Materiales de Construcción
Vol. 73, Issue 352, October-December 2023, e330
ISSN-L: 0465-2746
https://doi.org/10.3989/mc.2023.350123

The effect of water absorption distribution of recycled coarse aggregate on the compressive strength distribution of high-performance concrete

X. Chen [a] ✉, E. Gruyaert [b], Ö. Cizer [c], J. Li [a]

a. KU Leuven, Bruges Campus, Department of Civil Engineering, (Bruges, Belgium)
b. KU Leuven, Ghent Campus, Department of Civil Engineering, (Ghent, Belgium)
c. KU Leuven, Leuven Campus, Department of Civil Engineering, (Leuven, Belgium)
✉: xiaoguang.chen@xjtu.edu.cn

Received 12 March 2023
Accepted 25 May 2023
Available on line 2 November 2023

ABSTRACT: High water absorption is a typical characteristic of recycled coarse aggregate and is often used to explain the loss of performance of concrete when replacing natural coarse aggregate with recycled coarse aggregate. Extensive attention has been paid to the mean value of the water absorption of recycled coarse aggregate, but not to the standard deviation. This paper aims to assess whether recycled coarse aggregates with the same mean water absorption but different standard deviations will perform equally in high-performance concrete (HPC). The resulting HPC mixtures exhibited very similar compressive strength. Even so, it was hypothesised that as the standard deviation of the water absorption of recycled coarse aggregate increases over a wide range, the compressive strength of HPC will first increase due to local variations in the water/cement ratio, then decrease due to the presence of weak particles, and finally remain constant due to the role of the surrounding new mortar.

KEY WORDS: Recycled coarse aggregate; Water absorption distribution; Water gradient; Local water/cement ratio; High-performance concrete (HPC).

Citation/Citar como: Chen, X.; Gruyaert, E.; Cizer, Ö.; Li, J. (2023) The effect of water absorption distribution of recycled coarse aggregate on the compressive strength distribution of high-performance concrete. Mater. Construcc. 73 [352], e330. https://doi.org/10.3989/mc.2023.350123.

RESUMEN: *Efecto de la distribución de absorción de agua del árido grueso reciclado en la distribución de resistencia a la compresión del hormigón de altas prestaciones.* La elevada absorción de agua es una característica típica del árido grueso reciclado. Esta característica se utiliza a menudo para explicar la disminución en el rendimiento del hormigón cuando se sustituye el árido grueso natural por el árido grueso reciclado. Se ha prestado mucha atención al valor medio de absorción de agua en el árido grueso reciclado, pero no a la desviación estándar. Este artículo tiene como objetivo evaluar si áridos gruesos reciclados con la misma absorción media de agua, pero diferente desviación estándar, tienen un rendimiento igual en el hormigón de altas prestaciones (HPC). Las mezclas de HPC resultantes mostraron una resistencia a la compresión muy similar. Aun así, se planteó la hipótesis de que a medida que aumenta la desviación estándar de absorción de agua del árido grueso reciclado en un amplio rango, la resistencia a la compresión del HPC aumentará primero debido a las variaciones locales en la relación agua/cemento, posteriormente disminuirá debido a la presencia de partículas débiles y, finalmente, se mantendrá constante debido al papel del nuevo mortero circundante.

PALABRAS CLAVE: Árido grueso reciclado; Distribución de absorción de agua; Gradiente de agua; Relación agua/cemento local; Hormigón de altas prestaciones (HPC).

1. INTRODUCTION

The high water absorption of recycled coarse aggregate has been well addressed in concrete production, either by pre-soaking the aggregate prior to mixing the concrete (1-3) or by adding additional water during the mixing process (4-6). Regardless of the production method, a negative correlation has been generally drawn between the water absorption of recycled coarse aggregate and the compressive strength of the resulting concrete (7-9), although a considerable scattering is always observed. The exceptional increase in the compressive strength of concrete made with recycled coarse aggregate is often attributed to inadequate compensation water, leading to an effective water/cement ratio lower than the design value (6, 10, 11), or the use of recycled coarse aggregate from high-strength materials, resulting in a stronger aggregate skeleton and a higher bond strength between the aggregate and cement paste compared with the reference natural aggregate concrete (NAC) (9, 11, 12). In addition to those two reasons, this paper proposes a new mechanism, regarding the heterogenous nature of recycled coarse aggregate, which may help to explain the compressive strength gain.

The heterogeneity of recycled coarse aggregate is frequently identified as one of the biggest barriers to its large-scale application. There are only a few studies focusing on the effect of the heterogeneity of recycled coarse aggregate on the macroscopic properties of concrete. Khoury et al. (13) demonstrated the significant intra-batch variability in the water absorption of 6.3/10 mm recycled concrete aggregate (RCA) but did not discuss its effect on concrete. Xiao et al. (14), Etxeberria et al. (3), Pacheco et al. (15) and Sierens (16) investigated the effect of RCA from a single source on the compressive strength distribution of concrete. It was found that the use of RCA tended to increase the variability of the compressive strength of concrete, although a clear relationship between the RCA content and the variability of the compressive strength of concrete was not always noticed. Furthermore, Xiao et al. (17) and Devos and Huyghe (18) studied the effect of RCAs from different sources on the compressive strength distribution of concrete; however, the RCAs used had different mean values of the water absorption, preventing a direct comparison of the effect of the variability in the water absorption of recycled coarse aggregates.

It is still unclear whether recycled coarse aggregates from different sources having the same mean water absorption but different standard deviations can behave in the same way. For example, recycling plants often deliberately blend crushed concrete and masonry rubbles to decrease the water absorption of masonry-based aggregates (11), and the question thus arises whether the resulting mixed recycled aggregate (MRA) has the same effect on concrete as an RCA with the same water absorption? One issue of concern is the variation of the new interfacial transition zone (ITZ) with constituent type (19, 20) and parent concrete type (12), and another is the increased intra-batch variability in the water absorption of recycled coarse aggregate. To the best knowledge of the authors, the quantitative effect of such intra-batch heterogeneity of recycled coarse aggregate on the macroscopic properties of concrete has not been reported yet.

To bridge the aforementioned knowledge gap, this paper presents an experimental study that could help to scale up the use of recycled coarse aggregate in concrete practice. First, three types of recycled coarse aggregates (two RCAs and one MRA) were collected and extensively tested. Test results were statistically analysed using the Tukey's boxplot, histogram and the Pearson's chi-squared test. Afterwards, the aggregates were mixed in different proportions to obtain six recycled coarse aggregate mixes having each a water absorption distribution with a mean value of 4.79% and a standard deviation varied between 0.35% and 0.44%. Seven high-performance concrete (HPC) mixtures were produced with those six recycled coarse aggregate mixes as well as with one natural coarse aggregate. The compressive strength of each concrete mixture at an age of 28 d was determined using twenty 150 mm cubic specimens. The data were statistically analysed and the effect of the water absorption distribution of recycled coarse aggregate on the compressive strength distribution of HPC was investigated.

2. EXPERIMENTAL INVESTIGATION

2.1. Materials

Portland cement EN 197-1 - CEM I 52.5 R HES, superplasticizer of Sika ViscoCrete-4035M, 0/4 mm natural sand, and 2/6.3 and 6.3/14 mm crushed limestone coarse aggregates were employed in this work. Three types of 6.3/14 mm recycled coarse aggregates were involved, including a superior quality RCA produced using a three-stage crushing process (RCA++), a high-quality RCA manufactured through a two-stage crushing process (RCA+), and a normal quality MRA comprising not less than 50% crushed concrete in weight and processed by a single stage crushing process. They were sourced from demolition wastes, produced by recycling factories and further processed in the laboratory. Figure 1 shows some photos of the aggregates used, and Table 1 presents their main properties.

