EMPIRICAL DEFINITION OF EFFECTIVE WATER / CEMENT RATIO IN MORTARS WITH RECYCLED AGGREGATE DEPENDING ON THE ABSORPTION

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ABSTRACT

The use of recycled aggregates from construction and demolition wastes for the manufacture of mortars and concretes is a subject of great interest from the point of view of sustainable construction since it can reduce the exploitation of quarries replacing natural aggregate by recycled aggregate and it can reduce the volume of wastes in landfills.
In order to study the influence of recycled aggregate on concrete and mortar strength, the effective water/cement ratio must be the same in concretes or mortars compared. The effective water/cement ratio is defined as the amount of water available to react with the cement of the mixture. Discrepancies among authors arise in the definition of how much is the amount of available water, which depends on the absorption and moisture of the aggregates at the time of the batch.
Therefore, in this research, an experimental study is developed empirically to find the amount of water which reacts with the cement mortar in various mixtures with different ratios of recycled aggregate depending on the absorption of the aggregates. Subsequently, the relations between the amount of water which doesn't react with the cement and aggregate absorption of each of the mixtures were analyzed. Finally, a definition of the effective water/cement ratio depending on absorption is proposed, based on the empirical study developed.

Keywords: recycled aggregate, effective water/cement ratio, CDW, absorption, mortar

1.- Introduction

The term “effective water/cement ratio” has a clear definition: *“Total amount of water that reacts with cement, divided by the amount of cement“*. The problem appears when defining “the amount of water that reacts with cement”. The presence of aggregates, which absorb part of the water, causes that part of the water cannot react with cement and therefore, the effective water/cement ratio is lower than the real water/cement ratio.

When recycled aggregates utilization, this reduction in the effective water/cement ratio is considerable, due to the high absorption of the recycled aggregates and it has to be taken into consideration. If it were possible to find the amount of water not reacting due to the aggregates absorption, calculating the effective water/cement ratio would be something immediate.

The use of recycled aggregates coming from construction and demolition wastes to make mortar and concrete is very interesting from the point of view of sustainable construction. As well as reducing quarries exploitation replacing natural aggregates by recycled aggregates, the amount of wastes placed in tips is also reduced.

One way of studying de influence of recycled aggregates in mortars and concrete is testing specimens made with different ratios of recycled aggregates and compare them with the reference dosage with a replacement ratio of 0% in mortar and concrete. In order to make these mortars and concretes comparable, the only factor that can differ among them must be the replacement ratio. It is well known that the w/c relation or more specifically, effective w/c has influence on the strength results.

In order to compare concretes and mortars with different ratios, it is necessary that the w/c relation will be constant, not being a new variable to consider.

Consequently, it is really important to know the effective w/c according to the aggregates absorption, in order to make the necessary adjustments with the aim of having the same w/c relation in every specimen.

Discrepancies arise in defining what amount of water that recycled aggregates absorb and therefore is not available to react with the cement. Some authors recommend presaturating the aggregates [1, 2, 3, 4], others recommend their immersion in water for 30 minutes [5] and for 10 minutes [6, 7] with the aim of non-absorbing more water. Among the authors who recommend adding more water during de concrete production, there is no an agreement about this amount, some of them say that the best idea is adding 100% of absorption capacity [8], others 90% [9, 10], 85% [11], 80% [12] and 70% [13].

2.- Objective of the study

The objective of this study is to get a relation between the absorption of the aggregates and the effective w/c ratio based on an experimental development searching for relations between the w/c ratio and the microwaves frequencies in mortars whose aggregates have a different absorption. Getting, in this way, a definition of the effective w/c ratio based on the absorption of the aggregates utilized to make mortars, since there are discrepancies among authors about the influence of the absorption of recycled aggregates in the effective w/c ratio and the definition of the adjustment of water necessary to get dosages with different ratios of recycled aggregates but with the same water/cement ratio.

