Mechanical Behavior of Recycled Mortars Manufactured from Moisture Correction Using the Halogen Light Thermogravimetric Balance as an Alternative to the Traditional ASTM C 128 Method

Diana Gómez-Cano, J. C. Ochoa-Botero, Roberto Bernal Correa, Yhan Paul Arias

***Abstract*—**To obtain high mechanical performance, the fresh conditions of a mortar are decisive. Measuring the absorption of aggregates used in mortar mixes is a fundamental requirement for proper design of the mixes prior to their placement in construction sites. In this sense, absorption is a determining factor in the design of a mix because it conditions the amount of water, which in turn affects the water/cement ratio and the final porosity of the mortar. Thus, this work focuses on the mechanical behavior of recycled mortars manufactured from moisture correction using the Thermogravimetric Balancing Halogen Light (TBHL) technique in comparison with the traditional ASTM C 128 International Standard method. The advantages of using the TBHL technique are favorable in terms of reduced consumption of resources such as materials, energy and time. The results show that in contrast to the ASTM C 128 method, the TBHL alternative technique allows obtaining a higher precision in the absorption values of recycled aggregates, which is reflected not only in a more efficient process in terms of sustainability in the characterization of construction materials, but also in an effect on the mechanical performance of recycled mortars.

***Keywords*—**Alternative raw materials, halogen light, recycled mortar, resources optimization, water absorption.

I. Introduction

THE mechanical performance of concretes and mortars based on Portland hydraulic cement depends on the effective hydration of the cement, therefore a water-cement ratio is established that is kept constant according to a mix design, where a correction for moisture is determined. In this sense, it is necessary to measure the water absorption rate of the aggregates, which constitute between 60% and 80% of the total volume of the mix [1], [2].

Recycled aggregates (RA), as an alternative raw material to natural aggregates (NA), are characterized by a higher porosity, which can be 10-20 times higher than those of NAs [3], as well as a correspondingly higher degree of water absorption, defined as the amount of water required to completely fill the pores of the aggregate [4], [5]. This marked physical difference is due to the presence of the cement paste bonded to the surface of the RA, which is around 3-10% of its total volume [6], [7]. In this sense, the absorption rate of AR affects the fresh and hardened properties of concrete due to the time required for AR saturation which could affect its workability [8], [9]. On the other hand, in the hardened state, concrete becomes more porous, thus increasing the permeability to aggressive agents, which decreases its mechanical performance and durability [10]-[12].

The ASTM C 128 standard requires aggregate preparation of more than 24 hours to determine the water absorption value of a fine aggregate, which implies a high consumption of resources such as time, energy and materials [13]. Furthermore, the results obtained are highly variable and depend on the operator's ability to identify the state of saturated-surface-dried (SSD) associated with the degree of absorption of the aggregate [14]. Since RA has cement paste attached to its surface, which can detach during the absorption test based on water immersion and drying of the aggregates and modify its absorption, the ASTM C 128 test approach for water absorption cannot give accurate results for RA, which leads to errors in concrete mix designs.

Techniques have been proposed to measure water absorption in fine RA, based on water absorption measured as a function of drying at a temperature of 105 °C [15]. However, in the case of sulphoaluminate and aluminate cements, other studies recommend reducing the drying temperature to 70-75 °C to limit the alteration of the hardened cement paste, since in the case of cements the ettringite content in RA changes significantly with a small temperature variation. [16]. Théréné et al. [3] evaluated the effect of temperature and its influence on the pore distribution of the bonded paste. They found an increase in water absorption with increasing drying temperature, which originates from the dehydration of ettringite, resulting in an increase in the pore size of the hardened cement paste and, therefore, in an increase of the total porosity. Tam et al. [17] report the study of an alternative technique called real-time water absorption assessment (RAWA), which provides an easier way to obtain water absorption at different time intervals, avoiding the removal of the cement paste during the soaking and drying process of the RA sample. However, there is still some ambiguity in the use

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of these proposed techniques, due to the lack of systematization of the process to determine the SSD state in RA, taking into account the importance of the drying temperature required to obtain the degree of absorption, which in the case of RA its large variation could lead to a systematic error in the correction of the moisture applied to the mix design.

In this research, a technique based on a systematization of a thermogravimetric process: TBHL is proposed to obtain the water absorption of fine RA, as a follow-up of the research presented by Arias et al. [18] to determine the absorption in fine NA. The TBHL technique is evaluated in two phases, the first one by means of a comparative experimental design with the ASTM C 128 standard using fine RA with different particle size, and a second validation phase, where mortars are manufactured from the moisture correction with the absorption values obtained in the initial phase.