2.2. Particle size distribution of recycled coarse aggregates

The particle size distribution (also known as grading) of aggregates is crucial in ensuring the cohesion

Figure 1. Photos of coarse aggregates.

Table 1. Properties of aggregates.

Property	Sand	Limestone	Limestone	RCA++	RCA+	MRA	Standards
d/D (mm)	0/4	2/6.3	6.3/14	6.3/14	6.3/14	6.3/14	EN 933-1 (21)
G	G_F 85	G_C 85/20	G_C 90/10	G_C 90/10	G_C 90/10	G_C 90/10	
f (%)	f_3	f_1	f_1	f_1	f_1	f_1	
FI (%)	-	-	15	7	10	12	EN 933-3 (22)
SI (%)	-	-	17	8	17	16	EN 933-4 (23)
Rc (%)	-	-	-	≥ 90	≥ 90	58	EN 933-11 (24)
Rcu (%)	-	-	-	≥ 95	≥ 95	79	
Rb (%)	-	-	-	≤ 5	≤ 5	17	
M_{DE} (%)	-	-	16	10	19	43	EN 1097-1 (25)
LA (%)	-	-	19	15	25	42	EN 1097-2 (26)
w (%)	0.1	0.2	0.2	0.9	2.0	1.3	EN 1097-5 (27)
ρ_a (kg/m^3)	2602	2710	2680	2702	2664	2540	EN 1097-6 (28)
ρ_{rd} (kg/m^3)	2575	2677	2626	2552	2363	2108	
ρ_{ssd} (kg/m^3)	2585	2689	2650	2607	2476	2277	
WA_{24} (%)	0.40	0.45	0.81	2.16	4.79	8.27	

Note: "d/D" are the lower and upper aggregate sizes; "G" is grading category; "f" is category for fines content; "FI" is flakiness index; "SI" is shape index; "Rc" is mass content of concrete, concrete products, mortar, and concrete masonry units; "Ru" is mass content of unbound aggregate, natural stone, and hydraulically bound aggregate; "Rb" is mass content of clay masonry units, calcium silicate masonry units, and aerated non-floating concrete; "M_{DE}" is micro-Deval coefficient; "LA" is Los Angeles coefficient; "w" is water content; "ρ_a" is apparent particle density; "ρ_{rd}" is oven-dried particle density; "ρ_{ssd}" is saturated and surface-dried particle density; "WA_{24}" is water absorption after immersion for 24h.

of concrete and the associated feasibility of achieving a satisfactorily high density by normal compaction methods (29). Grading affects the aggregate proportions, cement paste demand, workability, pumpability, economy, porosity, shrinkage and durability of concrete (30). The effect of aggregate grading increases as the cement content decreases or as the required workability increases (29). It is therefore very important to keep the aggregates of the same gradation in comparison studies. To this end, the recycled coarse aggregates were screened into different single sizes, i.e., 4/6.3, 6.3/8, 8/10, 10/12.5, 12.5/14 and 14/16 mm, and subsequently recomposed according to the grading of the 6.3/14 mm limestone aggregate. The aggregate mass was measured to the nearest 0.05 kg.

The method of washing aggregates and adding fines manually was not applied, so the fines content of recycled coarse aggregate was not constant. Even so, the fines content in different concrete mixtures were considered to be limited and comparable due to an additional sieving process that was employed when sampling each single size of the recycled coarse aggregates. The only exception was the MRA used in RAC4, which was previously washed, and the consequence was rather difficult to predict. Chen et al. (31) reported that concrete made with washed recycled coarse aggregate obtained higher compressive strength than concrete made with unwashed recycled coarse aggregate. The authors claimed that upon washing, the impurities, powder and harmful materials on the aggregate surfaces were removed, resulting in a better bond between the cement paste and aggregates. On the contrary, the use of unwashed recycled coarse aggregate may increase the compressive strength of concrete, due to the fact that fines can reduce the inter-particle friction (32), increase the packing density (32) or bulk density (33), dilute cement to provide more available space for hydration (34), and increase nucleation sites (33) to accelerate the hydration (34). The quality of the fines ought to be an important factor. Additionally, the replacement percentage may also be an issue. For example, Bayraktar et al. (35) reported that replacing 10% in weight of natural sand in concrete with unwashed recycled fine aggregate resulted in less strength loss than replacing that with washed recycled fine aggregate; whilst for 80% replacement percentage, using washed aggregate was better than using unwashed one.

2.3. Water absorption distribution of recycled coarse aggregates

The recomposed RCA++, RCA+ and MRA were proportionally mixed to obtain six aggregate mixes (Mix1 to Mix6) with the same mean value but different standard deviations of water absorption. Prior to proportioning, the particle density and water absorption of the RCA++, RCA+ and MRA were extensively measured. The test data were first analysed using the Tukey's boxplot (36). Figure 2 shows that each set of test data contained a few outliers except for the water absorption of RCA++. Those outliers may indicate the intra-batch variability of the recycled coarse aggregates, such as different types of original natural aggregate and different volumes of residual mortar. Those outliers may also indicate the repeatability error introduced by different operators. In this work, all the detected outliers were excluded. Additionally, for each property, the interquartile range (the middle 50% of values) of MRA was wider than those of the other two, showing that the properties of MRA were more variable, in accordance with their constituent differences. The red median line was not at the centre of its blue box, indicating the test data were slightly skewed.

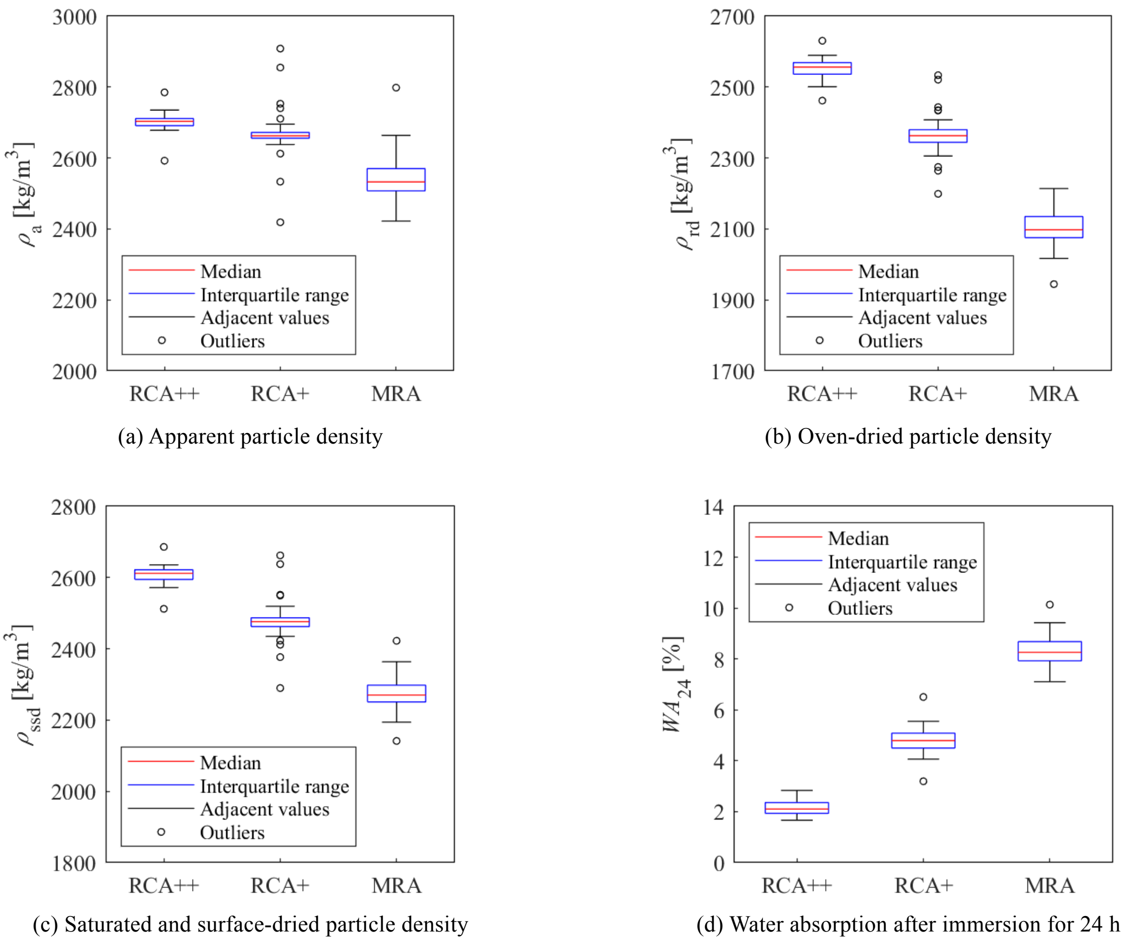

Figure 2. Particle density and water absorption of recycled coarse aggregates.