In order to compare the results of mortar strengths with different ratios of recycled aggregates and measure the influence of recycled aggregates in strength is necessary that every dosage has the same water/cement ratio. Otherwise, this factor would affect to strengths and it could not be said that the differences in strengths are only caused by an increment in the recycled aggregate. It is important to mention that getting the same effective w/c ratio is not equivalent to get the same consistence of the mixture.

3.- Basis of this study and methodology

It is known that the relation of the amount of water that reacts with cement in a mixture is delimited between the amount of water added and the difference between that amount and the amount of water that the aggregates can absorb. In other words:

$$\text{Water that reacts} = \text{water added} - \alpha * \text{absorption capacity of aggregates} \quad (1)$$

Being α a value between zero and one. If α had a zero value, it would be assumed that the whole water added would be available to react with the cement. If α had the value 1, it would be assumed that the supposition that all the water that aggregates can absorb is absorbed and therefore, it is not available to react with the cement. In other words, it would be equivalent to suppose that in order to have the same w/c relation between two concretes or mortars with different replacement ratios, it would be necessary to do and adjustment increasing the absorption total amount of water (adjustment of 100% of the absorption of the recycled aggregates).
Due to the amount of cement is constant, dividing by the amount of cement, it results:

$$\text{effective w/c} = \text{real w/c} - \alpha *(\text{absorption capacity / cement}) \quad (2)$$

On the other hand, there is a relation between the microwaves frequency and the w/c ratio. In fact, there is a device called “cementometer” that estimates the w/c ratio, previous calibration, through the relation between the w/c ratio and the microwaves frequency. This device is calibrated and designed to measure real w/c ratios in certain kinds of cement and using natural aggregates (whose difference in absorption is minimum, nearly negligible, so the real w/c and the effective w/c relations are identical). On the basis of the existence of an unknown relation between the microwaves frequency and the effective w/c ratio the first part of this study is developed.
If there was a natural aggregate with a 0% absorption, the whole added water would react with the cement, that is, the real w/c ratio would be the same than the effective w/c ratio. Measuring the frequency that corresponds to several effective w/c ratios of a mortar made with zero absorption aggregates, it could be found a function of the value of the effective w/c ratio according to the value of the frequency measured.
Next step would be calculating the effective w/c relation with the previous expression in mortars whose absorptions were changing; for instance, preserving the dosage and replacing only natural aggregate by recycled aggregate.
There is not a natural aggregate with zero absorption, so it is not possible to find an exact curve that relates frequency to the effective w/c ratio. However, it is possible to find an upper and lower bound where it is known that the correlation curve will be, as it will be explained in the next paragraphs.
It is known that the effective w/c ratio is delimited between the value of the real w/c ratio (without considering the influence of the aggregates absorption) and a minimum value of the effective w/c ratio. This “minimum value of w/c” is the result of assuming that the total amount of water that the aggregates could absorb does not react with the cement. In other words, in order to calculate the w/c ratio, the amount of water utilized to calculate de w/c ratio and the absorption water of the aggregates are added to the mixture.

$$effective\ {}^{w}/_{c} = (minimum\ {}^{a}/_{c}\ ,\text{real}\ {}^{a}/_{c})$$

Using a natural aggregate, with a low absorption, it is possible to find an upper and lower bound, calculating the curves that relate the w/c to the frequency; one of the curves relates real w/c to frequency and the other curve relates w/c correcting absorption water. The effective w/c ratio will be between these curves. In this way, for each frequency, a corresponding effective w/c ratio is delimited in a small interval.
The next graph (Fig. 1) shows the upper and lower bound of effective w/c according to the measured frequency in fresh mortar, using dry natural aggregates in the mixture.

