates and attached cement paste), crushed concrete aggregates (CCA) are not widely recommended in new concrete formulations. Their properties considerably complicate the determination of effective water in fresh concrete. The evolution of effective water in fresh concrete during mixing was studied using an original method based on the power evolution of the mixer. The presented experiments analyzed the water migration kinetics during mixing and the level of stabilization of the effective water at the end of the mixing. This analysis was established according to the initial moisture of the CCA and of the type of pores filled with water in these aggregate, and, of the total water in the new concrete mixture. It was shown that the exchange of water between recycled aggregate and the new concrete mixture during the mixing is more complex than generally considered. The water can get into or get out from the CCA, depending on the history of their initial moisture. The direction of water migration can also change at different stages of concrete mixing. Therefore, the amount of effective

water decreases or increases during mixing and tends to stabilize once the uniform new concrete is obtained.

Keywords: Recycled aggregate concrete, crushed concrete aggregates (CCA), effective water, initial moisture, power curves monitoring.

1. Introduction

The world faces crucial environmental issues such as the over exploitation of natural resources and the production of million tons of construction and demolition wastes (C&D) in the building and public works sector [1-3]. The reuse of recycled concrete aggregates (RCA) (aggregates containing crushed concrete, brick, asphalt and other impurities), representing a major part of the C&D wastes in new concretes seems a solution for these two problems [4-5]. In this paper, crushed concrete aggregates (CCA) will be used and distinguished from RCA. CCA were made of more than 99% concrete. Composed of several components (natural aggregates and adherent cement paste), CCA are not widely recommended in new concrete formulations [6-7]. However, different studies were aiming to develop concrete production with RCA that comply with applicable codes and standards [8-12]. Until now a small percentage (20-30%) of these materials was reused to produce new recycled concretes [13]. The new concretes are therefore part of the NF EN206-1 standard. This standard defines effective water as the difference between the total amount of water contained in fresh concrete and the amount of water absorbable by aggregates. Its determination is generally not a problem for non-porous natural aggregates, but this concept leads to different performance for porous natural aggregates [14] and recycled aggregates. Their intrinsic properties (high absorption, heterogeneity, etc.) [15-16], compared to natural aggregates, considerably complicates the control of effective water in fresh concrete [17]. It has been shown in previous works [18] that water exchange between recycled aggregates and a medium other than water (such as a fresh cement paste [18]) is more complex than generally considered. Therefore, the real effective water ($W_{\text{eff}}(\text{real})$) in recycled aggregate concrete may decrease and/or increase during mixing. $W_{\text{eff}}(\text{real})$ represents here the amount of water present in the cement paste at a given time of mixing, excluding the water present in the porosity of aggregates. When using RCA, the real effective water could differ, at a given mixing time, from the theoretical effective water ($W_{\text{eff}}(\text{th})$), computed according to standards from the difference between total water and water absorbed by aggregates.

Several technical solutions can be found in the literature to improve the quality of recycled aggregates before incorporating them in new formulations of recycled concretes [19-20]. The pre-saturation of RCA could be a potential technical solution to this problem. However, the pre-saturation of RCA, especially recycled fine aggregate, without excess water, is a very complex task in the industrial production of concrete [21].

In addition, usually the initial moisture found in RCA is greater than the initial moisture of natural aggregates. Thus, the initial water content in natural aggregates (NA) does not exceed 1% while in RCA it can exceed 3.5% [17]. A higher moisture is not problematic, in case of using the RCA without any preparation, the real question here is to know if the initial water will affect the effective water content in concrete formulation or not. The effective water content has a major influence on the properties of cement-based materials. Therefore, the formulations of new recycled concrete can be wrong due to the extra ignored water in mixing [22] according to the specifications. The determination of the water absorption capacity (WA) and the knowledge of the initial state of saturation of the RCA are necessary for the formulation of new concretes. Several studies, like [22], show the variability of the actual absorption of aggregates in water depending on their initial moisture state. Khoury et al. [22] investigated the influence of pre-wetting history of CCA on their water absorption capacity. For this purpose, 6.3/10 mm CCA were pre-wetted using different methods simulating long-term (LT) and short-term (ST) pre-moistened aggregates. It was shown that this pre-moistened history (LT or ST) leads to different levels of total water absorption for a same initial moisture level. Previous studies already demonstrated that different initial moisture conditions lead to different mixing results for the concrete [23].

Recent improvements [24-25] have been made to existing procedures to take into account the specifications of recycled aggregates and their water absorption kinetics. However, the results obtained from previous studies have left questions to which the present experimental work provides answers.

Concrete mixing goes through several stages leading to agglomeration of powders and granulation [26]. The wet agglomeration behaviors of powders and the granulation process can differ and be modified by several parameters like the amount of water in the mixture. In the literature, the different states of wet particles were described as a function of the amount of added liquid [27]. The use of the power curves consumed by the mixer during concrete

mixing is one of the methods for monitoring the evolution of the mixture. This technique was developed by Cazaciu et al. [26] and was more recently calibrated by coupling with image analysis [28].

The main objective of this paper is to estimate the evolution of W_{eff} (real) during the mixing of recycled aggregate concretes. At first, the effects of pre-wetting history of CCA (long-term (LT) and short-term (ST) pre-moistened aggregates) on fresh recycled concrete properties were investigated. Then, a relevant cut-points of the power consumption curves recorded during mixing was proposed and based on physical considerations (wet agglomeration steps [27]). A method was then proposed from this division to estimate the evolution of the W_{eff} (real) during the mixing as well as the absorption capacity of the CCA at the end of the mixing.

2. Experimental method

2.1. Materials

Normal concretes based on natural aggregates and recycled aggregates concretes based on coarse CCA were made. The common materials used for these two types of concretes were:

- CEMI 52.5 cement from Lafarge Cements (St Pierre La Cour, France), having a real dried density of 3.13 g/cm^3
- limestone filler (BETOCARBHP-EB, Omya) having a real dried density of 2.63 g/cm^3
- natural silico-calcareous sand 0/4 mm
- superplasticizer high water reducer of the Chryso company (HRWR) of type Optima 352 EMx.

In addition, recycled aggregates concretes were prepared using CCA as the coarse aggregates. The 6.3/10 mm CCA were sourced from the "Gonesse recycling platform" in France and were composed of 99% of crushed concrete and 1% of other inert materials. Normal concretes were made from 5.6/11.2 mm rolled natural siliceous aggregates (NA) as coarse aggregates.

Table 1 summarizes the most significant characteristics of the used materials. The water absorption coefficient (WA_{24}) and the real dried density in water of the CCA were determined according to European standard NF EN 1097-6.