Figure 3 presents the histogram of the water absorption data without outliers. The number of bins was the square root of the number of test data and then rounded to the next integer. Table 2 gives the descriptive statistics of those distributions. As illustrated, the water absorption distribution of each recycled coarse aggregate was unimodal and positively skewed ($S > 0$). It was assumed that the water absorption data of each aggregate followed a normal distribution, as shown in Equation [1]. That null hypothesis (H_0) was tested using the Pearson's chi-squared test, which determines whether there is a statistically significant difference between the expected frequencies and the observed frequencies. The significance level was 0.05, and the degree of freedom was the number of bins minus the number of estimated parameters and minus one. As given in Table 2, all the test statistic (χ^2) did not exceed the corresponding critical values, meaning that the null hypothesis (H_0) can be accepted. The normal distributions of the water absorption of RCA++, RCA+ and MRA are expressed as Equations [2-4] and plotted in Figure 3.

$$H_0: WA_{24} \sim N(\mu, \sigma^2) \quad [1]$$

$$WA_{24_{\text{RCA++}}} \sim N(\mu_1, \sigma_1^2) \quad [2]$$

$$WA_{24_{\text{RCA+}}} \sim N(\mu_2, \sigma_2^2) \quad [3]$$

$$WA_{24_{\text{MRA}}} \sim N(\mu_3, \sigma_3^2) \quad [4]$$

Since the water absorption of RCA++, RCA+ and MRA were independent random variables that were normally distributed, their weighted summation ought to be normally distributed, as shown in Equations [5-9]. The mean values of oven-dried particle density data without outliers were used as the weights (the values are given in Table 1). The volumetric proportions of the recycled coarse aggregate mixes (Mix1 to Mix6) are shown in Table 3 and their water absorption distributions are plotted in Figure 4.

$$k_1 \cdot WA_{24_{\text{RCA++}}} + k_2 \cdot WA_{24_{\text{RCA+}}} + k_3 \cdot WA_{24_{\text{MRA}}} \sim N(k_1 \cdot \mu_1 + k_2 \cdot \mu_2 + k_3 \cdot \mu_3, k_1 \cdot \sigma_1^2 + k_2 \cdot \sigma_2^2 + k_3 \cdot \sigma_3^2) \quad [5]$$

With

$$k_1 = \frac{V_{\text{RCA++}} \cdot \rho_{\text{rd}_{\text{RCA++}}}}{V_{\text{RCA++}} \cdot \rho_{\text{rd}_{\text{RCA++}}} + V_{\text{RCA+}} \cdot \rho_{\text{rd}_{\text{RCA+}}} + V_{\text{MRA}} \cdot \rho_{\text{rd}_{\text{MRA}}}} \quad [6]$$

$$k_2 = \frac{V_{\text{RCA+}} \cdot \rho_{\text{rd}_{\text{RCA+}}}}{V_{\text{RCA++}} \cdot \rho_{\text{rd}_{\text{RCA++}}} + V_{\text{RCA+}} \cdot \rho_{\text{rd}_{\text{RCA+}}} + V_{\text{MRA}} \cdot \rho_{\text{rd}_{\text{MRA}}}} \quad [7]$$

$$k_3 = \frac{V_{\text{MRA}} \cdot \rho_{\text{rd}_{\text{MRA}}}}{V_{\text{RCA++}} \cdot \rho_{\text{rd}_{\text{RCA++}}} + V_{\text{RCA+}} \cdot \rho_{\text{rd}_{\text{RCA+}}} + V_{\text{MRA}} \cdot \rho_{\text{rd}_{\text{MRA}}}} \quad [8]$$

$$V_{\text{RCA++}} + V_{\text{RCA+}} + V_{\text{MRA}} = 1 \quad [9]$$

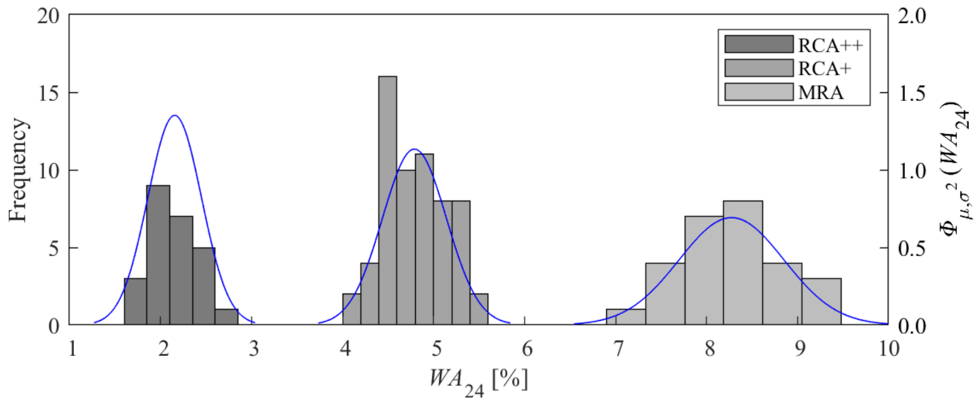

Figure 3. Water absorption distribution of recycled coarse aggregates.

Table 2. Descriptive statistics of water absorption of recycled coarse aggregates.

	N	Min (%)	Max (%)	μ (%)	Median (%)	Mode (%)	σ (%)	C_v (%)	S	K	χ^2	Critical value	H_0
RCA++	25	1.67	2.83	2.16	2.10	1.98	0.30	13.7	0.27	2.54	1.05	5.99	Accept
RCA+	61	4.07	5.55	4.79	4.79	4.50	0.35	7.3	0.19	2.23	7.44	11.07	Accept
MRA	27	7.11	9.42	8.27	8.26	8.41	0.58	7.0	0.17	2.72	0.84	7.81	Accept

Note: "N" is number of observations without outliers; "μ" is mean; "σ" is standard deviation; "C_v" is coefficient of variation; "S" is skewness; "K" is kurtosis; "χ^2" is chi-squared test statistic; "Critical value" is value from the chi-squared distribution with a certain degree of freedom and a selected confidence level; "H_0" is the null hypothesis, i.e., $WA_{24} \sim N(\mu, \sigma^2)$.

Table 3. Volumetric proportions of recycled coarse aggregate mixes.