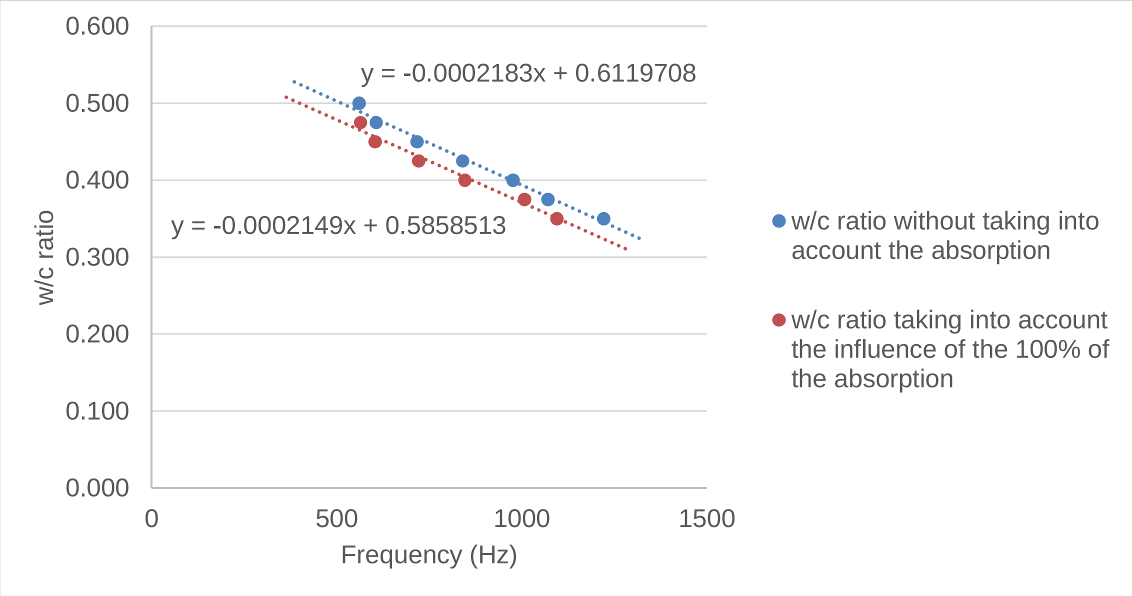

Fig. 1 “Upper and lower bound of effective w/c ratio according to the frequency”.

In order to find between the effective w/c ratio and the absorption, mortars are studied with the same dosage, varying only the rate of recycled aggregate that is replaced by natural aggregate. In this way, mortars whose aggregates have a different absorption capacity will be obtained.
The objective of this study is to find and expression that estimates the effective w/c relation according to the aggregates absorption, or in other way, the influence of the aggregates absorption in the effective w/c.
In order to obtain it, once the upper and lower bounds of the effective w/c ratio have been calculated in a reference mortar (Fig. 1), the methodology will be the following:

- Mortars with different replacement ratios will be tested. In every test, frequencies corresponding to several w/c relations will be measured.
- With the same expressions for estimating the effective w/c relation of the upper and lower bound, the minimum and maximum corresponding effective w/c relation will be found for every real w/c relation in every dosage. In other words, in each value of the real w/c relation (from 0.35 to 0.65 with incensements of 0.05) in every dosage, an interval of the corresponding effective w/c relation is obtained. For each value of real w/c, we will have a minimum and maximum value of effective w/c.
- Other way of calculating the w/c effective ratio is with the formula 2:

$$\text{Effective w/c} = \text{real w/c} - \alpha *(\text{absorption capacity / cement}) \qquad (2)$$

- Taken to be true the value of the lower bound of w/c for each mixture (and including in each mixture its corresponding absorption capacity), the value of α that minimises the root mean squared error of the estimations of effective w/c is calculated according to the formula 2.
- This process is repeated eight times, considering the values calculated in the previous upper and lower bound as real values. The corresponding value of α that minimises the root mean squared error between the values calculated according to the formula 2 and the experimental values of the frequency measurements using the upper bound is calculated.