Table 1. Properties of materials

Materials	Cement	Filler	Sand	CCA	NA
Size range (mm)			0/4	6.3/10	5.6/11.2
Real dried density (g/cm ³)	3.13	2.63	2.64	2.31	2.58
WA ₂₄ (%)			0.3	4.9	0.65

The CCA were prepared and pre-wetted prior to mixing using different initial moistures conditions and different modes of pre-wetting. Three different initial moisture conditions were used:

- Oven-dried (coded OD): samples were dried at 70±5°C in the oven for 48 hours to obtain constant mass and were cooled down to room temperature prior to mixing
- Under-saturated surface dry state (coded USSD)
- Saturated surface dry (coded SSD)

Under-saturated and saturated surface dry CCA were obtained from aggregates pre-wetted using four different methods:

- 1) In the first method, CCA were immersed in water under atmospheric pressure for 24 hours, then they were brought to saturated surface dry state by letting them drained on sieves and gently drying their surface with absorbing paper (according to NF EN 1097-6), they are coded by “air-SSD” (initial water content (w_i) = 4.9%)
- 2) In the second method, CCA were under-saturated: varying amounts of water (w_i = 1, 2, 3 or 4%) were sprayed on dry CCA sited on a sieve under the atmospheric pressure. The under-saturated CCA are coded by “air-USSD1%”, “air-USSD2%”, “air-USSD3%”, and “air-USSD4%”
- 3) In the third method, CCA were immersed in water under low pressure (40 mbar) for 24 hours then drained and gently towed, they are coded by “void-SSD” (w_i = 6%)
- 4) In the fourth method, CCA were soaked in water under partial vacuum according to the third method. Then, they were left air drying for several time intervals to obtain different water contents, w_i = 1.2, 2, 3.22, and 4.3%. These tests are coded

by “void-USSD1.2%”, “void-USSD2%”, “void-USSD3.22%”, and “void-USSD4.3%”.

For all cases, the real water content was measured before using the pre-wetted CCA in concrete mixtures by taking a sample from the pre-wetted aggregates. After their preparation, the CCA were kept in large waterproof bags then used in the formulations of the concrete.

2.2. Mix design

Normal and recycled aggregate concretes were produced following the recipes given in **Table 2**. Recycled aggregate concretes were formulated by performing a total substitution of NA with the same real volume of CCA. The values of the other parameters in the **Table 2** were changed according to the correction of the compositions to have total volume of 1 m³.

Table 2. Normal and recycled concrete formulations

Materials (kg/m ³)	Cement	Filler	NA	CCA	Sand	SP	W _{eff} (th)
Recycled concrete	293	146.5	-	740.3	861.2	8.8	132→152
Natural concrete	302.2	151.3	868.3	-	888.5	9	153→168

A total of 41 batches of recycled concrete and 4 batches of normal concrete were carried out. Four series of concretes are prepared by varying only the effective theoretical water-to-powder ratio (W_{eff} (th)/P), between 0.3 and 0.34 for recycled concretes and between 0.34 and 0.37 for normal ones. Here, W_{eff}(th) vary from 132 to 152 kg/m³ in the recycled concretes formulations and from 153 to 168 kg/m³ in the natural concretes.

Table 3 presents the different types of water that can be found in the concretes formulated with NA or CCA. For recycled aggregate concretes, and for each W_{eff}(th)/P, eleven batches were made incorporating CCA used in different conditions of initial moisture. Concretes are noted according to the initial moisture state of the CCA.

For each recycled concrete formulation, the W_{eff}(th) and the mixing water added after dry mixing of components (W_{mixing}) were determined according to **Eq.1** and **Eq.2** respectively. The total water (W_{total}) corresponds to the volume of water added to the mixer plus the initial water (w_i) contained in all the constituents (natural or recycled aggregates) and the water brought by the superplasticizer (w_{sp}). The W_{mixing} was calculated to have

approximately the same $W_{eff}(th)$ in all concretes of the same series, regardless of the initial moisture of CCA.

$$W_{eff}(th) = W_{total} - WA_{24, sand} \cdot M_{sand} - WA_{24,A} \cdot M_A \quad \text{Eq.1}$$

$$W_{mixing} = W_{total} - w_{SP} - w_i \cdot M_{CCA} \quad \text{Eq. 2}$$

In the **Eq. 1** and **Eq. 2**, $WA_{24, sand}$ and $WA_{24,A}$ correspond to the water absorption coefficients determined according to standard NF EN 1097-6 for aggregates. w_i is the initial water quantity in CCA and in the sand. The NA were used dry in the mixtures.

Table 3. Different types of water that can be found in normal concrete containing natural aggregates (NA) and in recycled concretes containing CCA with different initial humidification states (OD, air-SSD, void-SSD, air-USSD1%, ...)

Concretes	Types of water presented in the concretes (kg/m ³)				
	w_i (%)	W_{mixing}	W_{total}	$W_{eff}(th)$	$W_{eff}(th) / P$
NA	0	153.0	161.4	153.1	0.338
	0	159.0	167.4	159.1	0.351
	0	161.8	170.1	161.8	0.357
	0	168.0	176.4	168.1	0.371
OD	0.12%	162.5	171.6	132.7	0.302
	0.12%	166.8	175.8	137.0	0.312
	0.12%	168.8	177.8	139.0	0.316
	0.12%	179.0	188.1	149.2	0.340
air-SSD	4.90%	126.3	170.7	131.9	0.300
	4.90%	132.5	177.0	138.1	0.314
	4.90%	142.5	187.0	148.1	0.337
void-SSD	6.00%	122.0	174.6	135.7	0.309
	6.00%	126.3	178.9	140.0	0.319
	6.00%	128.0	180.6	141.7	0.323
	6.00%	138.3	190.9	152.0	0.346
air-USSD1%	1.00%	155.0	170.6	131.7	0.300
	1.00%	159.3	174.8	136.0	0.309
	1.00%	161.3	176.8	138.0	0.314
	1.00%	171.5	187.1	148.2	0.337
void-USSD1.2%	1.20%	155.0	172.1	133.2	0.303
	1.20%	161.3	178.3	139.5	0.317
	1.20%	171.5	188.6	149.7	0.341
air-USSD2%	2.00%	147.8	170.7	131.9	0.300
	2.00%	152.0	175.0	136.1	0.310
	2.00%	154.0	177.0	138.1	0.314
	2.00%	164.3	187.2	148.4	0.338
void-USSD2%	2.00%	147.8	170.7	131.9	0.300
	2.00%	152.0	175.0	136.1	0.310
	2.00%	154.0	177.0	138.1	0.314
	2.00%	164.3	187.2	148.4	0.338
air-USSD3%	3.00%	140.3	170.6	131.8	0.300
	3.00%	144.5	174.9	136.0	0.310
	3.00%	146.5	176.9	138.0	0.314
	3.00%	156.8	187.1	148.3	0.337
void-USSD3.22%	3.22%	140.3	172.3	133.4	0.304
	3.22%	144.5	176.5	137.7	0.313
	3.22%	146.5	178.5	139.7	0.318
	3.22%	154.0	186.0	147.2	0.335
air-USSD4%	4.00%	133.0	170.8	131.9	0.300

	4.00%	137.3	175.1	136.2	0.310
	4.00%	139.3	177.1	138.2	0.314
	4.00%	149.5	187.3	148.4	0.338
void- USSD4.3%	4.30%	133.0	173.0	134.2	0.305
	4.30%	139.3	179.3	140.4	0.319
	4.30%	149.5	189.5	150.7	0.343

2.3. Mixer and mixing power monitoring

An inverter with an acquisition frequency of 10 Hz was connected to the mixer to record the power. The power curves presented in the results were plotted after an application of two consecutive averages on 10 points each (in total over 2 seconds).

2.4. Experimental Procedure

The CCA were used immediately in the mixing of concrete after their preparation (oven dried, pre-saturated or pre-wetted). The mixer was first filled with coarse aggregates, sand, cement and filler. Then all components were dry mixed for 30 seconds. The mixing water together with the superplasticizer were then added during 10 seconds at a constant flow rate. Then, mixing was pursued for 5 minutes. Immediately after mixing, the slump of fresh concrete was measured according to standard slump test procedure (NF EN 12350-2) but using a mini Abrams cone, half size with the same geometric ratio as the Abrams cone.