II. Materials and Methods

A. Fine Recycled Aggregates

RA is used, obtained from primary and secondary crushing of concrete waste from on-site concrete cylinders for quality control, with 32 MPa compressive strength. Fig. 1 shows a diagram of the transformation process of the concrete waste, and the characteristics of the RA, highlighting its irregular shape and texture mainly due to the presence of the cement paste adhering to it, as well as the effect of crushing.

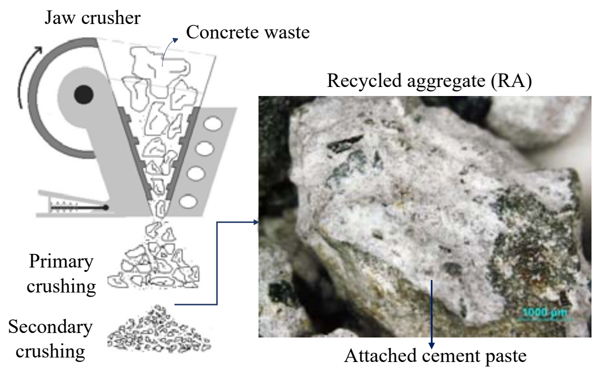

Fig. 1 Diagram of the transformation process and micrography with RA characteristics.

Mineralogy analysis was performed using X-ray diffraction on a PANalytical X'Pert MPD PRO between 15° and 55° for 120 min with a $CuK_{\alpha 1}$ (λ = 1.54059 Å) source. RA has a high silica content, calcium hydroxide and calcium carbonates, which are typical of concrete waste, see Fig. 2.

In order to identify the effect of particle size on the water absorption, six fractions of RA are evaluated (see Table I). According to the standard ASTM C33, the aggregates are standardized using several sieves with diameters between 0.075 and 4.75 mm, and also adjusted to two types of granulometric curve called inferior limit (IL) and superior limit (SL), as shown in Fig. 3.

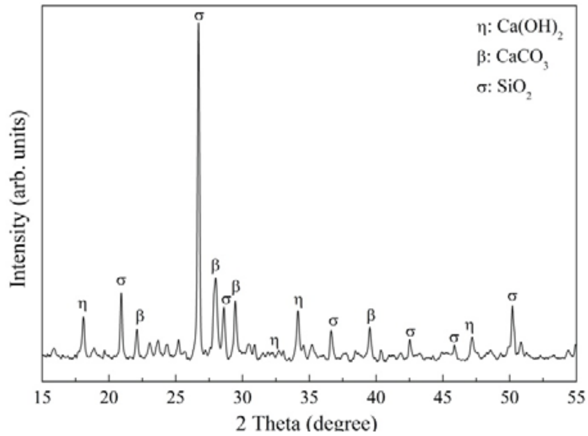

Fig. 2 Mineralogical composition

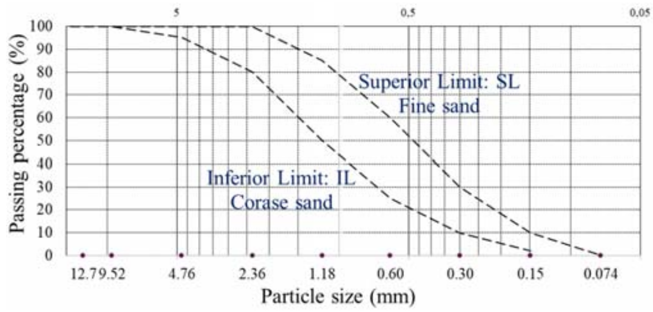

Fig. 3 Normalization of fine RA size

TABLE I
Factors for Determining Water Absorption

Type	PS	Code	Sieve diameter (mm)
RA	No.100	RA - No. 100	0.149
	No. 50	RA - No. 50	0.297
	No. 16	RA - No. 16	1.190
	No. 8	RA - No. 8	2.380
	SL	RA - No. SL	ASTM C 33
	IL	RA - No. IL	

*PS indicates the particle size of AR, retained on the sieve indicated in the table or normalized to SL and IL according to Fig. 3.