	RCA++ (vol%)	RCA+ (vol%)	MRA (vol%)	$\bar{\mu}(WA_{24})$ (%)	$\bar{\sigma}(WA_{24})$ (%)	$C_v(WA_{24})$ (%)
Mix1	0	100	0	4.79	0.35	7.3
Mix2	10.4	80	9.6	4.79	0.37	7.7
Mix3	20.9	60	19.1	4.79	0.39	8.1
Mix4	31.3	40	28.7	4.79	0.41	8.5
Mix5	41.8	20	38.2	4.79	0.42	8.8
Mix6	52.2	0	47.8	4.79	0.44	9.2

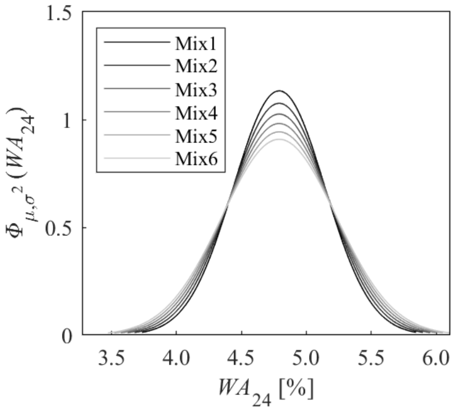

Figure 4. Water absorption distribution of recycled coarse aggregate mixes.

2.4. Concrete mixtures

Table 4 shows the concrete mixtures tested in this work. For NAC, a HPC mixture was used, with a design compressive strength class of C50/60 and a consistency class of S4. For recycled aggregate concrete (RAC), the 6.3/14 mm limestone aggregate was fully substituted in volume by recycled coarse aggregate mixes. In order not to alter the design effective water content, an extra amount of water that corresponds to the 24 h water absorption of all the aggregates was considered to compensate for the water absorbed by the aggregates. Note that the amount of compensation water varied slightly among different RAC mixtures because of the different weighted oven-dried particle densities of the recycled coarse aggregate mixes.

Table 4. Concrete mixture proportions.

Component (kg/m^3)	NAC	RAC1	RAC2	RAC3	RAC4	RAC5	RAC6
Cement	424	424	424	424	424	424	424
Effective water	170	170	170	170	170	170	170
Compensation water	10.1	36.8	36.7	36.6	36.6	36.5	36.4
0/4 mm sand	758	758	758	758	758	758	758
2/6.3 mm limestone	191	191	191	191	191	191	191
6.3/14 mm limestone	763	0	0	0	0	0	0
6.3/14 mm RCA++	0	0	77	155	232	310	387
6.3/14 mm RCA+	0	686	549	412	274	137	0
6.3/14 mm MRA	0	0	59	117	176	234	293
Superplasticizer	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Theoretical density	2317	2267	2265	2264	2263	2261	2260
Mass weighted average of the property of 6.3/14 mm aggregate mix							
$\overline{FI}$ (%)	15	10	10	10	9	9	9
$\overline{SI}$ (%)	17	17	16	15	14	13	11
$\bar{R}c$ (wt%)	-	90	87	85	82	79	76
$\bar{M}_{DE}$ (%)	16	19	20	21	22	23	24
$\overline{LA}$ (%)	19	25	25	26	26	26	27
$\bar{\rho}_{rd}$ (kg/m^3)	2626	2363	2358	2354	2349	2344	2340
$\overline{WA}_{24}$ (%)	0.81	4.79	4.79	4.79	4.79	4.79	4.79

2.5. Specimen preparation

Sand was dried in a ventilated oven at a temperature of 50°C for 24 h. Coarse aggregates were spread on the floor in the laboratory to dry for days. After drying, all the aggregates were stored in sealed buckets until use. Before concrete production, the water contents of aggregates were measured. The actual mixing water was equal to the amount of effective water plus the compensation water and minus the water content of aggregates. The mixer was pre-moistened so as not to alter the amount of mixing water. During the concrete production, a two-stage mixing approach (37) was adopted, not only because BS 1881-125 (38) recommends allowing the dry aggregate to soak with some mixing water before adding other materials until it has taken up most of the water it would eventually absorb, but also because Tam et al. (37) and Li et al. (39) observed that the premix process can fill up some pores and cracks of the recycled coarse aggregate, resulting in a denser ITZ compared with the traditional one-stage mixing approach.

A total of twenty 150 mm cubic specimens and three 100 mm cubic specimens were produced from each concrete mixture. Before casting, the inner surfaces of steel moulds were covered with a thin film of release agent. The freshly mixed concrete was filled in three layers, and each layer was compacted for 15 s using a vibrating table according to EN 12390-2 (40). After casting, the excess concrete above the upper edge of the mould, if any, was removed and the surface was levelled using a steel trowel. Subsequently, the specimens were sealed with polyethylene films and placed in a climate room at a temperature of (20 ± 2) °C. The specimens were stripped out of moulds at an age of (21 ± 2) h. The 150 mm cubic specimens were immediately wrapped with polyethylene films and placed in the same climate room. The 100 mm cubic specimens were cured in a water bath at a temperature of (20 ± 2) °C.

2.6. Test methods

Prepared specimens were tested at an age of 28 d. The density of hardened concrete was measured according to EN 12390-7 (41). The compressive strength of concrete was determined following EN 12390-3 (42), and the loading rate was 0.6 MPa/s. The surface electrical resistivity of concrete was measured according to AASHTO T 358 (43) using a Proceq Resipod concrete resistivity meter, although the used test specimens were not in a water-saturated state. Twenty 150 mm cubes were used in those three tests for each concrete mixture. The water absorption by immersion of concrete was measured based on the adjustment method proposed in previous work (44). Saturated specimens were dried in an oven for (120 ± 1) h, and three 100 mm cubes were used for each concrete mixture.

2.7. Test results

The test results of hardened concrete are given in Table 5. As expected (44), the RAC mixtures achieved lower density, higher water absorption and lower surface electrical resistivity than the NAC mixture. However, the RAC mixtures obtained comparable mean compressive strength with the NAC mixture, which was inconsistent with most observations (7). It may be due to the following reasons: a) the used recycled coarse aggregate mixes were of high quality in terms of the physical (7) and mechanical properties (44), resulting in a marginal effect on the compressive strength of concrete; b) air-dried aggregates and compensation water were used in the concrete production as this method has been reported to yield higher concrete compressive strength than the pre-soak method (8); c) a two-stage mixing approach was adopted, enhancing the compressive strength of RAC (37); d) although the replacement percentage was 100%, the

Table 5. Properties of concrete mixtures.

	D (kg/m³)	Δ (-)	$f_{\text{cm,cube}}$ (MPa)	Δ (-)	A (%)	Δ (-)	ρ_s (kΩcm)	Δ (-)
NAC	2346 (12)	-	74.0 (1.5)	-	4.4 (0.0)	-	17.2 (0.9)	-
RAC1	2252 (12)	0.960	74.9 (2.5)	1.013	5.7 (0.0)	1.295	15.3 (1.0)	0.887
RAC2	2276 (16)	0.970	76.7 (2.3)	1.036	6.5 (0.1)	1.473	14.2 (0.7)	0.827
RAC3	2271 (17)	0.968	76.3 (2.3)	1.032	6.0 (0.0)	1.362	14.7 (0.8)	0.857
RAC4	2250 (15)	0.959	73.6 (2.4)	0.995	6.1 (0.0)	1.388	14.0 (0.7)	0.811
RAC5	2261 (14)	0.964	75.6 (2.1)	1.022	5.9 (0.1)	1.330	14.3 (0.6)	0.830
RAC6	2253 (12)	0.961	73.7 (2.4)	0.996	6.1 (0.0)	1.394	13.6 (0.6)	0.793

Note: "D" is density of hardened concrete; "Δ" is ratio of the property of recycled aggregate concrete to that of natural aggregate concrete; "$f_{\text{cm,cube}}$" is mean compressive strength determined by testing 150 mm cubes at 28 d; "A" is absorption of water by immersion; "ρ_s" is surface electrical resistivity of concrete that were not in a water-saturated state; standard deviations are given in brackets.

volume fraction of recycled coarse aggregates was relatively small, leading to a limited change of concrete compressive strength (9); e) the strength loss might be underestimated by testing cubic specimens instead of cylindrical specimens due to different degrees of the lateral confinement of steel plates (6, 9); f) the use of sealed curing instead of water curing may allow an internal curing of recycled coarse aggregate (45, 46). Overall, the strength variations observed in this work were considered to be acceptable compared with the range from +20.5% to -38% when natural coarse aggregate was partially or fully replaced by recycled coarse aggregate, as reported by Silva et al. (7).