4.-Development of the experimental campaign and analysis of results

Once the upper and lower bound that correlates the frequencies with the effective w/c relation have been found, mortars with replacement ratios of 25%, 50%, 75% and 100% of natural aggregates by recycled aggregates are studied. The cement/sand dosage is 1:3, because of that, the quantities of cement, natural sand and recycled sand are:

	Replacement rate				
	0%	25%	50%	75%	100%
Cement (g)	450	450	450	450	450
Natural sand (g)	1350	1012.5	675	337.5	---
Recycled sand (g)	---	337.5	675	1012.5	1350

Table 1 “Dosages”

All the aggregates will be added dry (with zero moisture).

The natural aggregate has an absorption of 0.19% and the recycled aggregate has an absorption of 6.43%.
As the replacement rate increases, the amount of water that the aggregates can absorb is higher, since the recycled aggregates have a higher absorption. The maximum amount of water that the aggregates can absorb in each mortar studied is shown in the next table:

	Replacement rate				
	0%	25%	50%	75%	100%
Water to saturate natural sand (g)	2.6	1.9	1.3	0.6	0.0
Water to saturate recycled aggregate (g)	0.0	22.7	45.4	68.1	90.9
Total absorption capacity (g)	2.6	24.6	46.7	68.8	90.9
Total absorption capacity / cement	0.006	0.062	0.117	0.172	0.227

Table 2 “Maximum absorption capacity of the utilized aggregates divided by the cement added”

For each replacement rate, the next steps are followed:

- For each dosage, a mixture is made. That mixture starts with a low real w/c relation, around 0.35 (in same dosages, the real w/c has to be higher due to the high absorption of the aggregates produces a non-homogeneous mixture because it does not have the minimum amount of water to form a paste.
- More than 12 measurements of frequency are made for the first real w/c ratio. The mean frequency corresponding to each real w/c ratio is found.

- The necessary water is added to reach the following real w/c ratio, increasing the w/c ratio in 0.05 and the step of measuring the frequency and calculating the mean 12 times is repeated. This process is repeated every possible time until the mixture has an excess of water and it is too liquid. In other words, the mean frequency corresponding to each real w/c relation is measured, from the lowest real w/c to the highest, with increases of 0.05. (See table 3)
- The value of the effective w/c ratio corresponding to that frequency is calculated through formulas that delimit the upper and lower bound of the effective w/c ratio calculated previously. In this way, an interval with the effective w/c ratio for each frequency is obtained. Values are shown on table 3.

	Real w/c	Mean Frequency	Effective w/c lower bound	Effective w/c upper bound
MORTAR WITH A 25% REPLACEMENT OF R.A.	0,375	1194,25	0,33	0,35
	0,400	1056,00	0,36	0,38
	0,425	970,75	0,38	0,40
	0,450	898,50	0,39	0,42
	0,475	742,88	0,43	0,45
	0,500	649,75	0,45	0,47
	0,525	594,25	0,46	0,48
MORTAR WITH A 50% REPLACEMENT OF R.A.	0,400	1197	0,33	0,35
	0,425	1177	0,33	0,36
	0,450	1095	0,35	0,37
	0,475	945	0,38	0,41
	0,500	913	0,39	0,41
	0,525	725	0,43	0,45
	0,550	621	0,45	0,48
MORTAR WITH A 75% REPLACEMENT OF R.A.	0,450	1191	0,33	0,35
	0,475	1093	0,35	0,37
	0,500	1001	0,37	0,39
	0,525	911	0,39	0,41
	0,550	813	0,41	0,43
	0,575	753	0,42	0,45
	0,600	639	0,45	0,47
MORTAR WITH A 100% REPLACEMENT OF R.A.	0,475	1211	0,33	0,35
	0,500	1162	0,34	0,36
	0,525	1071	0,36	0,38
	0,550	981	0,38	0,40
	0,575	899	0,39	0,42
	0,600	771	0,42	0,44
	0,625	690	0,44	0,46

