TOWARDS THE STRUCTURAL CODIFICATION OF RECYCLED AGGREGATE CONCRETE

J Pacheco[1], J de Brito[2], C Chastre[3], L Evangelista[4]

1. CERIS, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
2. CERIS, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
3. Department of Civil Engineering of FCT, NOVA University of Lisbon.
4. CERIS, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Portugal

ABSTRACT. This paper analyses the studies made so far on the variability and reliability of recycled aggregate concrete. Since recycled aggregate concrete is seen by different agents of the construction industry as a variable material and no structural code has specifically been calibrated to its use, its role as a structural material is limited. Such calibration is hindered since specific research on the statistical and probabilistic data of recycled aggregate concrete properties is lacking.

Investigations on the probabilistic knowledge of recycled aggregates and recycled aggregate concrete properties are discussed, and the studies made so far on the reliability of recycled aggregate concrete elements are summarised. Final remarks regarding the future prospects towards the consensual acceptance of recycled aggregate concrete structures are provided.

Keywords: Recycled aggregates, Concrete, Sustainable construction, Variability, Reliability, Structural codes**.**

João Pacheco is a PhD student at Instituto Superior Técnico, Universidade de Lisboa, Portugal. His research interest includes recycled aggregate concrete, structural reliability and experimental testing. Email Id:joaonpacheco@ist.utl.pt

Professor Jorge de Brito is a Full Professor in the Department of Civil Engineering, Architecture and Georresources of IST, University of Lisbon and the Head of the CERIS Research Centre. Professor Jorge de Brito has published extensively on the subject of sustainability of concrete, and on service life prediction of construction materials.
Email Id:jb@civil.ist.utl.pt

Professor Carlos Chastre is an Assistant Professor in the Department of Civil Engineering of FCT, NOVA University of Lisbon. His research interests include FRP composite structures, the strengthening of structures, precast concrete structures, and materials and durability testing. Email Id: chastre@fct.unl.pt

Professor Luís Evangelista is an Assistant Professor in the Department of Civil Engineering of ISEL, Polytechnic Institute of Lisbon. His research interests include concrete structures, experimental testing, and recycled aggregate concrete.

INTRODUCTION

Regulations and public awareness are pushing the construction sector towards more sustainable production technologies. A fundamental concern regarding the environmental impacts of the construction industry is the disposal of construction and demolition waste (CDW). Simultaneously, several countries either have scarce natural aggregate (NA) sources or plan to reduce NA consumption because of the detrimental consequences of the aggregate industry towards the environment.

The use of recycled aggregates (RA) in concrete would minimize CDW dumping and NA consumption, allowing a significant reduction of the environmental impacts of the concrete industry. However, construction agents are unsure and sceptical about the use of what is perceived as a material with rather variable properties.

All parameters affecting structural performance, such as loads, load-effects, geometry, and material properties, are uncertain to some extent. The material properties of virtually all structural materials, including conventional concrete, are variable and, notwithstanding this fact, structural materials are seen as safe by construction agents and society alike. What is perceived as safe and rational design of a structural material is the result of the calibration of structural codes.

This calibration considers the aforementioned variability in the parameters that are involved in structural behaviour, as well as in what is seen by society as an acceptable risk.

Different studies on the material [1, 2], durability [3, 4] and structural properties [5, 6] of recycled aggregate concrete (RAC) have shown that the differences in expected behaviour between RAC and natural aggregate concrete (NAC) do not hinder the applicability of RAC.

However, research on RAC has been focused on its expected performance and very few studies on the variability of RAC properties have been made, which partly explains the concerns of the construction sector. Furthermore, few reliability analyses on RAC structural behaviour have been made, and most of these analyses are based on suppositions concerning the variability of RAC material properties that have not been scientifically validated.

STRUCTURAL CODES AND RELIABILITY

Code stipulations are based on underlying calculations that aim at guaranteeing that the probability that a performance requirement is not complied with (probability of failure - p_f) is below a society-accepted target value.

These p_f are defined considering the consequences of failure of different types of safety verifications. For ultimate limit-states (ULS), defined as those related to the possibility of collapse, acceptable p_f are typically in the region of 10^{-3} to 10^{-6}. Serviceability limit states (SLS) concern the loss of functionality of a structure, hence their p_f are higher. Acceptable values of p_f for irreversible SLS are as high as 0.5 [7].