Figure 5 shows the histogram of the cube compressive strength data of concrete at an age of 28 d. The compressive strength distribution of RAC was wider and more asymmetric than that of NAC, indicating that the incorporation of recycled coarse aggregates made the concrete more inhomogeneous. Table 6 gives the descriptive statistics of the cube compressive strength data. The higher variation coefficient of the compressive strength of RAC than that of NAC confirmed the inhomogeneity difference. Previous studies (3, 9, 14-16) reported similar findings although the conclusions on complete replacement remained inconsistent. Furthermore, it was often assumed that an increase of the intra-batch variability of recycled coarse aggregate will increase the variability of the properties of RAC. However, interestingly, such an assumption was not observed in this work. The variation coefficient of the compressive strength of RAC did not increase monotonically with the increase in the variation coefficient of the water absorption of the recycled coarse aggregate mixes, as illustrated in Figure 6. It was very likely due to the fact that the range of variation coefficients of the water absorption of the recycled coarse aggregate mixes was so narrow (0.35% to 0.44%) that the effect it may have on the variability of the compressive strength of concrete was residual. More specifically, that effect can be easily offset by other factors, such as variations in the fines content of aggregates, small errors in the concrete production, small differences in the curing condition of test specimens, the randomness of spatial distributions of recycled coarse aggregates within test specimens, the randomness of failure surfaces of test specimens, the error of the equipment, and so on.

The normality of the compressive strength distribution of concrete was examined using the Pearson's chi-squared test. As shown in Table 6, the compressive strength distribution of each concrete mixture was normally distributed with a significance level of 0.05, except for RAC6. Figure 7 presents the compressive strength data of concrete using Tukey's boxplot. There were a few outliers in RAC1, RAC2 and RAC6, corresponding to the lower tails presented in Figure 6. Since only the intra-batch variability was involved in the dataset, those outliers were not excluded.

More importantly, the actual control group in this work was RAC1. Although the mean value of the water absorption of the recycled coarse aggregate mixes remained the same, the other properties suggested a slightly decreasing trend in the aggregate quality from Mix1 to Mix6. Therefore, the mean compressive strength of concrete from RAC1 to RAC6 was conventionally expected to be reduced monotonically and slightly; however, RAC2, RAC3 and RAC5 obtained slightly higher mean compressive strength than RAC1, with an increase up to 1.8 MPa or 2.4%, and RAC4 and RAC6 gained slightly lower mean compressive strength than RAC1, with a decrease up to 1.4 MPa or 1.8%. Since the experimental errors were carefully controlled, it was suspected that an undiscovered mechanism may exist, leading to a minor compressive strength gain, which is discussed in the next section. The strength loss in RAC4 was possibly due to the lack of filler effect (34) using the washed MRA, whereas that in RAC6 was likely due to the lowest crushed concrete content. It needs to be noted that all those strength changes were generally small, making the interpretations of the test data rather subjective. The effect of the water absorption distribution of recycled coarse aggregate on the mean compressive strength of

Table 6. Descriptive statistics of concrete compressive strength.

		Min (MPa)	Max (MPa)	μ (MPa)	Median (MPa)	Mode (MPa)	f_{ck} (MPa)	σ (MPa)	C_v (%)	S	K	χ^2	Critical value	H_0
NAC	20	71.5	76.6	74.0	74.0	74.0	71.5	1.5	2.0	0.1	2.1	2.77	5.99	Accept
RAC1	20	68.1	79.1	74.9	74.8	73.8	68.2	2.5	3.3	-0.9	4.5	1.97	5.99	Accept
RAC2	20	71.1	80.5	76.7	76.6	75.8	71.2	2.3	2.9	-0.5	3.4	5.50	5.99	Accept
RAC3	20	72.0	81.2	76.3	75.8	74.9	72.1	2.3	3.0	0.5	2.9	4.10	5.99	Accept
RAC4	20	68.1	76.9	73.6	73.6	75.2	68.2	2.4	3.3	-0.5	2.5	2.26	5.99	Accept
RAC5	20	71.8	80.0	75.6	75.3	75.8	71.9	2.1	2.8	0.3	2.7	1.05	5.99	Accept
RAC6	20	68.4	76.9	73.7	74.0	76.1	68.4	2.4	3.2	-0.9	3.1	6.17	5.99	Reject

Note: "f_{ck}" is the characteristic compressive strength of concrete (the 5th percentile); "H_0" is the null hypothesis, i.e., $f_{\mathrm{cm,cube}} \sim N(\mu, \sigma^2)$.

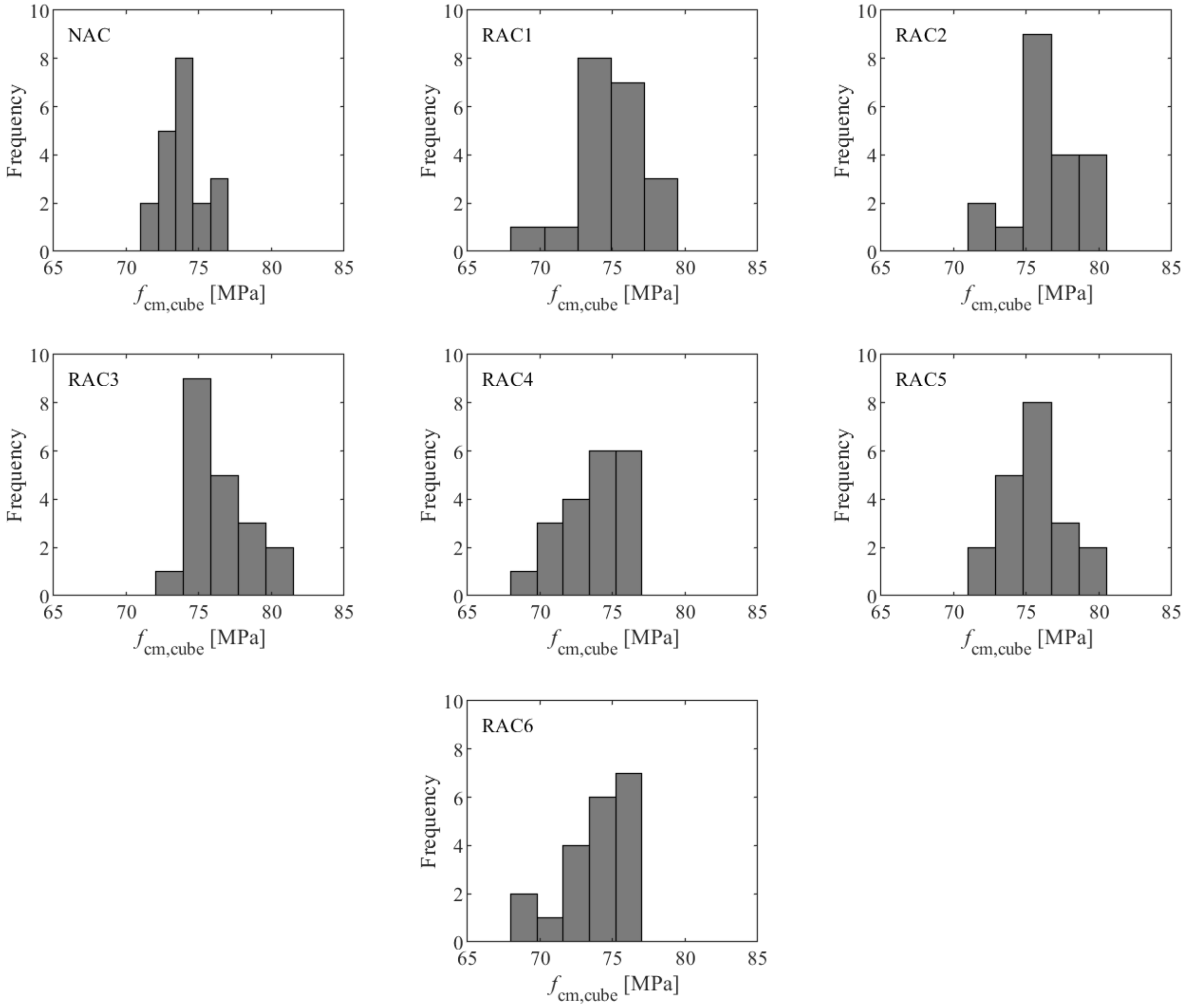

Figure 5. Cube compressive strength distribution of concrete mixtures.