3. Results and discussions

3.1. Slump after mixing

Figure 1 shows the variation of the initial slump of the fresh recycled concretes as a function of $W_{\text{eff}}(\text{th})/P$ for different initial moisture contents and different pre-wetting methods of CCA. For each initial water content, the variations of the initial slump were established for the two types of pre-humidification under air and under partial vacuum.

The slump values of all mixes increased with the $W_{\text{eff}}(\text{th})/P$ and the initial slump varies between 0 and 12 cm. In addition, the initial slumps of all the concretes tested increase with the $W_{\text{eff}}(\text{th})/P$ ratio, whatever the conditions of initial humidity. It is also observed that recycled concretes containing LT pre-wetted CCA (dashed lines) are less fluid than those containing ST pre-wetted CCA (continuous lines), for the same ratio $W_{\text{eff}}(\text{th})/P$ and the same amount of the initial water in CCA. This observation can be explained by the fact that, in recycled concrete, the LT pre-wetted RCA absorb more water than the ST pre-wetted CCA, leading to lack of free water in the mixture influencing the slump. However,

for $w_i = 3\%$, it is noted that at low $W_{eff}(th)/P$, the pre- humidification mode (under atmospheric or low pressure) did not affect the initial slump of fresh concrete. On the other hand, the maximum difference was obtained between the initial slump of fresh recycled concrete containing air-USSD4% CCA and void-USSS4.3% CCA. This is in complete agreement with the results observed on water absorption tests performed in water on pre-wetted recycled concrete aggregate in the study of Khoury et al. [22].

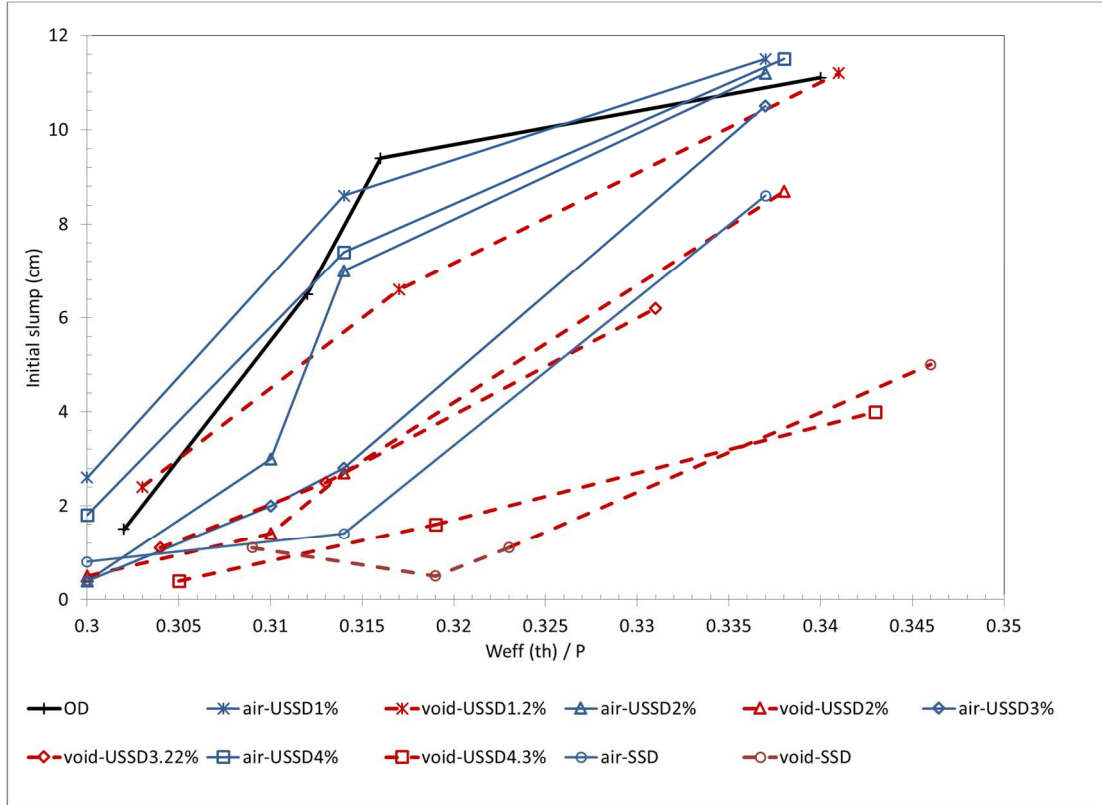


Figure 1. Initial slumps of recycled concretes containing 100% CCA, oven dried (OD), saturated surface dried (void-SSD and air-SSD) long-term pre-wetted (void-USSD) and short-term pre wetted (air-USSD) and with different initial moisture condition for different $W_{eff}(th)/P$.

At low initial moisture, the behavior of both LT and ST pre-wetted samples was rather similar to the oven dried sample. The behavior remained similar for all ST under saturated samples, but with some more free water in the mixture for the lower initial moisture CCA. At opposite, the LT under saturated CCA induced less free water in the mixture for the higher initial moisture cases. To finish, the air-saturated CCA (air-SSD) had intermediate behavior between the ST pre-wetted samples and the LT pre-wetted samples.

3.2. Mixing power curves

Figures 2 presents the results of mixing power recorded for different batches of recycled concrete with $W_{eff}(th)/P$ near to 0.34. These results show that variation in the initial

moisture condition changed the mixing behavior of the mixture. By considering the higher water content level (0.34) it can be observed that the mixing power remains constant during the dry mixing of the components for 30 seconds (after the stabilization of the effect of mixer starting). The level of stabilized power is dependent on the initial moisture condition. When the addition of the mixing water began, the power increased considerably. The power continued to increase after the end of the addition of the mixing water until reaching the point of maximum cohesion [26]. This can be explained by the fact that, after the addition of the mixing water, the amount of liquid in the overall mixture increases. The space between the particles begins to be filled, it is the funicular state. When the spaces are completely filled with water, the bridges are saturated but with a dry outer surface, this is the capillary state. When particles are totally enclosed in a liquid, a state of solid-liquid dispersion is obtained. So the mixture needs less power to be well mixed.

Subsequently, the power gradually decreased during the formation of the granular paste and continued decreasing to reach the fluidity point [26], in these cases there is a limitation of detection of the point of fluidity. After fluidity point, the power continued to decrease at a lower rate up to the end of the mixing as a consequence of the dispersion of fine particles produced by the plasticizer.