The estimation of p_f is made by defining the mathematical functions that relate load-effects (E) and resistance (R) with the parameters involved in each verification. Each uncertain parameter is treated as a random variable (RV) and the probability that E exceed R is estimated:

$$p_f = p(R - E < 0) \tag{1}$$

Since a structural code based on probabilistic calculations would be cumbersome and prone to user errors, codes assure the compliance with p_f through the verification of deterministic sets of equations that resort to partial safety factors. In these equations, each RV is replaced by a design value, which is a conservative estimate of its specified value. Equation (2) is a representation of the calculation of load-effects using a partial safety factors format.

$$E_d = E\{\gamma_1 RV_1;\ \gamma_2 RV_2; \ldots\} \tag{2}$$

In Eq. (2) γ_i is the partial safety factor (γ) corresponding to the RV_i and E is the function that estimates load-effects based on the RVs and deterministic parameters.

In general terms, parameters related to load-effects are increased and those related to material strength and geometry are reduced. This process is made by code developers by calibrating safety formats in a way that the target p_f are complied with in most cases of design.

From this definition it is clear that safety verifications fail in extreme events: exceptionally high loads, extremely reduced material properties or a combination of both lead to failures by ULS. More probable phenomena cause failure by SLS.

The calculation of the p_f is frequently replaced by the reliability index (β) for practicability. In its simplest form, β is exactly equal to $-\Phi^{-1}(p_f)$ for uncorrelated normally distributed RVs with linear limit-state functions and is given by:

$$\beta = {(\mu_R - \mu_E)}\Big/{\sqrt{{\sigma_R}^2 + {\sigma_E}^2}} \approx -\Phi^{-1}(p_f) \tag{3}$$

Where μ is the expected value, σ^2 the variance of an RV and $\Phi^{-1}(p_f)$ the inverse of the standardized normal distribution. Target β corresponding to the target p_f of ULS are typically in the range of 3.1 to 4.2 and for irreversible SLS, β is usually taken as 1.5 [7].

RAC PROPERTIES AND BEHAVIOUR

Reinforced concrete is a structural material with fairly uncertain material strength and cross-sectional resistance. Part of the production process of concrete (placing, compaction, and curing in a typical ready-mixed concrete scenario) is made onsite, with lower quality control standards than those of other materials. Geometry is also dependent on human activities, and despite reinforcement steel being produced in controlled environments, its placing is made onsite and concrete covers tend to deviate from design ones, affecting load capacity and durability. Moreover, codified constitutive models are dependent on several aspects that in most situations are not imposed by designers, such as: binder composition and content, aggregate nature and grading, admixtures or water content - constitutive modelling is thus made assuming a given margin of uncertainty between design values of material properties and the actual properties, under simplified "one-size-fits-all" assumptions.

Actual onsite conditions also differ from designed: load history and application rate differ from standardized tests and design assumptions, load redistributions are ignored or considered using simplified models, standardized tests on material properties are made on specimens with specific dimensions that differ from the actual structural elements. Other factors, such as the intrinsic variability in material quality, labour and environmental conditions are the cause for random differences from the assumed values.

Since the knowledge of statistical and probabilistic properties of RVs requires tests on several samples, this document only appraises experiments that satisfy this requirement. The properties of the other RVs are not discussed - in the reliability analyses presented in this article all authors used models that are widely known such as those presented in [8].

Due to the current state-of-the-art knowledge, the scope of this work is restricted to reliability analyses and statistical/probabilistic properties of RAC with coarse RA sourced from concrete.

RAC Properties

The properties of RAC are expected to be more variable than the analogue properties of NAC for three fundamental reasons that are directly related to the attached mortar that partly composes the RAs:

1. the attached mortar is intrinsically more heterogeneous than stone;
2. the attached mortar results in additional interfacial transition zones, increasing the number of possible different types of failure of RAC specimens/elements [9];
3. different RA particles produced from the same concrete source and using the same process will have different ratios of attached mortar to NA stone [10].

Other factors contribute to further uncertainty when RAC properties and behaviour are compared to those of NAC, such as the reduced knowledge on the constitutive relations (and scatter) between RAC properties.

This section is limited by the current state-of-the-art knowledge: up to date studies on RAC statistics and probabilistic distributions have been limited to compressive strength, with two publications also addressing the splitting tensile strength, and a single publication concerning the Young's modulus.

28-day compressive strength

The 28-day compressive strength is the only material property of RAC that has been studied in probabilistic terms to a certain extent. This is due to the importance of compressive strength in reinforced concrete design and quality control: this property is involved in several ULS verifications, is the basic property used in virtually all codified constitutive models, and is widely used in acceptance criteria of onsite concrete quality.