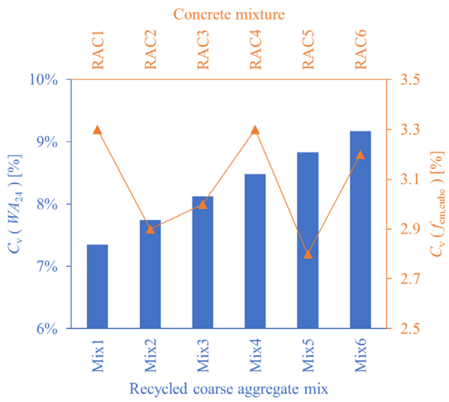

Figure 6. Comparison between variation coefficient of water absorption of recycled coarse aggregate mix and variation coefficient of compressive strength of concrete.

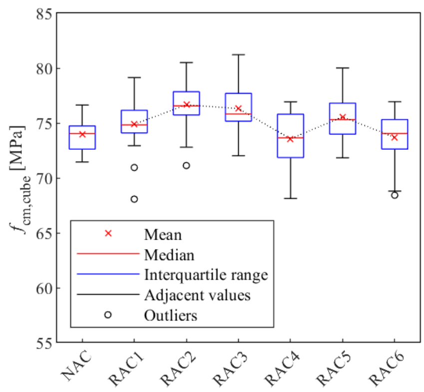

Figure 7. Cube compressive strength evolution of concrete mixtures.

HPC might have been masked by other factors, as discussed above. Therefore, in the interest of caution, no definite conclusions about the effect of the water absorption distribution of recycled coarse aggregate on the compressive strength distribution of HPC could be drawn from this work.

2.8. Hypotheses

Two hypotheses were proposed in this paper to describe the effect of water absorption distribution of recycled coarse aggregate on the compressive strength distribution of HPC. The first hypothesis is that a certain intra-batch variability in the water absorption of recycled coarse aggregate may have a positive effect on the compressive strength of concrete, due to variations in the local water/cement ratio of the new ITZ. Figure 8 illustrates a simple case when two recycled coarse aggregate particles are embedded in a thoroughly mixed mortar. It is assumed that the recycled coarse aggregate particles are dry prior to embedding. Ideally, the compensation water will be absorbed completely by the recycled coarse aggregates so as to achieve the design effective water/cement ratio (w/c_0). However, here it is assumed that the absorption process actually generates a water gradient in the new mortar around each recycled coarse aggregate particle. Recycled coarse aggregate particles with different water absorption values create different water gradients in the surrounding new mortar. Particularly, the local water/cement ratio of the new ITZ differs from particle to particle (w/c_{0+} and w/c_{0-}). Consequently, a lower local water/cement ratio (w/c_{0-}) results in a higher local compressive strength of the new mortar and higher bond strength at the new ITZ, whereas a higher local water/cement ratio (w/c_{0+}) does the opposite. A key issue is, as Figure 8 demonstrates, the local compressive strength increment is assumed to be larger than the local compressive strength decrement, due to the non-linear relationship between the macroscopic compressive strength and overall water/cement ratio of concrete (Abrams' law or Bolomey equation, for example (47)). Therefore, the mathematical sum of the local compressive strength changes is positive, indicating a positive effect on the macroscopic compressive strength of concrete. Theoretically, the lower the design effective water/cement ratio, the more pronounced the positive effect.

However, the macroscopic compressive strength of concrete is indeed not the mathematical sum of local compressive strength of a finite number of elements. Concrete is more like a "series-parallel system". The macroscopic compressive strength of concrete is affected by the weakest component but does not completely follow the Liebig's law of the minimum. The individual components in concrete in fact constrain each other, and a stress redistribution can occur upon local failure. A good example is the marginal effect on concrete strength when no more than 20% of natural coarse aggregate is replaced by recycled coarse aggregate (9, 48). An extreme case is the presence of a cavity supported by the surrounding mortar. Therefore, the second hypothesis proposed in this paper is that for a given mean value of the water absorption of recycled coarse aggregate, as the standard deviation of the water absorption increases, the macroscopic compressive strength of concrete first increases due to the proposed positive effect, then decreases due to the Liebig's law of the minimum, and finally remains constant due to the role of the surrounding new mortar, as presented in Figure 9.

2.9. Other factors

First, the constituent and parent concrete types of recycled coarse aggregate affect the microstructure of the new ITZ between the new cement paste and recycled coarse aggregate (12, 19, 20), which was not considered in the above hypotheses. On the flip side, the mean and standard deviation of the compressive strength among different RAC mixtures were generally comparable, suggesting that the consequence of different new ITZs may be small. In terms of the cube compressive strength of concrete, this work supported

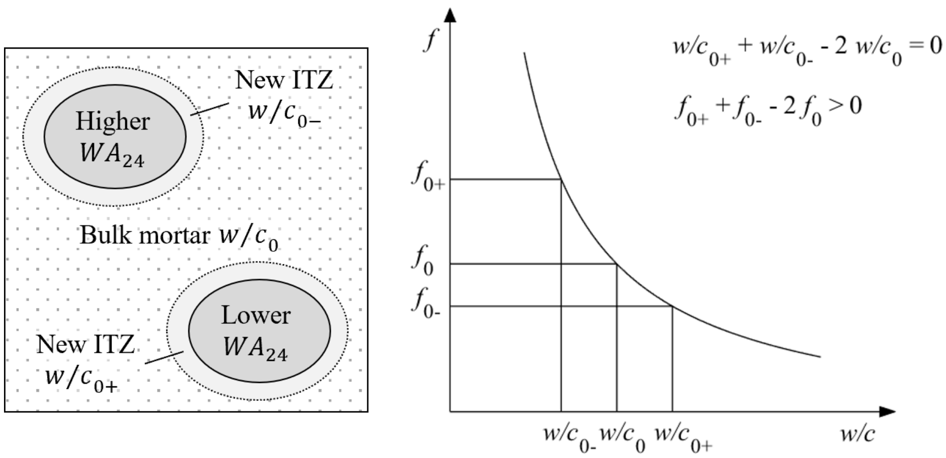

Figure 8. Hypothesis for a positive effect of local water/cement ratio variations in the new interfacial transition zone (ITZ) on the macroscopic compressive strength of concrete.