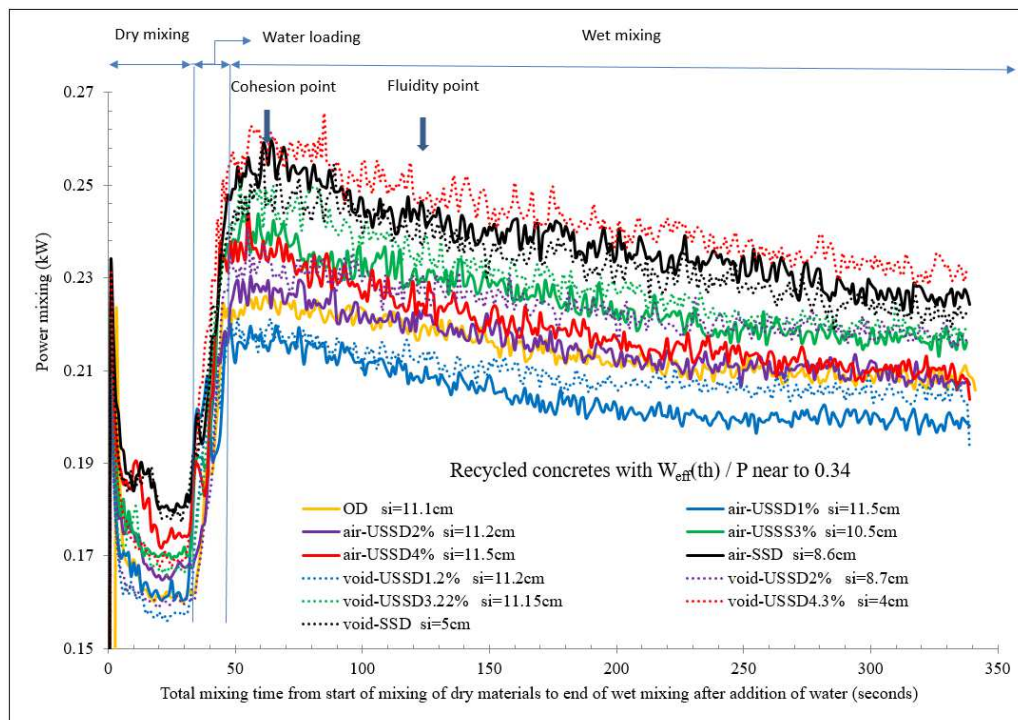


Figure 2. Mixing power evolution with the mixing time for mixture with theoretical effective water to powder ratio of 0.34 and different initial moisture conditions of the CCA; the initial slump (s_i) of each corresponding initial moisture condition is indicated in the legend

It can be observed that the power curves of recycled concrete incorporating CCA pre-moistened under partial vacuum (LT) are upper than the power curves of recycled concrete incorporating CCA that were pre-moistened under atmospheric pressure (ST). This can be explained by the fact that the LT pre-wetted CCA absorbed more water than the ST pre-wetted CCA [22]. So, there was less free water in recycled concrete mixture using LT pre-wetted CCA, the concrete was less fluid, and the mixer consumed more power.

A very particular case is the 4% of initial moisture. It was shown in a previous work that the nearly saturated CCA under spraying, blocked the absorption of new water during subsequent immersion in water [22]. So, the total **water absorbed** was lower in this case compared to all other initial moisture conditions [22]. This was not the case for the same level of initial moisture obtained by long-term wetting. This phenomenon explains the large difference between the levels of the power curves for these two tests: the LT test shows much more absorbed water by the CCA than the ST test.

Results in **Figure 2** also show that slightly under-saturated samples (both LT and ST tests) were more workable than oven dry CCA. The saturated CCA produced much less workable mixture. These conclusions are in agreement with the experimental results presented in [23].

The behavior at lower total water content globally presented the main trends as for the previously discussed situation. It is interesting to underline that in all cases the lower fluidity with short-term under saturated CCA was obtained for an intermediate level – 3% (OD, 1%, 2% and 4% produced more workable mixture). The LT and ST saturated CCA produced very similar workability and had very similar mixing power evolutions with the mixing time, even if the level of saturation was significantly different for these situations. Finally, in all cases, the less workable mixture was obtained for the LT highest level under-saturated CCA (4%). The water absorbed by these CCA during mixing was even higher than the water absorbed by the LT saturated CCA which was supposed to liberate some water into the mixture during the mixing. This was a very surprising result consistently observed.

4. Interpretation of power results

4.1. Different steps of agglomeration during concrete mixing

In the literature, the evolution of wet granular mixtures is described as a function of the amount of added liquid [29].

In this part, the mixing procedure is divided into three stages: - dry mixing - start of the wet mixing (after the addition of the mixing water) and - end of the wet mixing. During these three mixing steps, the effective water content in the granular mixture varies.

In the following analysis, three averages of recorded power are performed over three time intervals: 1- power during dry mixing (average power over the first 30 seconds), 2- power at the beginning of wet mixing (average between 50 and 60 seconds) and 3- power at the end of wet mixing (average over the last 10 seconds).

- **Dry mixing**

Figure 3 shows the average of the power results recorded during dry mixing of the components of recycled aggregates with different $W_{\text{eff}}(\text{th})/P$ ratios in function of initial moisture of CCA incorporated in the formulations. In this figure, each point represents the average power measured during dry mixing for concretes with the same initial water content, corresponding to the four $W_{\text{eff}}(\text{th})/P$ ratios tested. Here, the ratio $W_{\text{eff}}(\text{th})/P$ does not affect the interpretation of the powers during the dry mixing. In all recycled concrete mixtures, the same quantities of dry materials (cement, filler and sand) were used and the only difference was in the initial saturation state of the CCA. At the beginning of the dry mixing the power fluctuations are negligible (average standard deviation for all the mixtures is around 0.0018 kW). These differences are very small compared to the small amount of concrete produced (4 liters) and the error can be considered systematic because the mixing tests were performed at the same time, in the same period of the year.

It can be observed that, during the dry mixing, and when the w_i increases the power increases because the capillary bridges increase in the mixture. This observation can be explained by the fact that during dry mixing, the water in the pre-moistened CCA tends to come out in the mixture. The power of the mixer therefore increases with the initial humidity of the CCA. But it should not be forgotten that at this stage the water content is very low in the overall mixture (CCA pre-humidified or not, dry sand, cement and filler) before the addition of the mixing water. The phenomenon observed at the beginning of dry mixing corresponds to the distribution of the liquid on the surface of the particles. The amount of water is still low so as not to form enough liquid bridges and increase the cohesion of the system.

In addition, it can be observed that, in the recycled concrete with CCA pre-moistened with LT mode, the power during dry mixing is smaller than that for concretes with GBR pre-moistened with ST. This can be explained by the fact that, in LT pre-wetted CCA, the water was located in a less accessible porosity than that contained in ST pre-wetted CCA. The amount of water released in the mixture is therefore in this case lower than in the concrete with ST pre-wetted CCA.

The recycled concrete incorporating dry CCA and LT pre-wetted CCA with small $w_i = 1.2\%$ have the same power in dry mixing. Therefore, initially wet CCA with a very small amount of water have the same behavior in the concrete as if they are dry.

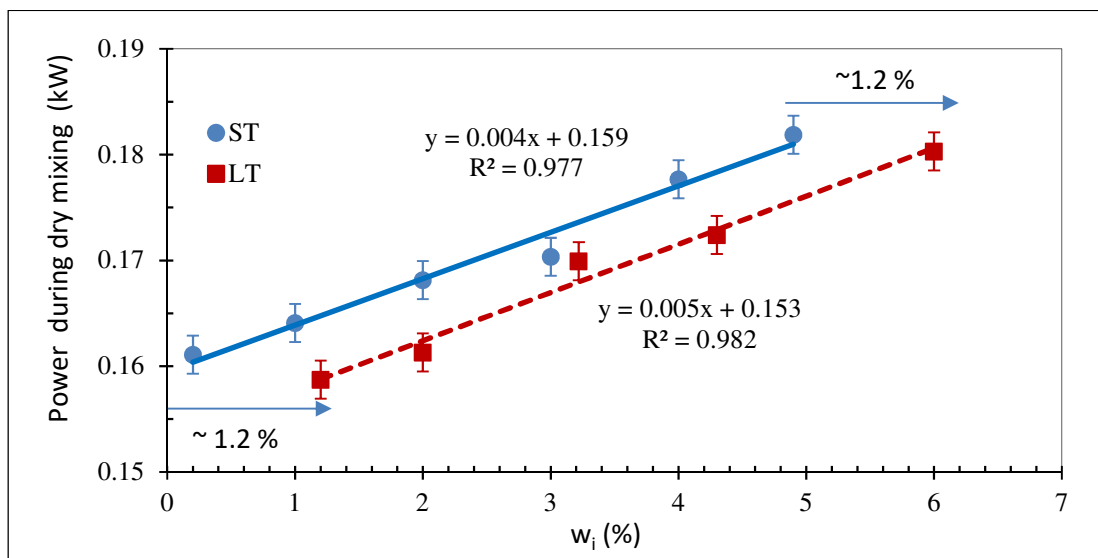


Figure 3. Global average of power of the mixing of recycled aggregates with four ratios $W_{\text{eff}}(\text{th})/P$ for each initial moisture amount w_i and modes under atmospheric pressure (ST) and under lower pressure (LT)

