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Probabilistic Performance Assessment of Recycled Concrete Blocks Using Compressive Rheometry

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Abstract. According to the Brazilian Association of Public Cleaning and Special Waste Companies [1], the Northeast region of Brazil stands out as one of the country's leading producers of construction and demolition waste (CDW). Using this waste as recycled aggregate offers the potential for sustainable disposal while generating new materials for the construction sector. Accordingly, the Brazilian standard ABNT NBR 15116 [2] establishes the basic requirements for using these aggregates in cementitious materials. In this context, Brazilian standards for concrete blocks consider compressive strength a key factor in structural design. Therefore, it is important to take into account the uncertainties inherent to the block production process. To this end, a probabilistic analysis is proposed, based on the parameters of test specimens, totaling 96 samples. Data were collected on dry density, height, and compressive strength. The samples encompass different compositions – in terms of both natural and recycled aggregates (coarse and fine), as well as moisture content ranging from 6% to 12%. The specimens are produced using the compressive rheometry technique, which simulates the behavior of dry concrete used in block manufacturing, reproducing the compressive deformation conditions characteristic of the vibropress process. A calibrated experimental parameter (α) is proposed to correlate the compressive strengths of the test specimens with those of the blocks, enabling a structural reliability analysis. The study aims to contribute to the discussion on the variability of block performance compared to the strength values established by standards. Furthermore, it will be possible to identify the random variables that most significantly influence the probabilistic response of the problem. Based on experimental measurements and tests, data were obtained for the statistical characterization of dry density, height, and compressive strength. A reliability analysis was then conducted to evaluate the probabilistic performance of blocks under compression, using the Monte Carlo simulation.

Keywords: Probabilistic analysis, Random variables, Concrete blocks, Recycled aggregates

1 Introduction

The scarcity of studies on dry concretes, such as those used in concrete blocks, is due to the difficulty of reproducing the high pressing energy of vibropresses in the laboratory. Frasson Júnior [3] was the first to propose a methodology for simulating production on a laboratory scale. This technique has been improved, for example, by compressive rheometry, based on Marchioni [4], a methodology that aims to simulate the molding conditions of a vibropress and allows a controlled analysis of the material by standardizing the compression conditions and eliminating the vibration variable. However, the compressive strength of concrete blocks is generally lower than that of test specimens because the latter are solid pieces of small dimensions, while blocks have voids, altering the loading area [5].

Studies such as that by Pastor [6] show that the results obtained in test specimens are not always replicated in concrete blocks. Thus, this study uses compressive strength data from test specimens molded by compressive rheometry, obtained in Pastor's study [6], with the aim of correlating these results with the strength of concrete blocks using an alpha (α) parameter, seeking a more assertive predictability of the performance of concrete blocks. In addition, the study evaluates the uncertainty related to the proposed correlation using structural reliability, which seeks to estimate the probability of occurrence of limit states in the context of structural safety [7]. Thus, the correlation was evaluated through Monte Carlo simulations, which generate random scenarios and numerically sample the experiment, testing several possible combinations [8].

2 Methodology

2.1 Description of Materials and Testing

- **Materials Used**

The mixtures were prepared with high initial strength Portland cement (CP-V) with proportions of 75% fine aggregate and 25% coarse aggregate. The recycled aggregates came from construction and demolition waste (CDW) and were sent to the Laboratory of Structures and Materials (LEMA) at the Federal University of Alagoas (UFAL). The water used in the mixture was obtained from the campus water supply network.

- **Compositions and Moisture Contents**

Four combinations of aggregates were tested:
AMN (natural fine aggregate) + AGN (natural coarse aggregate): 100% natural aggregates;
AMR (recycled fine aggregate) + AGN: recycled sand and natural gravel;
AMN + AGR (recycled coarse aggregate): natural sand and recycled gravel;
AMR + AGR: 100% recycled aggregates.
For each composition, 24 cylindrical test specimens (SPs) were molded, distributed equally between moisture contents of 6%, 8%, 10%, and 12% (six samples per content). The concrete blocks were molded and broken at the optimum moisture content which was determined in situ, totaling six blocks per composition.

- **Characterization of Test Specimens**

The SPs were molded by pressing in equipment adapted to reproduce the typical vibro-compaction of concrete block manufacturing. The procedure followed Marchioni [4]: initially, the aggregates remained in water absorption for 10 minutes; then, the cement and mixing water were added. The mixture was poured into cylindrical molds, subjected to vibration for 5 s, and then to a static load of 3 tf. The SPs were cured by sprinkling water until they were 21 days old. Next, the axial compression test was performed using neoprene sheets as face regulators in order to uniform the stress distribution.