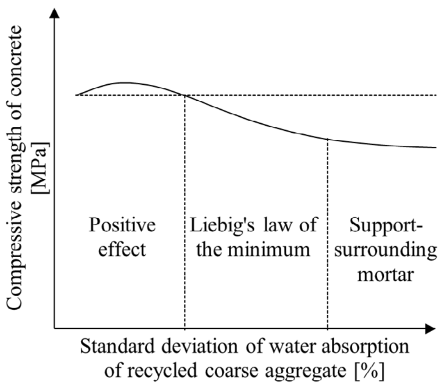

Figure 9. Hypothesis for the compressive strength of concrete as a function of standard deviation of water absorption of recycled coarse aggregate (when the mean value is constant).

the opinion of Silva et al. (49) that some specifications take the composition of recycled coarse aggregate too much into account. To reduce the disturbance from the different new ITZs, a supplementary option could be the use of pure RCAs to design recycled coarse aggregate mixes; however, it is difficult to collect RCA with a water absorption up to around 8% (49).

Second, the local internal curing degree of each recycled coarse aggregate particle on the new ITZ was in fact different. Variations in the local internal curing degree may also have contributed to changes in the compressive strength data, but the qualitative and quantitative impacts are not yet clear. To distinguish that impact from the proposed positive effect, a supplementary protocol could be to test the compressive strength development of concrete over time; however, the number of concrete specimens in a single batch is limited and the use of several batches for the same concrete mixture will introduce inter-batch variability to the test data. Besides, the testing period at an early age is required to be short, limiting the number of test specimens as well.

Third, as mentioned earlier, the proposed positive effect was assumed to increase with the decrease of the design effective water/cement ratio. Concrete with strength classes other than C50/60 can be tested to verify whether there are different degrees of that positive effect.

Finally, attention should be paid to the mixing time of fresh concrete. The longer the mixing time, the more compensation water is absorbed by the aggregates during the mixing process, the lower the slope of the water gradient generated during the setting and hardening, and the smaller the degree of the proposed positive effect.

3. CLOSING REMARKS

Recycled coarse aggregate exhibits an increased heterogeneity in its constituents and properties and is often specified according to its physical (as well as mechanical and/or durability) aspects. Previous studies have been focused on the mean value of those properties in terms of their measurements and effects on concrete. The effect of the variability of those parameters on the properties of the resulting concrete remains unexplored until now. To bridge this knowledge gap, this paper presents an experimental study on the impact of the water absorption distribution of recycled coarse aggregate on the compressive strength distribution of HPC.

The results showed that HPC mixtures made with the six recycled coarse aggregate mixes obtained comparable mean compressive strength. This indicates that as long as the mean value of the water absorption of recycled coarse aggregate remains constant, its composition does not have a significant effect on the mean compressive strength of concrete. Therefore, it can be more reasonable to specify recycled coarse aggregate according to its engineering properties rather than the constituent present, provided that the mean compressive strength of concrete is the main interest.

Within the scope of this study, no definite relationship between the variability of the water absorption of recycled coarse aggregate and the variability of the compressive strength of the resulting concrete could be established. It is not yet possible to draw a more general and reliable conclusion, because the range of standard deviations of the water absorption of the six recycled coarse aggregate mixes (ranging from 0.35% to 0.44%) was rather limited. The procedure used can be generalised to other situations in which the properties of recycled coarse aggregates are worse and more scattered. The authors believe that this kind of research can make great sense for upscaling of the use of recycled coarse aggregate in concrete.

ACKNOWLEDGMENTS

This work was funded by China Scholarship Council through the doctoral scholarship (No. 201808110212). The authors would like to thank ing. Pepijn Debergh, ing. Jens Degroote, ing. Laurent Capiau and ing. Ibbe Reynaert from KU Leuven for their efforts in carrying out extensive water absorption tests on recycled coarse aggregates. The two anonymous reviewers are specially acknowledged for their constructive comments.

AUTHOR CONTRIBUTIONS:

Conceptualization: X. Chen. Data curation: X. Chen. Formal analysis: X. Chen. Funding acquisition: X. Chen. Investigation: X. Chen. Methodology: X. Chen. Resources: J. Li. Supervision: E. Gruyaert, Ö. Cizer, J. Li. Visualization: X. Chen. Writing, original draft: X. Chen. Writing, review & editing: E. Gruyaert, Ö. Cizer, J. Li.