- Wet mixing: beginning and end

Figure 4 shows the evolution of the power of the mixer at the beginning and the end of wet mixing for one case with $w_i = 4-4.3\%$. The wet mixing begins just at the end of loading of mixing water. In the two graphs presented in **Figure 4**, same phenomenon is observed at the beginning and at the end of the wet mixing. It can be observed that, the power decreases with the W_{eff}/P ratio. And this is observed for all initial conditions of pre-wetting of CCA.

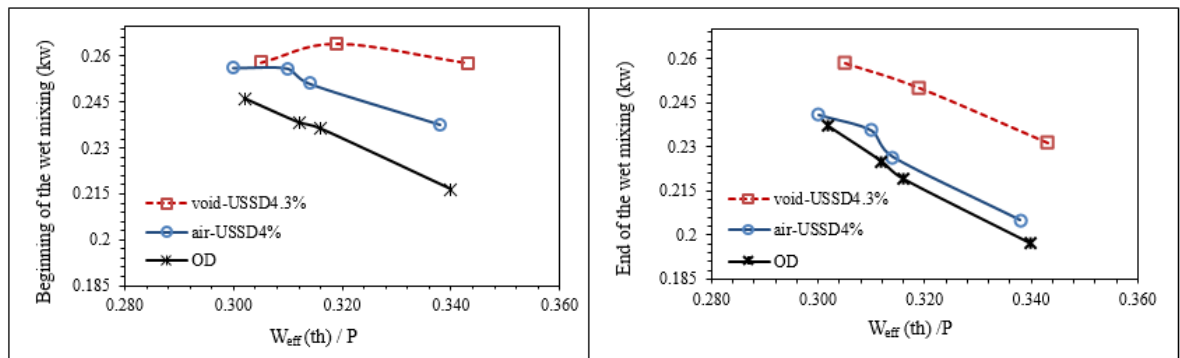


Figure 4. Powers of the mixer at the beginning (left) and the end (right) of wet mixing of recycled concrete with 4% initial moisture (LT and ST) for CCA incorporated in recycled concretes in function of the ratio $W_{eff}(th)/P$.

4.2. Evolution of the real effective water according to the power curves

In this section, an original method to estimate the evolution of $W_{eff}(real)$ in recycled aggregates concrete during mixing is developed. To do this, the power curves registered during mixing of normal concretes are used as calculation charts for the recycled aggregate concretes.

Figure 5 shows the power consumed during the mixing of normal concretes for the four $W_{eff}(th)/P$ ratios (0.338, 0.351, 0.357 and 0.371). It is observed that the power consumed increases when the ratio $W_{eff}(th)/P$ decreases, therefore with the $W_{eff}(real)$ reduction in the mixer. It can be considered in this analysis that the $W_{eff}(th)/P$ ratios of normal concretes are equal to $W_{eff}(real)/P$ because the NA used are quasi non absorbing. It is thus considered that there was no water exchange between the NA and the mixture of normal concrete.

In addition, we hypothesize that, when the dissipated power for a recycled concrete is the same as that dissipated for a normal concrete, then the $W_{eff}(real)$ they contain are identical for the two concretes. This assumption can be justified on the basis of the following arguments:

- Formulations of recycled aggregate concrete were close to those of normal concretes and were designed to remain in the same consistency range as normal concretes (initial slumps ranged from 0 to 11 cm). The NA were notably replaced by the same real volume of CCA

- In the 4 formulations of normal concrete, only the effective amount of water changed. Consequently, the differences observed between the powers of these 4 concretes are due solely to the variation of the effective water from one batch to another

- Finally, the power consumed during the dry mixing of normal concrete was almost identical to the power consumed by recycled concrete. It is therefore assumed here that it was only the variation of the effective water during mixing which was responsible for the variation of power from one concrete to another.

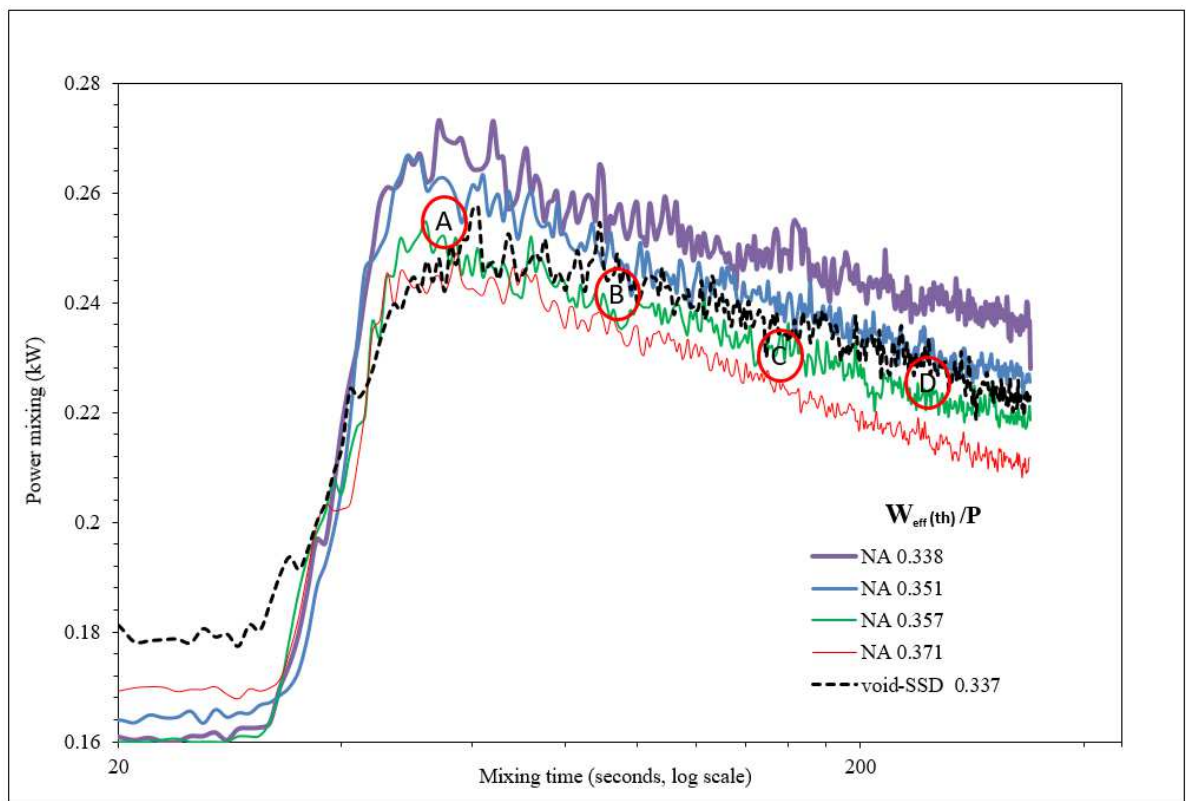


Figure 5. Mixing power curves for ordinary concrete, and intersection with an example of power curve of recycled concrete

In addition, **Figure 5** shows an example of how to exploit a power curve obtained for a normal concrete in order to estimate the $W_{\text{eff}}(\text{real})/P$ in a recycled aggregate concrete (void-SSD 0.337). We can, from the points of intersection and with an interpolation, determine the evolution of the $W_{\text{eff}}(\text{real})/P$ at every moment of concrete mixing.