B. Thermogravimetric Balance Halogen Light

As RA has a porous structure, it exhibits different states depending on its moisture content. The TBHL technique starts from the saturated state to find the SSD state by a thermogravimetric process using a halogen light balance, which ensures a uniform and gentle heating of the sample up to a maximum temperature of 80 °C, a fixed temperature to obtain reproducible results within a few minutes. The halogen balance is coupled to a software tool to measure the mass loss of the fully saturated aggregate sample as a function of time. The SSD state is determined by applying the third derivative reflected in the change of the slope and the inflection point of the function plotted, as shown in Fig. 4. In this sense, the initial moisture loss rate will be higher, and will decrease as the particles move from losing moisture at the surface (adsorption water) to losing water inside the pores (adsorption water).

The software developed is called ABSORPTION INNOVATION, with registration No. 13-87-33 at the National

Directorate of Copyright, Ministry of the Interior, Colombia. Its validity lies in its ability to read the data from the halogen light balance to construct the mass loss curve as a function of time, perform the calculations and provide the final absorption report in real time.

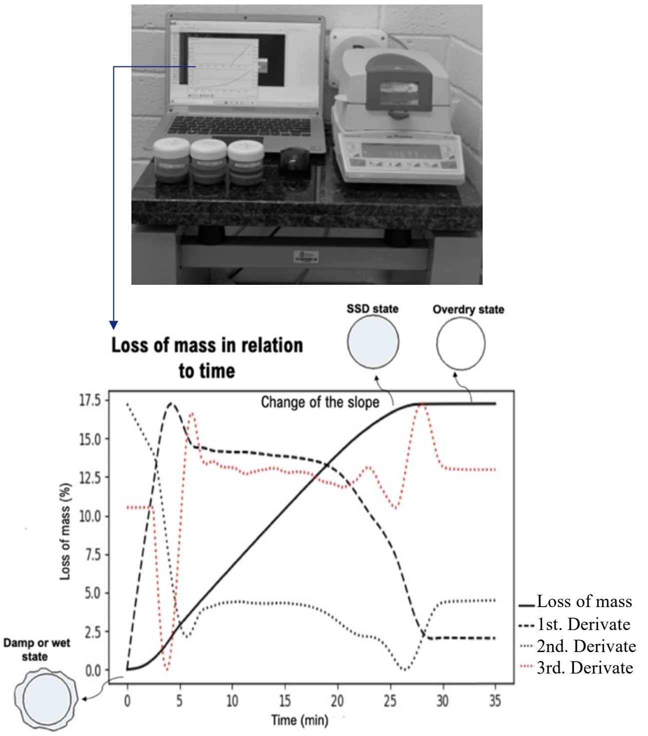

Fig. 4 Mass loss over time model to obtain SSD of RA

TABLE II
RESOURCES FOR RA ABSORPTION TEST

Resource	TBHL	ASMT C 128
Total RA (g)	20	1000
Total energy (kJ)	6.7	48.96
Total time (h)	25	33

TABLE III
MORTAR MIX PROPORTIONS AND MOISTURE CORRELATION

Code	W/C	Cement (g)	RA (g)	Moisture correction			
				Water (g)	Total water (g)	Adit. Water (g)	Adit. Water (%)
[1]No.100	0.45	300	600	135	189.93	54.93	29%
[2]No.100	0.45	300	600	135	184.32	49.32	27%
[1]No. 50	0.45	300	600	135	185.88	50.88	27%
[2]No. 50	0.45	300	600	135	170.89	35.89	21%
[1]No. 16	0.45	300	600	135	178.23	43.23	24%
[2]No. 16	0.45	300	600	135	170.79	35.79	21%
[1]No. 8	0.45	300	600	135	243.13	63.13	26%
[2]No. 8	0.45	300	600	135	222.44	42.44	19%
[1]SL	0.45	300	600	135	190.05	55.05	29%
[2]SL	0.45	300	600	135	162.97	27.97	17%
[1]IL	0.45	300	600	135	185.08	50.08	27%
[2]IL	0.45	300	600	135	161.92	26.92	17%

[1]Proportions for mix design corrected for ASTM C128, [2]proportions for mix design corrected for TBHL

Sample preparation for both TBHL and ASTM C 128 test starts with a minimum of 24 h RA saturation. Table II presents a summary of the resources used for each test, where it is possible to see the optimization with the use of the alternative BTHL technique.