REFERENCES

1. Hansen, T.C. (1986) Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. *Mater. Struct.* 19, 201–246. https://doi.org/10.1007/BF02472036.
2. De Oliveira, M.B.; Vazquez, E. (1996) The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. *Waste Manage.* 16 [1-3], 113-117. https://doi.org/10.1016/S0956-053X(96)00033-5.
3. Etxeberria, M.; Vázquez, E.; Marí, A., Barra, M. (2007) Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cem. Concr. Res.* 37 [5], 735-742. https://doi.org/10.1016/j.cemconres.2007.02.002.
4. Poon, C.S.; Shui, Z.H.; Lam, L.; Fok, H.; Kou, S.C. (2004) Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cem. Concr. Res.* 34 [1], 31-36. https://doi.org/10.1016/S0008-8846(03)00186-8.
5. Ferreira, L., De Brito, J.; Barra, M. (2011) Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Mag. Concr. Res.* 63 [8], 617-627. https://doi.org/10.1680/macr.2011.63.8.617.
6. Chen, X., Sierens, Z.; Gruyaert, E.; Li, J. (2023) Precast concrete wall panels incorporating mixed recycled aggregates. *ACI Mater. J.* 120 [1], 75-88. https://doi.org/10.14359/51737333.
7. Silva, R.V.; De Brito, J.; Dhir, R.K. (2015) The influence of the use of recycled aggregates on the compressive strength of concrete: A review. *Eur. J. Environ. Civ. Eng.* 19 [7], 825-849. https://doi.org/10.1080/19648189.2014.974831.
8. González-Taboada, I.; González-Fonteboa, B.; Martínez-Abella, F.; Pérez-Ordóñez, J.L. (2016) Prediction of the mechanical properties of structural recycled concrete using multivariable regression and genetic programming. *Constr. Build. Mater.* 106, 480-499. https://doi.org/10.1016/j.conbuildmat.2015.12.136.
9. Chen, X.; Gruyaert, E.; Li, J. (2021) Modelling the effect of coarse recycled concrete aggregate on compressive strength of Portland cement concrete using volume fraction-based approach. *Constr. Build. Mater.* 309, 125159. https://doi.org/10.1016/j.conbuildmat.2021.125159.
10. Joseph, M.; Sierens, Z.; Boehme, L.; Vandewalle, L. (2015) Water absorption variability of recycled concrete aggregates. *Mag. Concr. Res.* 67 [11], 592-597. http://doi.org/10.1680/macr.14.00210.
11. Dhir, R.K.; De Brito, J.; Silva, R.V.; Lye, C.Q. (2019) Sustainable construction materials: Recycled aggregates. Woodhead Publishing. https://doi.org/10.1016/C2015-0-00466-X.
12. Poon, C.S.; Shui, Z.H.; Lam, L. (2004) Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Constr. Build. Mater.* 18 [6], 461-468. https://doi.org/10.1016/j.conbuildmat.2004.03.005.
13. Khoury, E.; Ambrós, W.; Cazacliu, B.; Sampaio, C.H.; Remond, S. (2018) Heterogeneity of recycled concrete aggregates, an intrinsic variability. *Constr. Build. Mater.* 175, 705-713. https://doi.org/10.1016/j.conbuildmat.2018.04.163.
14. Xiao, J.; Li, J.; Zhang, Ch. (2005) On statistical characteristics of the compressive strength of recycled aggregate concrete. *Struct. Concr.* 6 [4], 149-153. https://doi.org/10.1680/stco.2005.6.4.149.
15. Pacheco, J.; De Brito, J.; Chastre, C.; Evangelista, L. (2019) Experimental investigation on the variability of the main mechanical properties of concrete produced with coarse recycled concrete aggregates. *Constr. Build. Mater.* 201, 110-120. https://doi.org/10.1016/j.conbuildmat.2018.12.200.
16. Sierens, Z. (2021) The use of high-quality recycled concrete aggregates in precast non prestressed and prestressed concrete. PhD Dissertation, Bruges Campus, KU Leuven, Belgium.
17. Xiao, J.Z.; Lei, B.; Yuan, B. (2008) Compressive strength distribution of recycled aggregate concrete derived from different origins. *J. Build. Struct.* 29 [5], 94-100. https://doi.org/10.14006/j.jzjgxb.2008.05.012 (In Chinese).
18. Devos, T.; Huyghe, A. (2022) Batch-to-batch variabiliteit van de druksterkte van recyclagebeton (Batch-to-batch variability of compressive strength of recycled concrete) Masters Dissertation, Bruges Campus, KU Leuven, Belgium. (In Dutch).
19. Sidorova, A.; Vazquez-Ramonich, E.; Barra-Bizinotto, M.; Roa-Rovira, J.J.; Jimenez-Pique, E. (2014) Study of the recycled aggregates nature's influence on the aggregate–cement paste interface and ITZ. *Constr. Build. Mater.* 68, 677-684. https://doi.org/10.1016/j.conbuildmat.2014.06.076.
20. Sáez del Bosque, I.F.; Zhu, W.; Howind, T.; Matías, A.; Sánchez de Rojas, M.I.; Medina, C. (2017) Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate. *Cem. Concr. Compos.* 81, 25-34. https://doi.org/10.1016/j.cemconcomp.2017.04.011.
21. Bureau of Normalization. (2012) Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method (NBN EN 933-1:2012). https://www.nbn.be/.
22. Bureau of Normalization. (2012) Tests for geometrical properties of aggregates – Part 3: Determination of particle shape – Flakiness index (NBN EN 933-3:2012). https://www.nbn.be/.
23. Bureau of Normalization. (2008) Tests for geometrical properties of aggregates – Part 4: Determination of particle shape – Shape index (NBN EN 933-4:2008). https://www.nbn.be/
24. Bureau of Normalization. (2009) Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate (NBN EN 933-11:2009). https://www.nbn.be/.
25. Bureau of Normalization. (2011) Tests for mechanical and physical properties of aggregates – Part 1: Determination of the resistance to wear (micro-Deval) (NBN EN 1097-1:2011). https://www.nbn.be/.
26. Bureau of Normalization. (2020) Tests for mechanical and physical properties of aggregates – Part 2: Methods for the determination of resistance to fragmentation (NBN EN 1097-2:2020). https://www.nbn.be/.
27. Bureau of Normalization. (2008) Tests for mechanical and physical properties of aggregates – Part 5: Determination of the water content by drying in a ventilated oven (NBN EN 1097-5:2008). https://www.nbn.be/.
28. Bureau of Normalization. (2013) Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption (NBN EN 1097-6:2013). https://www.nbn.be/.
29. Mehta, P.K.; Monteiro, P.J.M. (2014) Concrete: Microstructure, Properties, and Materials (4th ed.) New York: McGraw-Hill Education. Retrieved form https://www.accessengineeringlibrary.com/content/book/9780071797870.
30. Kosmatka, S.H.; Wilson, M.L. (2011) Design and Control of Concrete Mixtures: The Guide to Applications, Methods, and Materials (15th ed.) Washington, United States: Portland Cement Association.
31. Chen, H.; Yen, T.; Chen K. (2003) Use of building rubbles as recycled aggregates. *Cem. Concr. Res.* 33 [1], 125-132. https://doi.org/10.1016/S0008-8846(02)00938-9.
32. Elyamany, H.E.; Abd-Elmoaty, A.E.M.; Mohamed, B. (2014) Effect of filler types on physical, mechanical and microstructure of self compacting concrete and Flow-able concrete. *Alex. Eng. J.* 53 [2], 295-307. https://doi.org/10.1016/j.aej.2014.03.010.
33. Ferreira, R.L.S.; Anjos, M.A.S.; Nóbrega, A.K.C.; Pereira, J.E.S.; Ledesma, E.F. (2019) The role of powder content of the recycled aggregates of CDW in the behaviour of rendering mortars. *Constr. Build. Mater.* 208, 601-612. https://doi.org/10.1016/j.conbuildmat.2019.03.058.
34. Berodier, E.; Scrivener, K. (2014) Understanding the filler effect on the nucleation and growth of C-S-H. *J. Am. Ceram. Soc.* 97 [12], 3764-3773. https://doi.org/10.1111/jace.13177.
35. Bayraktar, O.Y.; Kaplan, G.; Benli, A. (2022) The effect of recycled fine aggregates treated as washed, less washed and unwashed on the mechanical and durability characteristics of concrete under $MgSO_4$ and freeze-thaw cycles. *J. Build. Eng.* 48, 103924. https://doi.org/10.1016/j.jobe.2021.103924.
36. Tukey, J.W. (1977) Exploratory Data Analysis. Reading, United States: Addison-Wesley Publishing Company.
37. Tam, V.W.Y.; Gao, X.F.; Tam, C.M. (2005) Microstructural analysis of recycled aggregate concrete produced from

two-stage mixing approach. *Cem. Concr. Res.* 35 [6], 1195-1203. https://doi.org/10.1016/j.cemconres.2004.10.025.
38. British Standards Institution. (2013) Testing concrete – Methods for mixing and sampling fresh concrete in the laboratory (BS 1881-125:2013) https://www.bsigroup.com/.
39. Li, W.; Xiao, J.; Sun, Z.; Kawashima, S.; Shah, S.P. (2012) Interfacial transition zones in recycled aggregate concrete with different mixing approaches. *Constr. Build. Mater.* 35, 1045-1055. https://doi.org/10.1016/j.conbuildmat.2012.06.022.
40. Bureau of Normalization. (2019) Testing hardened concrete – Part 2: Making and curing specimens for strength tests (NBN EN 12390-2:2019) https://www.nbn.be/
41. Bureau of Normalization. (2019) Testing hardened concrete – Part 7: Density of hardened concrete (NBN EN 12390-7:2019) https://www.nbn.be/
42. Bureau of Normalization. (2019) Testing hardened concrete – Part 3: Compressive strength of test specimens (NBN EN 12390-3:2019) https://www.nbn.be/
43. American Association of State Highway and Transportation Officials. (2019) Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T 358-19). https://www.transportation.org/.
44. Chen, X.; Capiau, L.; Reynaert, I.; Zheng, K.; Gruyaert, E.; Li, J. (2022) Comparative study on modelling concrete properties using physical and mechanical properties of recycled coarse aggregate. *Constr. Build. Mater.* 345, 128249. https://doi.org/10.1016/j.conbuildmat.2022.128249.
45. Sierens, Z.; Vandevyvere, B.; Chen, X.; Li, J. (2021) Green concrete with high quality recycled concrete aggregate for precast elements: mechanical properties at early ages. *Indian Concr J.* 95 [12], 7-19.
46. Fonseca, N.; De Brito, J.; Evangelista, L. (2011) The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. *Cem. Concr. Compos.* 33 [6], 637-643. https://doi.org/10.1016/j.cemconcomp.2011.04.002
47. De Brito, J.; Kurda, R.; Da Silva, P.R. (2018) Can we truly predict the compressive strength of concrete without knowing the properties of aggregates?. *Appl. Sci.* 8 [7], 1095. https://doi.org/10.3390/app8071095.
48. Dhir, R.K.; Limbachiya, M.C.; Leelawat, T. (1999) Suitability of recycled concrete aggregate for use in BS 5328 designed mixes. *Struct. Build.* 134 [3], 257-274. https://doi.org/10.1680/istbu.1999.31568.
49. Silva, R.V.; De Brito, J.; Dhir, R.K. (2014) Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Constr. Build. Mater.* 65, 201-217. https://doi.org/10.1016/j.conbuildmat.2014.04.117.