- **Characterization of Blocks**

The blocks were produced in a 120 L concrete mixer and compacted in a manual vibropress. After detecting the pellet point, the dry concrete was transported to the machine, molded, and vibropressed. The nominal dimensions adopted were 14 cm × 19 cm × 39 cm, following ABNT NBR 6136 [9]. The optimum moisture contents defined for each composition were 7% for AMN + AGN, 10% for AMR + AGN, 6% for AMN + AGR, and 10% for AMR + AGR. Curing and simple compression testing were performed analogously to that of the SPs, according to ABNT NBR 12118 [10], in a 490 kN Amsler universal press.

2.2 Adjustment of resistances and calculation of the α coefficient

To compare the compressive strengths of the SPs and blocks, it was necessary to adjust the values obtained in the SPs according to the moisture at which they were molded. The adjustment was important because the blocks were tested only at the optimum moisture for each mix, while the SPs were tested at four different moisture contents. Thus, the strengths of the SPs had to be normalized to the same moisture as the blocks.

If the comparison were direct, only six SPs per mix could be used, reducing statistical robustness. To

overcome this limitation, a procedure was adopted to project the SP strengths to the corresponding optimum moisture content, expanding the database to 24 samples adjusted by composition.

- **Resistance Normalization Methodology**

It was experimentally verified that compressive strength varies with the moisture content of the mixture. For each composition, the average ratios between pairs of strengths obtained at different moisture contents (6x6=36 pairs) were calculated. These ratios served as correction factors, allowing a measured value at a given moisture content to be projected to the equivalent value at the optimum moisture content of the composition.

As an example, in the AMN + AGN composition, it was observed that SPs molded with 8% moisture content had 7% higher strength than those molded with 6%. Therefore, the results at 8% were divided by 1.07 to obtain values equivalent to the 6% condition. The same reasoning was applied to all moisture combinations, considering the averages of the 36 possible comparisons. In the end, for each composition, a set of 24 adjusted resistances was obtained, all referring to the same moisture content of the blocks.

- **Calculation of the Weighting Coefficient α**

With the adjusted data, the weighting coefficient α was calculated as the ratio between the average resistance of the blocks and the average resistance of the adjusted SPs:

$$\alpha = \frac{f_{cm,block}}{f_{cm,sp}} \tag{1}$$

This coefficient represents the difference in performance between SPs and blocks. The values obtained for α will be used in the reliability models presented in the next section.

2.3 Reliability model

The Monte Carlo simulation was applied to the structural reliability assessment of different groups of SPs, composed of four different combinations of aggregates. This approach allowed the incorporation of the intrinsic variability of the materials' strength, as well as the strength reduction factor and the minimum strength specified by technical standards as key parameters of the analysis. The simulations were implemented in Python and aimed to estimate the probability of failure (P_f) and the reliability index (β).

The strength data used as input for the simulations were obtained experimentally from simple compression strength tests performed on the SPs. To statistically infer the data, the Shapiro-Wilk test and the homogeneity of variances test were applied. In addition, a visual characterization of the experimental samples was performed.

The limit state equation adopted in this study is a mathematical representation that expresses the safety or failure condition of a structural element by comparing the effective strength of the material, obtained experimentally, multiplied by a reduction factor, and the minimum strength value established by technical standards for the classification of the block, as follows:

$$G = \alpha R - S \tag{2}$$

Where R corresponds to the resistance of the material, modeled as a random variable with normal distribution, whose statistical parameters (mean and standard deviation) were estimated from the experimental data of each group; α represents the reduction factor applied to the resistance, responsible for incorporating uncertainties arising from geometric imperfections, variability in the construction process, safety coefficients, and limitations of structural modeling; S refers to the reference strength defined by technical standards, considered in this initial stage of the study as a constant equal to 3 MPa (resistance of non-structural concrete blocks - ABNT NBR 6136 [9]).

Based on the limit state equation presented above, three distinct stages of Monte Carlo simulations were performed, where the first simulation considered α as a deterministic parameter, with fixed values assigned to each experimental group, thus assigning a more conservative analysis. The second simulation introduced a refinement step in the probabilistic modeling by considering α as a Gaussian distributed continuous random variable in order to incorporate it more realistically. In the third and final stage, the analysis focused on modeling the uncertainty associated with the structural demand S.

3 Results and Discussions

3.1 Normalization of compressive strengths

In order to mitigate the statistical limitation, the sample of test specimens (SPs) was expanded to a total of 24 units. The compressive strength values were then normalized so that all SPs had the same moisture content corresponding to the optimum point, previously determined experimentally for the blocks. Table 1 shows the experimental data obtained for each composition.

Table 1. Compressive strength of experimental SPs.