Table 3 **“**Measured mean frequencies corresponding to each real w/c ratio and its corresponding effective w/c estimated according to limit functions of upper and lower bound”

- In Table 3, values of real w/c, mean frequency, effective w/c lower bound, effective w/c upper bound are shown.
- Data Processing: Firstly, data of the w/c lower bound will be processed. Curves correlating real w/c and effective w/c in its minimum bound are shown. (Figure 1)

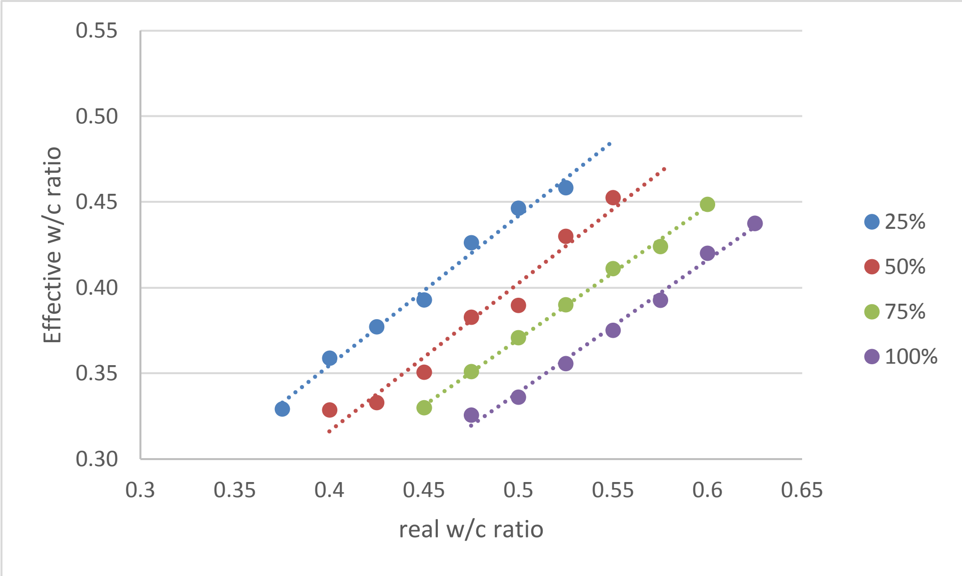

Fig. 2 "Curves of real w/c ratio vs effective w/c ratio, calculated with lower bound of calibrated curves"

- As can be seen in Figure 2, a relation between the w/c effective lower bound and the real w/c has been obtained. Nevertheless, as it has been said previously, it is possible to estimate the effective w/c relation with the formula 2, according to the absorption capacity of the aggregates

$$\text{Effective w/c} = \text{real w/c} - \alpha \,*(\text{absorption capacity / cement}) \qquad (2)$$

- Since we know the value of the lower bound of the effective w/c ratio corresponding to each real w/c ratio and the absorption capacity is a data too (See table 2). The only unknown data is the value of the parameter α, whose value will be between 0 and 1.
- The value of α that minimises the total root mean squared error of the whole values of effective w/c estimated for every dosage according to the formula 2, with the minimum squared method is found. In other words, we search for the value of α that estimates the effective w/c relation calculated according to the aggregates absorption (2) and will be similar to the calculated experimentally with the lower bound that relates frequency with effective w/c relation (Fig. 1); so that this value of α minimises the total root mean squared error of the estimations of effective w/c in accordance with the absorption.
- In this way, the relation between the effective w/c ratio lower bound and the aggregates absorption is found, since the value of α multiplied by 100 is the percentage of absorption water necessary to add in order to adjust the water with the aim of having the same effective w/c relation. The value of α that minimises the root mean squared error of the effective w/c ratio lower bound is 0.7775; in other words, it would be necessary to do an adjustment of the w/c adding a 77.75% of aggregates absorption water to the real water. (See table 4)