From the intersection of the power curves of each recycled aggregate concrete with the power curves of the four normal concretes, the $W_{\text{eff}}(\text{real})/P$ is determined for each recycled aggregates concrete for 9 given intervals of mixing time ($T_i = 0, 10, 30, 60, 90, 120, 180, 260$ and 290 seconds?). Here, the intervals of time are taken from the end of the introduction

of water into the mixture. For each of these intervals (T_i), the power taken into account is the average of the powers consumed between the instants T_i and $T_i + 10s$.

At the instant T_0 , $W_{eff}(real, T_0)/P$ is determined according to **Eq. 3** neglecting the water exchanged by the humidified CCA with the mixture during dry mixing.

$$W_{eff}(real, T_0) = W_{total} - w_i * M_{CCA} \quad \text{Eq. 3}$$

Where, w_i is the initial amount of water and M_{CCA} mass of CCA.

At 10, 30, 60, 90, 120, 180, 260 and 290 seconds after the end of the water introduction, $W_{eff}(real)/P$ is extrapolated linearly at each moment using the power curves and the $W_{eff}(th)/P$ of the normal concretes. The same procedure is used for all formulations with CCA in different initial moisture states and with different $W_{eff}(th)/P$. For the presentation of results in the following figures the very beginning of wet dry mixing is considered as the origin of the time axis.

Figure 6 shows the evolution of $W_{eff}(real)/P$ in recycled aggregate concrete, incorporating OD CCA, during mixing. It can be observed in this figure that the $W_{eff}(real)/P$ estimated decreases with the mixing time. It is also observed that, whatever the mixing time is, the effective water actually present in the concrete is systematically higher than the effective water theoretically determined according to the European standard NF EN 206-1/CN. As a result, CCA are unable to absorb the full amount of water added according to the standard to compensate for their absorption. We can conclude from this that the water absorption of CCA in concrete must be determined by another method than that used for NA in normal concretes.

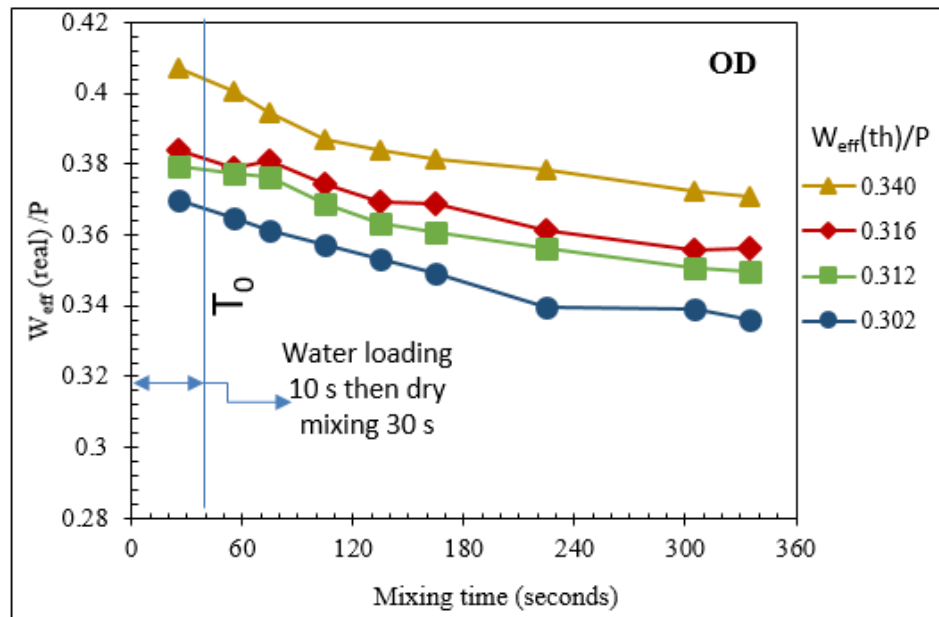


Figure 6. Evolution of the $W_{eff} (real)/P$ ratios for recycled concretes incorporating dry CCA for different theoretical $W_{eff} (th) / P$ ratios.

Figure 7 shows the evolution of $W_{eff}(real)/P$ in the recycled concrete mixture containing CCA pre-wetted with different modes under air (ST) and under partial vacuum (LT) and with different amounts of initial water ($w_i = 2\%$ and $4-4.3\%$). First, it is observed that the same behavior is obtained for the evolution of $W_{eff} (real) / P$ in all the cases presented. Indeed the effective water decreases during the first 300 seconds of mixing time. After it remains substantially constant until the end of mixing. $W_{eff} (real) / P$ thus stabilizes after about 300 seconds during mixing, for recycled concretes incorporating initially CCA pre-moistened with small amounts of water either under vacuum or under air. Second, for the recycled concretes contained initially CCA pre-moistened with larger amounts of water either under vacuum or under air, the actual effective water estimated increases at the beginning of mixing up to about 60 seconds and then decreases during mixing until stabilization is achieved. This stabilization appears to occur earlier than for the lower initial water contents, approximately 240 seconds instead of 300 seconds previously. Thus, with pre-humidification under partial vacuum, the stabilization of the $W_{eff} (real)$ seems to be faster.