The importance of compressive strength in ULS design is particularly relevant in the scope of code development, because of the very reduced target probabilities of failure that lead to the calibration of γ_c - such reduced probabilities mean that the knowledge of the lower tail of the probabilistic distributions of the RVs involved in material strength needs to be reasonably good.

Table 1 is an appraisal of experiments on statistical and probabilistic experiments on this property. The expected value and the coefficient of variation (CoV) of the concrete compositions are shown. Only results of compositions with incorporation of coarse RA from a single source are presented. There is no consensus on the effect of RA on the variability of this property: from [11,15] it seems that the highest CoVs result from mixes with intermediate RA incorporation ratios, whilst the results of [12] suggest that the total RA incorporation results in higher CoV. In [13] the CoV for total RA incorporation is significantly scattered and in [14] the mixes had very reduced CoVs. All studies reported reductions of the expected value of the compressive strength caused by RA incorporation.

Table 1 Studies on the statistical descriptors of the 28-day compressive strength of RAC

INVESTIGATION	SAMPLE SIZE	RCA (%)	EXPECTED VALUE (MPA)	STANDARD DEVIATION (MPA)	COV (%)
China - Xiao et al. [11] 10 cm cubic specimens	75	0	41.6	3.4	8.3
	100	30	41.5	3.9	9.5
	98	50	40.2	3.9	9.7
	98	100	36.5	3.0	8.2
Spain - Etxeberria et al. [12] 15 cm cubic specimens	24	0	44.0	3.9	8.8
	43	25	41.5	4.6	11.0
	33	100	40.0	6.7	16.7
China -Xiao et al. [13] cubes specimens of undisclosed dimensions	83	100	18.5	2.6	13.8
	83	100	27.2	4.2	15.5
	83	100	43.7	8.0	18.3
	40	100	20.2	1.6	7.7
	40	100	31.1	1.8	5.8
	40	100	46.7	3.2	6.9
Japan - Henry et al. [14] Cylinders (d=10 cm, h=20 cm)	30	0	41.9	1.2	2.9
	30	50	31.3	1.4	3.9
	30	100	34.4	1.3	3.9
	30	100	32.7	1.3	4.3
	30	100	28.8	1.2	4.4
Portugal - Pacheco et al. [15] 15 cm cubic specimens	41	0	51.42	2.65	5.2%
	40	25	51.09	2.98	5.8%
	39	50	48.22	2.91	6.0%
	40	100	46.71	2.10	4.5%
	40	0	38.69	2.24	5.8%
	40	100	34.14	1.36	4.0%
	40	0	45.24	2.56	5.7%
	40	100	39.77	1.81	4.6%
	11	0	39.38	2.00	5.1%
	12	100	38.64	2.05	5.3%
	40	0	71.86	4.75	6.6%
	40	100	63.62	3.12	4.9%

Some aspects that differ in each study might contribute to these varying trends: each study used specimens with different shapes and sizes, different mixers and mixing procedures, RA sourced from different source concrete and produced with different crushers, and different number of specimens tested.

Despite the different trends detected when the statistics of the experiments of Table 1 are analysed, three investigations [11,14,15] studied the probabilistic distributions of the compressive strength and agreed that normal distributions suited the data. In [11,15], lognormal distributions were also tested and accepted. Standards and investigations on NAC properties are also in favour of modelling the 28-day compressive strength of NAC as either lognormally or normally distributed [8,16,17].

A lower standard deviation/CoV of RAC in comparison with NAC standards [16, 17] was reported. This is due to the fact that these experiments were performed under laboratory conditions and that usually laboratory trials only evaluate the within-batch variability. If the results in Table 1 are compared with ACI214-R11 [17], one may conclude that the variability of these results corresponds to concrete quality within the range of good to excellent laboratory conditions, or to very good to excellent general construction quality.

28-day splitting tensile strength

Table 2 shows the results of the two only studies [13,15] on the variability of the splitting tensile strength known to the authors. The CoV of the splitting tensile strength is significantly higher than the CoV of compressive strength, a phenomenon common to NAC.

As shown in the table, the full incorporation of concrete RA does not seem to influence the variability of this property. Conversely, and as in the case of the compressive strength, intermediate RCA incorporations lead to higher variability. Normal and lognormal distributions suited the data of [15].