	Real w/c	Mean frequency	Effective w/c ratio (Calculated lower bound, according to the frequency)	Effective w/c estimated according the absorption (Calculated with formula 2)	Difference between estimated w/c and effective w/c lower bound
MORTAR WITH A 25% REPLACEMENT OF R.A.	0,375	1194	0,33	0,33	-0,0021
	0,400	1056	0,36	0,35	-0,0068
	0,425	971	0,38	0,38	-0,0001
	0,450	899	0,39	0,40	0,0094
	0,475	743	0,43	0,43	0,0009
	0,500	650	0,45	0,45	0,0059
	0,525	594	0,46	0,48	0,0190
MORTAR WITH A 50% REPLACEMENT OF R.A.	0,400	1197	0,33	0,31	-0,0194
	0,425	1177	0,33	0,33	0,0013
	0,450	1095	0,35	0,36	0,0087
	0,475	945	0,38	0,38	0,0014
	0,500	913	0,39	0,41	0,0196
	0,525	725	0,43	0,43	0,0042
	0,550	621	0,45	0,46	0,0068
MORTAR WITH A 75% REPLACEMENT OF R.A.	0,450	1191	0,33	0,32	-0,0136
	0,475	1093	0,35	0,34	-0,0097
	0,500	1001	0,37	0,37	-0,0044
	0,525	911	0,39	0,39	0,0012
	0,550	813	0,41	0,42	0,0052
	0,575	753	0,42	0,44	0,0173
	0,600	639	0,45	0,47	0,0178
MORTAR WITH A 100% REPLACEMENT OF R.A.	0,475	1211	0,33	0,30	-0,0272
	0,500	1162	0,34	0,32	-0,0127
	0,525	1071	0,36	0,35	-0,0073
	0,550	981	0,38	0,37	-0,0016
	0,575	899	0,39	0,40	0,0057
	0,600	771	0,42	0,42	0,0032
	0,625	690	0,44	0,45	0,0108
α that minimises el root mean squared error	**0,7775**		Root mean squared error		0,0112

Table 4 “effective w/c relation (according to frequency and lower bound) compared with the w/c ratio calculated with the formula 2 according to the absorption capacity. Value of the α parameter that minimises the root mean squared error between these two values”

- Then, the steps of data processing are repeated, but this time, considering as real values of effective w/c the values calculated with the function that limits the upper bound that relates effective w/c relation to frequencies. (Fig. 1)
- Next, it is calculated the parameter α that minimises the root mean squared error between the values of effective w/c calculated with the formula 2 and the

values of effective w/c calculated through the correlation with the frequency and using the upper bound.

- The value of α that minimises the root mean squared error is 0.6432. In other words, an adjustment of water, adding a 64.32% of the aggregates absorption water. (See Fig. 3 and Table 5)