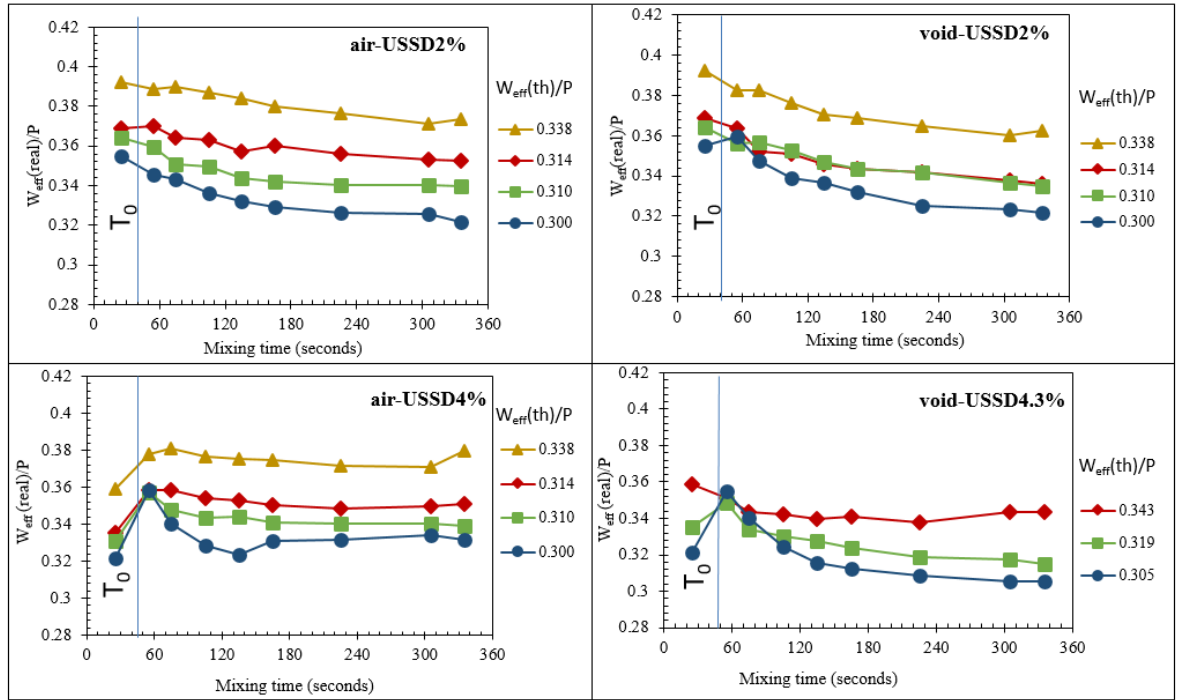


Figure 7. Evolution of the $W_{eff} (real) / P$ ratios for recycled concretes incorporating CCA pre-moistened with CT and LT method with different w_i (2% and 4%) in function of mixing time and theoretical ratios $W_{eff} (th) / P$.

4.3. Estimation of the water absorbed by CCA during the mixing of recycled concrete

The data analyzed above make it possible to determine the trapped water (W_T) in the CCA at each moment of mixing (T) according to **Eq.4**. The latter takes into account: $W_{eff} (th)$, $W_{eff, T} (real)$ at the instant T determined by the method discussed above, the quantity of powders P (cement and filler), the mass of CCA (M_{CCA}) and the water absorption coefficient of CCA ($WA_{24, CCA}$). Then the water absorption capacity of CCA during mixing ($W_{abs, concrete}$) is estimated using **Eq.5**. $W_{abs, concrete}$ therefore represents the amount of water absorbed by the CCA during mixing.

$$W_T = \left(\left(\frac{W_{eff}(th)}{P} \right) - \left(\frac{W_{eff, T}(real)}{P} \right) \right) * \frac{P}{M_{CCA}} + WA_{24, CCA} \quad \text{Eq. 4}$$

$$W_{abs, concrete} = W_{(T=5 \text{ minutes})} - w_i \quad \text{Eq. 5}$$

Figure 8 shows the variation of the water absorption capacity of CCA in recycled concrete during mixing in function of their initial moisture conditions and pre-

humidification mode, and in function of $W_{eff}(th)/P$. A difference can be observed between the water absorption capacity of dry CCA (OD) and under saturated CCA with $w_i = 2\%$ at CT and LT. With a long-term pre-humidification (partial vacuum) the absorption of CCA in concrete is higher. For partially saturated CCA (USSS2%, USSS3-3.2% and USSS4-4.3%), water absorption is 0.5 to 1% greater when CCA were pre-wetted under partial vacuum than when they were pre-wetted under atmospheric pressure. The same observations were made in a previous work [22].

Figure 9 shows the variation of the water absorption capacity of CCA in recycled concrete in function of their initial moisture states, and their pre-humidification mode, and in function of $W_{eff}(th)/P$. Here, the studied cases are under saturation states with w_i close to 80% of WA_{24} (air-USSS4% and void-USSS4.3%) and saturation states (air-SSS and void-SSS).

Apart from the initial state void-USSS4.3% which absorbs a small amount of water, the absorptions of the other 3 states studied are all negative and this can be explained by the fact that the CCA release water during mixing. This result differs from what was observed in previous work [22] where the absorption in water was negligible. In addition, CCA under saturated with 80% of WA_{24} (air-USS4%) releases more water into the mixture than CCA saturated under vacuum. These results confirm the observations on the results of the initial slump of these concretes and the power curves.

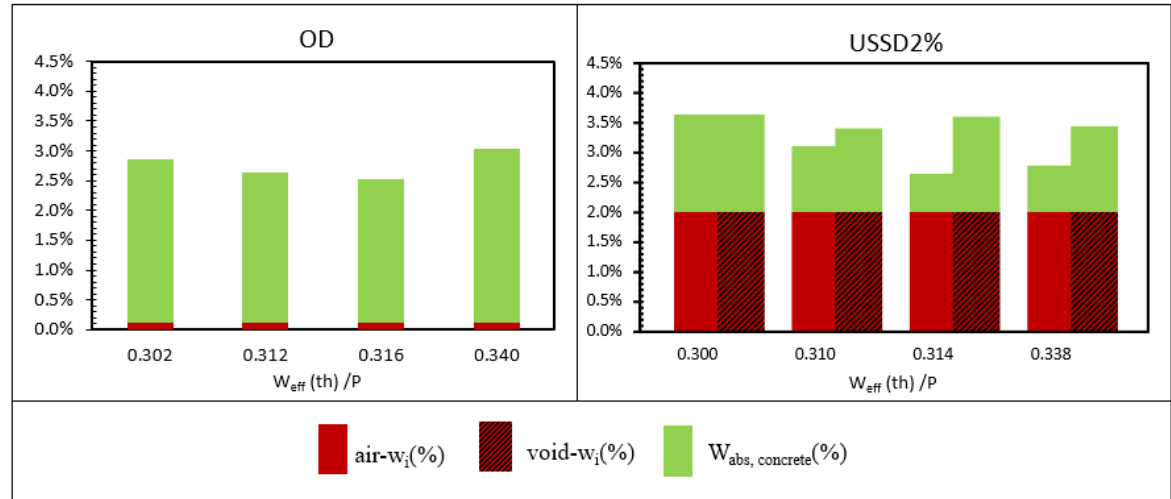


Figure 8. CCA water absorption capacity with different pre-humidification states, OD, air-USSD and void-USSD with lower amount of initial water in CCA. The red bars represent the water initially present in the CCA after their humidification and before their incorporation into the mixture of concrete at atmospheric pressure. The red bars with pattern correspond to pre-humidification under partial vacuum. Green bars represent water absorbed by CCA during concrete mixing.

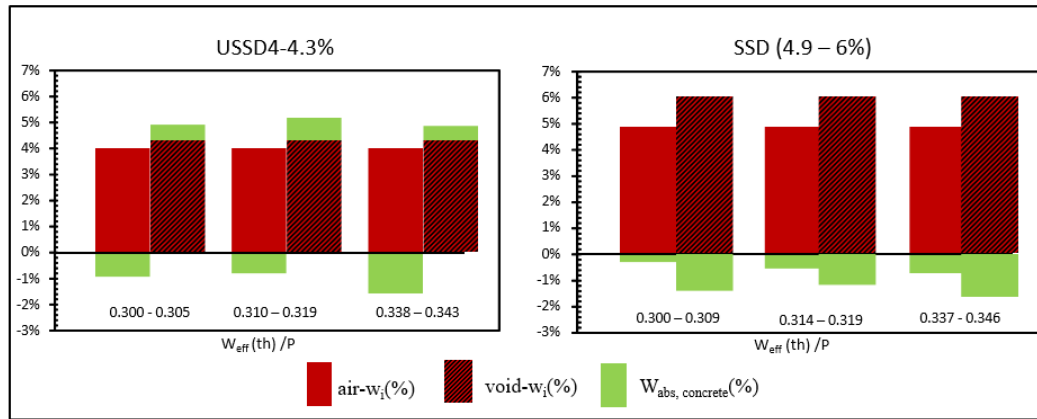


Figure 9. CCA water absorption capacity in different pre-humidification states, air-USSS4%, void-USSS4.3%, air-SSD and void-SSD. The red bars represent the water initially present in the CCA after their humidification and before their incorporation into the mixture of concrete at atmospheric pressure. The red bars with pattern correspond to pre-humidification under partial vacuum. Green bars represent water absorbed by CCA during concrete mixing.