Table 2 Studies on the statistical descriptors of the 28-splitting tensile strength of RAC

	SAMPLE SIZE	RCA %	EXPECTED VALUE (MPA)	COV (%)
China -Xiao et al. [13] undisclosed specimens	83	100	1.39	29.3
	83	100	1.97	4.7
	83	100	2.65	22.2
	40	100	1.90	16.0
	40	100	2.31	14.5
	40	100	2.83	20.9
Portugal - Pacheco et al. [15] cubes (d=15 cm, h=30 cm)	12	0	3.06	13.6
	12	25	2.76	19.1
	12	50	2.95	17.5
	12	100	2.92	14.6
	12	0	2.72	17.0
	12	100	1.89	12.9
	12	0	2.93	6.4
	12	100	2.84	9.6
	5	0	3.22	12.4
	5	100	2.65	14.3
	12	0	4.67	20.9
	12	100	3.95	19.6

28-day Young's modulus

Table 3 shows the Young's moduli results of [15]. As in the case of the compressive strength and of the splitting tensile strength, lognormal and normal distributions model the data well. Ra incorporation does not seem to increase the variability of this property.

Table 3 Expected values and CoV of the 28-day splitting tensile strength as reported in [15]

	SAMPLE SIZE	RCA %	EXPECTED VALUE (GPA)	COV (%)
Portugal - Pacheco et al. [15] cubes (d=15 cm, h=30 cm)	12	0	47.41	3.9
	12	25	45.50	4.8
	12	50	40.08	4.1
	11	100	37.53	3.3
	12	0	41.78	2.7
	11	100	31.47	2.5
	10	0	43.02	3.6
	12	100	32.36	4.2
	5	0	43.13	4.5
	5	100	34.36	4.1
	11	0	49.56	7.3
	12	100	42.04	6.1

Further studies should follow and not only the knowledge on the statistical and probabilistic distributions of the Young's modulus of RAC should be expanded, but also the uncertainties introduced by constitutive models that relate this property to the compressive strength. This reasoning is valid for virtually all concrete properties relevant to structural engineering, including the splitting tensile strength.

Limitations of the Current Knowledge

The probabilistic and/or statistical knowledge concerning RAC is scarce. The knowledge on the statistics of the 28-day compressive strength should be increased, there are only two investigations on the variability of the splitting tensile strength, and a single source has studied the Young's modulus. Nevertheless, the current state-of-the-art suggests that the probabilistic distributions commonly used to model the compressive strength of NAC (normal and lognormal distributions) are applicable to RAC and the variability of concrete properties is only increased when intermediate RA incorporations are used.

It is expected that the CoVs of some of the other concrete properties (those that are mostly dependent on concrete porosity and deformability, for instance the Young's modulus) are more affected by RA incorporation than compressive strength. This expectation is based on the fact that properties dependent on the porosity and deformability of concrete will also be more affected by the main factor that contributes to the differences in RAC variability when compared to NAC: the attached mortar of the RAs. This reasoning is also applicable (and has been verified experimentally) to the expected value of these properties. To the authors' best knowledge, only a study on the onsite conditions of RAC has been made to date [18] and its number of samples (5 standard cube specimens and 7 cores of different elements per concrete composition) does not allow a statistical analysis within the purpose of reliability analysis. In NAC codification, mathematical functions that account for the worse production conditions of onsite mixing, placing, and/or curing are used [19] and were based on experimental data on onsite NAC properties.

Reliability of RAC elements

The goal of reliability analyses on RAC is the calibration of a set of γ that ensures that the reliability of RAC is similar to that of NAC. Since laboratory conditions do not reflect actual onsite quality, the soundness of these reliability assessments is compromised: the investigations on the reliability of RAC made so far had to opt between arbitrarily considering high CoVs for RAC or analysing the reliability of NAC and RAC based on the statistics of limited experimental data from laboratory tests, which are dependent on specific mix design and are unrepresentative of onsite conditions.

Another restriction caused by the lack of state-of-the-art knowledge is that the types of reliability verifications and γ calibration are limited to those corresponding to cases where the only concrete property relevant to the limit-state function is compressive strength.

A summary of the studies made so far on the reliability of RAC elements is given in Table 3. In all studies the compressive strength of concrete was modelled as either normally or lognormally distributed.