Once the water absorption has been obtained by comparison between TBHL and ASTM C 128, the validation phase proceeds, in which mortars are manufactured from the moisture correction with the absorption values obtained in the initial phase. The mix design is shown in Table III. Structural Portland cement is used with a cement-sand ratio of 1:2 by mass, and the water-cement ratio is constant at 0.45. The compressive strength was tested using 50 × 50 × 50 mm cubes at 28 days after curing, while three replicate cylinders were tested.

Additionally, a comparison of means of the compressive strength obtained considering humidity correction from both ASTM C128 and TBHL techniques is performed, whose premise assumes that the populations are normally distributed and independent. The following hypotheses are proposed: Ho: Ux = Uy and H_A: Ux ≠ Uy, where the test statistic (t_0) follows a T student distribution (see (1)). The hypothesis indicates that the mean strengths are the same regardless of the technique under which the moisture correlation in the mix design is performed, meaning that for a significance α = 0.05, with a confidence associated with β = 95%, if the value of t_0 is less than the value associated with that confidence level ($t_{\alpha/2}$), the null hypothesis is rejected. The test statistic is given by (1):

$$t_0 = \frac{\bar{x}-\bar{y}}{S_P\sqrt{\frac{1}{n_x}+\frac{1}{n_y}}} \quad (1)$$

where, x and y correspond to the means of the compressive strength of each population, n_x and n_y correspond to the amount of data from each population and Sp is an estimator of the common master variance.

III. RESULTS AND DISCUSSION

Fig. 5 shows the water absorption results for all ARs, where the values obtained are in a range between 4.5% and 10% approximately, which coincides with the characteristic absorption values of reported ARs [19], [20], and demonstrating that the innovative TBHL technique is suitable for any fine AR size below 4.75 mm.

In contrast to ASTM C128, the TBHL technique presents lower dispersion of the absorption values for all RA sizes tested, which means that the tests were performed with precision, not exceeding 10% of the standard deviation. In this sense, it is remarkable that the absorption values obtained with the TBHL technique decrease with increasing particle size, which is explained by the fact that the smaller the particle size, the higher the specific surface area. This is consistent with that reported by Behera et al. [1], which indicates that the water absorption capacity of RA is higher for smaller particle sizes, since the larger the specific surface area, the higher the mortar content. And also reported that fine AR with more than 13% absorption is not desirable for use in concrete. Additionally, for some AR sizes a greater difference is observed between the absorption values obtained from both techniques, this could be associated with the ASTM C 128 methodology, where the ambiguity of the process to find the SSD condition leads to the need to require larger amounts of water to generate a layer on the surface of the particles that allows the adherence between them to achieve the suggested conical shape between 15º-20º, in other words, the SSD condition, see Fig. 6.

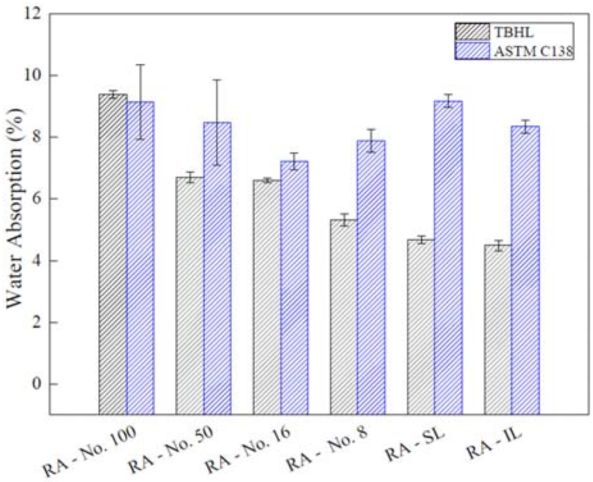

Fig. 5 Water absorption of RA by TBHL and ASTM C128

Fig. 6 Cone shape suggested by ASTM C128 for determining SSD state

Fig. 7 presents the compressive strength results of mortars with RA (different particle sizes) and reference mortar with NA under the same mix design conditions as a function of the moisture correction technique. It is possible to identify a significant effect of the moisture content of the mix, finding that the higher the water demand in the mix, the lower the compressive strength, which is in agreement with that reported by Cortas et al. [21] for mortars cured at 28 days, and has a direct relationship with the calculated moisture correction conditioned by the real absorption value of the aggregates.