4.4. Saturation level in the CCA

Till this section, two modes of humidification are distinguished. Short-term humidification, where water is initially located in pores accessible to water and long-term using partial vacuum, in this case the initial water is also located in the less accessible pores.

In this section, the saturation rate of CCA during concrete mixing is investigated. To do this a comparison between $W_{eff}(th)$ and $W_{eff}(real, T=335s)$ is carried.

Figure 10 shows the evolution of $W_{eff}(real, T = 335s)/P$ as a function of $W_{eff}(th)/P$. the recycled concretes incorporating CCA with different initial moisture are separated into 4 groups: a first group with concretes based on OD, air-USSS (1 to 4%) and void- USSS1% CCA, a second group with recycled concretes based on air-SSS and void-USSS3.22% CCA, a third group with recycled concrete based on void-USSS2% CCA, and a last group with recycled concretes based on void-SSS and void-USSS4.3% CCA.

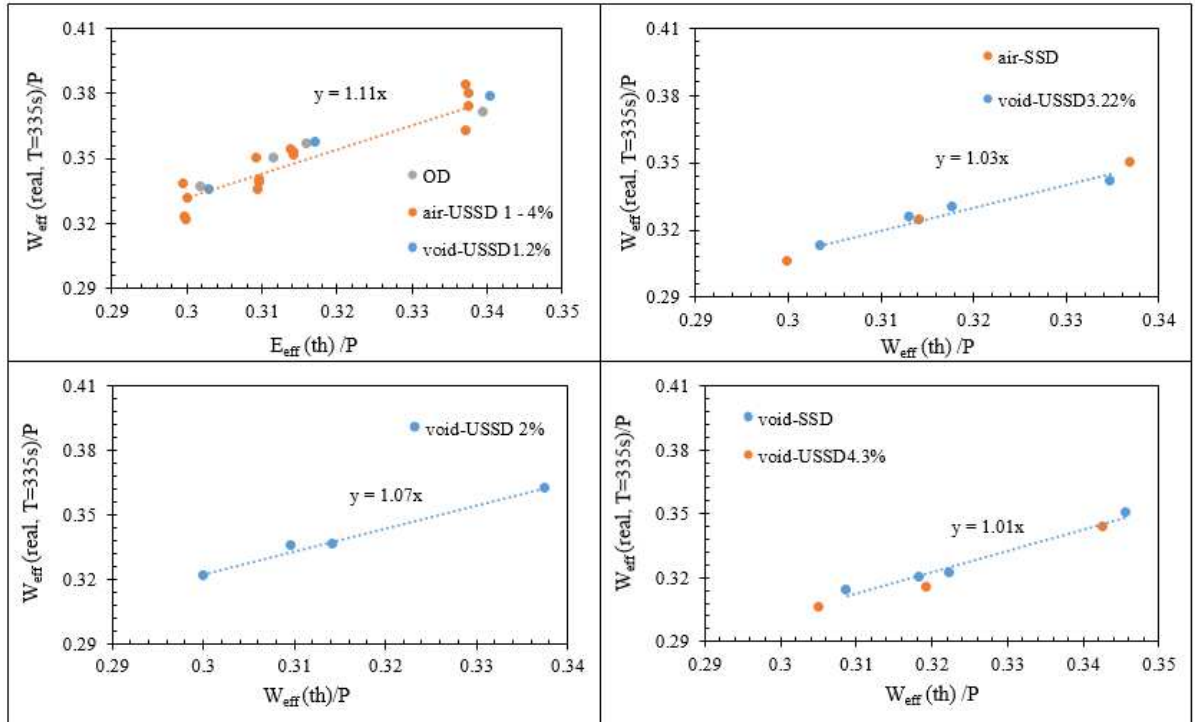


Figure 10. Comparison of the effective water to powder ratio at $T = 335s$ ($W_{eff}(real, T=335s)/P$) and the theoretical effective water to powder ratio ($W_{eff}(th)/P$) in function of the saturation levels of CCA during concrete mixing.

For concretes initially containing small quantities of initial water (OD, air-USSS1-4% and void-USSS1%) the slope of the evolution of $W_{eff}(real, T=335s)/P$ in function of $W_{eff}(th)$ is 1.11. Therefore, the actual effective water estimated is 11% larger than the theoretical effective water. For concrete based on air-SSS and void-USSS3.22% CCA, the slope is 1.03. The actual effective water is 3% larger compared to the theoretical effective water. For saturated CCA with vacuum (void-SSS and void-USSS4.3%) the slope is 1.01. In this case the calculation of the effective theoretical water provides a good estimate of the actual effective water. Therefore, to control the actual effective water in fresh concrete, the theoretical water calculation must consider not only the water absorption capacity of CCA in concrete but also the humidification history of these ones.

5. Conclusion

This paper presents an original method for tracking the actual effective water exchanges as well as the water absorption capacity of a CCA when mixing new concrete. The method consists in following the power curves evolution of the mixer during mixing for different scenarios of initial moisture porous aggregates. Some previously observed phenomena were confirmed, and several new phenomena were consistently observed.

Actual effective water is estimated from a comparison between fresh recycled aggregate concrete power curves and those of normal concretes with compositions and properties like recycled concrete. One of the main advantages of the method is that it allows continuous monitoring of water exchanges between the aggregate and the mixture.

The results show that, except for some saturation conditions (high saturation rate for LT saturation), the actual effective water in the mixture is consistently higher than the theoretical effective water calculated according to water absorption capacity measured according to EN 1097-6. This deduction was confirmed by the results of the initial slumps of fresh recycled concretes incorporating OD CCA that were more fluid than expected. This can be explained by the fact that the CCA cannot absorb during mixing the total amount of water added to compensate for its absorption determined by EN 1097-6. Thus, effective water must be determined considering not only the water absorption capacity but also the history of its pre-humidification or its initial moisture.

In addition, it can be deduced that the W_{eff} (real /P) in the mixture with CCA that were LT pre-wetted stabilizes faster than that in a mixture with CCA that were ST pre-wetted. For pre-saturated CCA after immersion in water for 24 hours under partial vacuum or under air respectively, the real effective water decreases with the mixing time but with a stabilization at 180 seconds.

The results show also that with a vacuum saturation the real effective water can be controlled by determining the effective theoretical water at the beginning of the concrete production as a function of the initial state of saturation. Long-term humidification allows the least accessible pores of CCA to be filled and then reduces water exchange between CCA and cement paste in concrete. On the contrary, for ST saturation with spraying, the water is located essentially in the most accessible pores and is thus easily exchangeable during mixing. However, these results have yet to be completed in order to be able to further the analyses.

Finally, recommendation could be considered in the use of CCA in new concrete formulation for example using a lower nominal absorption value than the standard WA_{24} in calculating effective water. This value can be equal to 60-75% of WA_{24} if the CCA is used dry. And if used pre-humidified the value will be proportional to the initial water content in the porosity of CCA and higher for the CCA slowly pre-wetted (LT pre-wetted).

Conflict of interest: The authors declare that they have no conflict of interest.

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