Table 3 Appraisal of studies on the reliability of RAC elements

AUTHORS	TYPE OF VERIFICATION (ULS)	OBJECTIVE	MAX. COV \\σ_{RAC}	BASIS FOR COV / σ_{CRAC}	CONCLUSION
Breccolotti and Materazzi [20]	Anchorage bond	γ_c for anchorage length. β_{RAC}=β_{NAC}	30%	Assumed as worse than CoV σ_{cNAC}	γ_{cRAC}=1.57
Woerner and Moerland [22]	Bending: beam	γ_c calibration for RAC. β_{RAC}=β_{NAC}	26%	Assumed as worse than CoV σ_{cNAC} based on EC2 provisions	$\gamma_{cNAC} = \gamma_{cRAC}$
Xiao et al. [13]	Bending: beam	Increase in reinforcement area for β_{RAC}=β_{NAC}	20%	Majorant of CoV surveyed	Maximum reinforcement increase of 3.5%
Breccolotti and Materazzi [23]	Eccentric columns	γ_{cRAC} calibration for β_{RAC}=β_{NAC}.	4.5%	Laboratory tests (β_{NAC} calculated identically)	γc_{RAC}=1.65 - high eccentricity γc_{NAC}=2.10 - pure compression

In [20] the reliability of the bond strength between reinforcement steel and RAC was investigated. The limit state function was made by comparing the reinforcement's yield strength - considered as a load, with the bond strength, modelled following Model Code 2010 predictions [21].

Different RAC mixes with RA incorporation ratios (0, 50 and 100%) were tested and it was found that the CoV was higher when RA were incorporated - the number of specimens tested was not disclosed. The CoVs and standard deviations of the cubes tested (produced under laboratory conditions) were respectively in the ranges of 3 to 5% and 1.42 to 2.3 MPa. In the reliability analysis, to account for on-site conditions, the CoV of the NAC was considered as 15% and different CoVs for RAC were considered, with a maximum of 30%. The γ of RAC was calibrated in order to ensure similar β to that of NAC. The authors concluded that the difference between γ_{NAC} and γ_{RAC} was marginal.

A similar methodology but in respect to the ULS of beams subject to bending was presented in [22]. The authors arbitrarily defined CoVs for the RAC compressive strength after referring that such data had not been investigated yet.

A different calibration criterion was made in [13]. Rather than calibrating the γ_{RAC} of the concrete strength, the amount of reinforcement ratio of RAC beams was increased as a means to achieve similar reliability to that of analogue NAC beams. The target β was 3.2 following the Chinese code. Different expected values of the compressive strength were tested, and a range of different CoV of RAC was considered (between 13% and 20%). With increasing reinforcement ratios, the reliability of RAC beams was reduced, since in those cases the limiting role of the concrete's compressive strength increases.

The reliability of columns subject to eccentric loading was analysed in [23]. The statistics of the compressive strength of RAC were assessed by laboratory-produced mixes. In order to circumvent the lower CoVs of such mixes, NAC mixes were also produced and the criteria for the calibration of γ_{cRAC} was not the compliance with a target standardized β. The authors designed NAC columns following Eurocode 2 and then calculated β for the NAC columns using their laboratory data, which led to a significantly higher β than standardized target β values, because of the reduced CoV values of the laboratory-produced NAC specimens. Afterwards, an iterative process where the γ values of RAC were calibrated was made. The calibration criterion was β for the RAC columns being equal to β calculated for the NAC columns. The authors reported a maximum γ_c of 2.1, associated to the most heterogeneous RA tested and to columns subject to pure compression (when bending is involved, reinforcement strength plays a relevant role in cross-sectional strength and the variability in RAC's compressive strength is mitigated).

CONCLUSIONS

The state-of-the-art on the reliability of RAC elements is scarce and further developments require experimental campaigns on the probabilistic/statistical properties of the material properties of concrete. Since the properties and heterogeneity of RA and RAC are dependent on the RA source, it makes sense, at least at a preliminary level, to separate reliability assessments by RA source. So far, studies have been limited to RAC with coarse RA sourced from concrete only, which is a logical starting point in this area, since: a) the knowledge on coarse RA sourced from concrete is more substantial than that on other RA sources; b) this type of RA has proven to be the most adequate for structural concrete.

Since the probabilistic/statistical data has been focused on 28-day compressive strength, reliability analyses on durability and serviceability of RAC have not been investigated. Data that would allow the consideration of onsite concrete production, rather than laboratory concrete specimens, does not exist.

Nevertheless, different authors have made reliability analyses on different ULS states of RAC elements and their results are promising. Since a key aspect of structural codification is the calibration of structural materials towards standardized reliability and safety, full-scope studies in this area would be a significant step towards RAC acceptance by designers, constructors and clients.

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