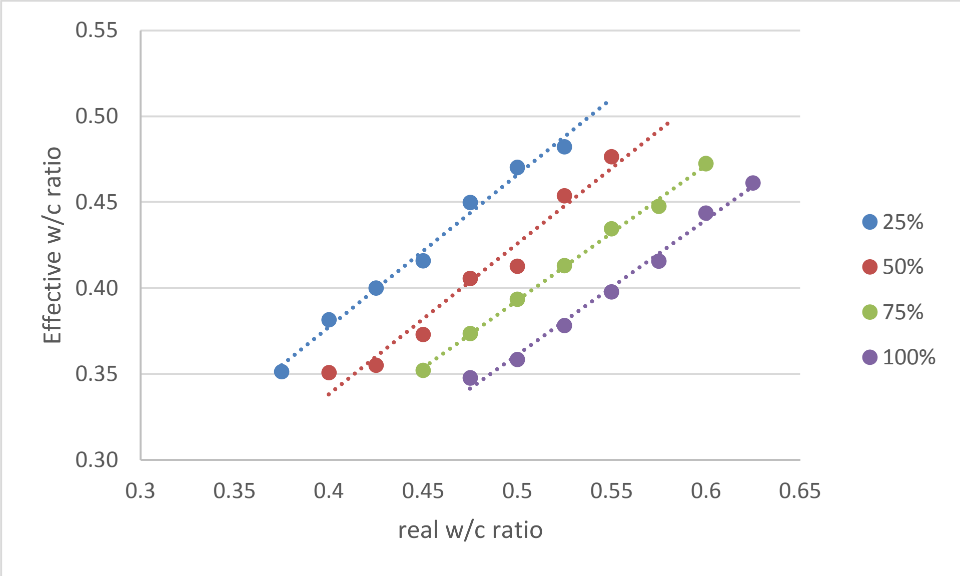

Fig. 3“Curves of real w/c ratio vs effective w/c ratio, calculated with upper bound of calibrated curves”

	Real w/c	Mean frequency	Effective w/c ratio (Calculated upper bound, according to the frequency)	Effective w/c estimated according the absorption (Calculated with formula 2)	Difference between estimated w/c and effective w/c upper bound
MORTAR WITH A 25% REPLACEMENT OF R.A.	0,375	1194	0,35	0,34	-0,0159
	0,400	1056	0,38	0,36	-0,0211
	0,425	971	0,40	0,39	-0,0147
	0,450	899	0,42	0,41	-0,0054
	0,475	743	0,45	0,44	-0,0144
	0,500	650	0,47	0,46	-0,0097
	0,525	594	0,48	0,49	0,0031
MORTAR WITH A 50% REPLACEMENT OF R.A.	0,400	1197	0,35	0,32	-0,0258
	0,425	1177	0,36	0,35	-0,0051
	0,450	1095	0,37	0,37	0,0020
	0,475	945	0,41	0,40	-0,0058
	0,500	913	0,41	0,42	0,0122
	0,525	725	0,45	0,45	-0,0038
	0,550	621	0,48	0,47	-0,0015
MORTAR WITH A 75% REPLACEMENT OF R.A.	0,450	1191	0,35	0,34	-0,0126
	0,475	1093	0,37	0,36	-0,0090
	0,500	1001	0,39	0,39	-0,0041
	0,525	911	0,41	0,41	0,0013
	0,550	813	0,43	0,44	0,0049
	0,575	753	0,45	0,46	0,0168
	0,600	639	0,47	0,49	0,0169
MORTAR WITH A 100% REPLACEMENT OF R.A.	0,475	1211	0,35	0,33	-0,0187
	0,500	1162	0,36	0,35	-0,0044
	0,525	1071	0,38	0,38	0,0007
	0,550	981	0,40	0,40	0,0061
	0,575	899	0,42	0,43	0,0132
	0,600	771	0,44	0,45	0,0102
	0,625	690	0,46	0,48	0,0176
α that minimises el root mean squared error	**0,6432**		Root mean squared error		0,0119

Table 5"Effective w/c relation (according to frequency and upper bound) compared with w/c ratio calculated with the formula 2 according to the absorption capacity. Value of the α parameter that minimises the root mean squared error between these two values"

5.- Conclusions

As we can see, the coefficient α is higher in the expression calculated with the data of the effective w/c lower bound. This is consistent with the formula 1, so the higher α is, the lower effective w/c relation resulting from the formula is.

Since the coefficient correction α is between 0.64 and 0.78, it can be said that, in order to have the same effective w/c ratio in mortars with different replacement ratios, it is necessary to correct the water adding an amount of water that is between 64 % and 78 % water required to saturate the aggregates that comprise the mixture.

That is why, it is recommended doing an adjustment in the amount of water between 64% and 78% of the absorption capacity of the aggregates that comprise the mixture. A possible adjustment would be to add the 71% (interval mean point) of water needed to saturate the aggregates, in the case that the aggregates have been added dry to the mixture.

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