Table IV shows that the mean compressive strengths of the mortars taking into account the correction for moisture with both the TBHL and ASTM 128 techniques are the same for all cases except for mortars with RA with a fine size, around 0.15 mm (sieve No. 100). These differences are directly associated with the moisture content of the mixes from the degree of absorption in the AR, much higher for the smaller sizes (see Table III), showing a significant effect on the compressive strength. This situation confirms the importance of reducing the dispersion of water absorption values for moisture adjustment in mix design.

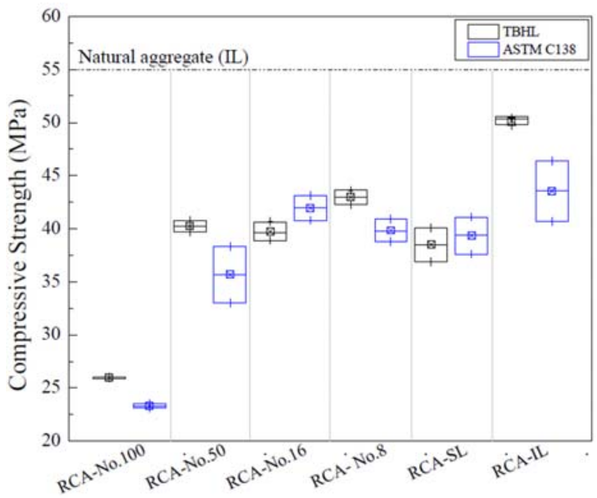

Fig. 7 Compressive strength of mortars with RA

TABLE IV
MEAN COMPARISON OF THE COMPRESSIVE STRENGTH OF MORTARS

Particle size	Compressive Strength (MPa)				t_o	$t_{\alpha/2}$	Ho: Ux=Uy
	ASTM C 128		TBHL				
No. 100	23.32	*0.21*	25.99	*0.06*	10.43	4.30	Reject
No. 50	35.67	*2.63*	40.22	*0.55*	1.45		Accept
No. 16	41.95	*1.17*	39.64	*1.04*	1.48		Accept
No. 8	39.80	*1.05*	42.97	*0.66*	2.44		Accept
SL	38.50	*1.59*	39.36	*1,74*	0.36		Accept
IL	43.54	*4.00*	44.53	*0,47*	0.83		Accept

Despite the differences found between the results of water absorption and compressive strength of mortars using both techniques, a similarity of the results is evidenced, which allows identifying a feasibility in the alternative use of the TBHL technique for obtaining water absorption of fine RA with greater accuracy in results (see Fig 5 and Table IV).

IV. CONCLUSIONS

The following conclusions are obtained from the experimental results and discussion.

- The results found by this study in relation to the use of the TBHL technique for obtaining water absorption in fine RA are similar and comparable to those obtained from ASTM C 128, indicating a feasibility of the TBHL technique, especially in terms of resource optimization and reproducibility, because the ASTM C 128 requires more resources and individual skills to determine the SSD status of fine RA.
- The halogen light used by the TBHL technique allows to reduce the time needed to obtain accurate results, the amount of energy consumed and the probability of human error associated with ASTM C 128 experiments. Thus, the TBHL technique requires a temperature of 85 °C (achieved in a soft mode) and only a mass of approximately 25 g to obtain the water absorption value of a fine AR.

- The feasibility of the alternative use of the TBHL technique for obtaining the water absorption of fine RA with greater precision is evident, since the absorption values do not exceed 30% standard deviation, in contrast to ASTM C 128 with deviations greater than 100%. This is significant in the case of recycled fine aggregates which are difficult to be characterized.
- The mechanical performance for mortars with different particle size varied depending on the technique under which the moisture correction was performed. The higher the water demand in the mix, the lower the compressive strength for mortars cured in 28 days.

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References

[1] M. Behera, S.K. Bhattacharyya, A.K. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review, Constr. Build. Mater. 68 (2014) 501–516. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.07.003.

[2] G. Dimitriou, P. Savva, M.F. Petrou, Enhancing mechanical and durability properties of recycled aggregate concrete, Constr. Build. Mater. 158 (2018) 228–235. https://doi.org/10.1016/j.conbuildmat.2017.09.137.

[3] F. Théréné, E. Keita, J. Naël-Redolfi, P. Boustingorry, L. Bonafous, N. Roussel, Water absorption of recycled aggregates: Measurements, influence of temperature and practical consequences, Cem. Concr. Res. 137 (2020) 106196. https://doi.org/10.1016/j.cemconres.2020.106196.

[4] R. V. Silva, J. De Brito, R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Constr. Build. Mater. 65 (2014) 201–217. https://doi.org/10.1016/j.conbuildmat.2014.04.117.

[5] J. Kim, Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview, Constr. Build. Mater. 328 (2022) 127071. https://doi.org/10.1016/j.conbuildmat.2022.127071.

[6] H.-B. Le, Q.-B. Bui, Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance, Constr. Build. Mater. 257 (2020) 119522. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.119522.

[7] H. Guo, C. Shi, X. Guan, J. Zhu, Y. Ding, T.C. Ling, H. Zhang, Y. Wang, Durability of recycled aggregate concrete – A review, Cem. Concr. Compos. 89 (2018) 251–259. https://doi.org/10.1016/j.cemconcomp.2018.03.008.

[8] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (2007) 735–742. https://doi.org/https://doi.org/10.1016/j.cemconres.2007.02.002.

[9] H. Mefteh, O. Kebaïli, H. Oucief, L. Berredjem, N. Arabi, Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete, J. Clean. Prod. 54 (2013) 282–288. https://doi.org/10.1016/j.jclepro.2013.05.009.

[10] M. Chakradhara Rao, S.K. Bhattacharyya, S. V Barai, Influence of field recycled coarse aggregate on properties of concrete, Mater. Struct. 44 (2011) 205–220. https://doi.org/10.1617/s11527-010-9620-x.

[11] F.T. Olorunsogo, N. Padayachee, Performance of recycled aggregate concrete monitored by durability indexes, Cem. Concr. Res. 32 (2002) 179–185. https://doi.org/https://doi.org/10.1016/S0008-8846(01)00653-6.

[12] Y.E. Ibrahim, Durability and structural performance of recycled aggregate concrete: A review, Int. Rev. Civ. Eng. 10 (2019) 135–141. https://doi.org/10.15866/irece.v10i3.15870.

[13] D.P. Gómez, D.G. Cano, Y.P. Arias, J.C. Ochoa, R.B. Correa, A. P-c-li, A. P-c-li, Innovative technique for obtaining water absorption of fine aggregates and its relationship with the mineralogical characteristics and mechanical performance of mortars, in: Poster Present. IMAT SOLVING Glob. Mater. CHALLENGES, Sant Louis,Missuri, 2021.

[14] J. Naël-Redolfi, E. Keita, N. Roussel, Water absorption measurement of fine porous aggregates using an evaporative method: Experimental results and physical analysis, Cem. Concr. Res. 104 (2018) 61–67. https://doi.org/10.1016/j.cemconres.2017.11.003.

[15] J. Zhang, C. Shi, Y. Li, X. Pan, C.-S. Poon, Z. Xie, Influence of carbonated recycled concrete aggregate on properties of cement mortar, Constr. Build. Mater. 98 (2015) 1–7. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2015.08.087.

[16] L.G. Baquerizo, T. Matschei, K.L. Scrivener, Impact of water activity on the stability of ettringite, Cem. Concr. Res. 79 (2016) 31–44. https://doi.org/10.1016/j.cemconres.2015.07.008.

[17] V.W.Y. Tam, X.F. Gao, C.M. Tam, C.H. Chan, New approach in measuring water absorption of recycled aggregates, Constr. Build. Mater. 22 (2008) 364–369. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2006.08.009.

[18] Y.P. Arias, J. Payá, J.C. Ochoa, Halogen light thermogravimetric technique for determining the retained water in fine aggregates used for concrete mixing design, J. Therm. Anal. Calorim. 123 (2016) 127–134. https://doi.org/10.1007/s10973-015-4902-8.

[19] G. Chinzorigt, M.K. Lim, M. Yu, H. Lee, O. Enkbold, D. Choi, Strength, shrinkage and creep and durability aspects of concrete including CO2 treated recycled fine aggregate, Cem. Concr. Res. 136 (2020) 106062. https://doi.org/10.1016/j.cemconres.2020.106062.

[20] L. Wang, J. Wang, X. Qian, Y. Fang, P. Chen, A. Tuinukuafe, Tea stain-inspired treatment for fine recycled concrete aggregates, Constr. Build. Mater. 262 (2020) 120027. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.120027.

[21] R. Cortas, E. Rozière, S. Staquet, A. Hamami, A. Loukili, M.-P. Delplancke-Ogletree, Effect of the water saturation of aggregates on the shrinkage induced cracking risk of concrete at early age, Cem. Concr. Compos. 50 (2014) 1–9. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2014.02.006.