AMN+AGN							AMR+AGR						
Moisture	**SP1**	**SP2**	**SP3**	**SP4**	**SP5**	**SP6**	**Moisture**	**SP1**	**SP2**	**SP3**	**SP4**	**SP5**	**SP6**
6%	5.37	6.16	6.06	6.76	5.93	4.57	**6%**	5.49	4.63	7.37	6.65	6.90	8.03
8%	5.49	5.39	6.04	6.32	6.09	5.00	**8%**	6.49	6.00	5.53	6.37	6.84	6.52
10%	5.65	5.61	6.38	5.38	5.72	5.58	**10%**	5.60	6.64	6.96	5.87	7.29	5.38
12%	5.06	5.97	6.68	4.86	6.26	5.49	**12%**	5.02	7.00	6.18	5.88	6.86	6.80
AMN+AGR							**AMR+AGN**						
Moisture	**SP1**	**SP2**	**SP3**	**SP4**	**SP5**	**SP6**	**Moisture**	**SP1**	**SP2**	**SP3**	**SP4**	**SP5**	**SP6**
6%	5.01	6,14	4,14	5,97	6,73	5,97	**6%**	8.30	7.85	8.74	7.69	8.23	7.77
8%	5.54	6,01	5,65	6,38	5,81	3,71	**8%**	7.75	7.62	8.53	8.91	8.61	7.06
10%	5.48	5,99	5,42	5,17	5,52	-	**10%**	7.97	7.92	9.09	8.06	7.58	7.86
12%	5.17	5,21	4,29	5,79	6,76	5,89	**12%**	7.15	8.44	9.43	6.87	8.84	7.75

Based on the compressive strength results of the SPs presented in Table 1, correction factors were determined to adjust the experimental moisture content values to the theoretical optimum moisture content of the blocks. The average values of the normalization factors, organized according to moisture content and composition, are presented in Table 2.

Table 2. Average normalization factor of SPs by moisture and composition.

AMN+AGN		AMR+AGR		AMN+AGR		AMR+AGN	
Moisture	**Average Factor**	**Moisture**	**Average Factor**	**Moisture**	**Average Factor**	**Moisture**	**Average Factor**
6%	100%	**6%**	65%	**6%**	100%	**6%**	70%
8%	107%	**8%**	100%	**8%**	120%	**8%**	76%
10%	141%	**10%**	100%	**10%**	119%	**10%**	100%
12%	124%	**12%**	87%	**12%**	104%	**12%**	88%

Through sample projection, it was possible to determine a weighting coefficient (α) to correlate the theoretical compressive strengths of the SPs with the experimental strengths of the blocks. The reduction in SPs performance revealed by α suggests that the compressive strengths of the experimental blocks are lower than those of the theoretical SPs. This demonstrates the importance of considering factors such as density and vibro-compaction during the molding process. The compressive strength values of the theoretical blocks are shown in Table 3.

Figure 1 shows the graphs for the adjustment of the correlation coefficient (α) between the theoretical SPs and the tested blocks. The equation that relates the weighting coefficient of compressive strength to moisture content varies according to the composition of the mixture. For mixtures with natural aggregates and for the combination of recycled fine aggregate with natural coarse aggregate, the adjustment corresponds to a third-degree exponential function. On the other hand, for compositions using recycled aggregates and for the combination of natural fine aggregate with recycled coarse aggregate, the adjustment corresponds to a second-degree exponential function. This variation in the degrees of the adjusted functions indicates that higher-grade mixtures exhibit greater sensitivity to the factors analyzed, notably the influence of moisture content on compressive strength. This finding shows that, in these mixtures, moisture content is a critical variable for the variation in mechanical strength.

Table 3. Compressive strength of theoretical blocks.

	SP1	SP2	SP3	SP4	SP5	SP6		SP1	SP2	SP3	SP4	SP5	SP6
	5.37	6.16	6.06	6.76	5.93	4.57		5.23	4.42	7.03	6.35	6.58	7.66
AMN+AGN	5.49	5.39	6.04	6.32	6.09	5.00	**AMR+AGR**	6.40	5.93	5.46	6.28	6.75	6.43
$W_{opt.} = 6\%$	5.65	5.61	6.38	5.38	5.72	5.58	$W_{opt} = 10\%$	5.60	6.64	6.96	5.87	7.29	5.38
	5.06	5.97	6.68	4.86	6.26	5.49		4.96	6.91	6.10	5.80	6.77	6.71
	5.01	6.14	4.14	5.97	6.73	5.97		8.25	7.81	8.70	7.65	8.18	7.73
AMN+AGR	5.54	6.01	5.65	6.38	5.81	3.71	**AMR+AGN**	7.73	7.60	8.50	8.88	8.58	7.03
$W_{opt} = 6\%$	5.48	5.99	5.42	5.17	5.52	-	$W_{opt} = 10\%$	7.97	7.92	9.09	8.06	7.58	7.86
	5.17	5.21	4.29	5.79	6.76	5.89		7.13	8.41	9.40	6.85	8.81	7.7

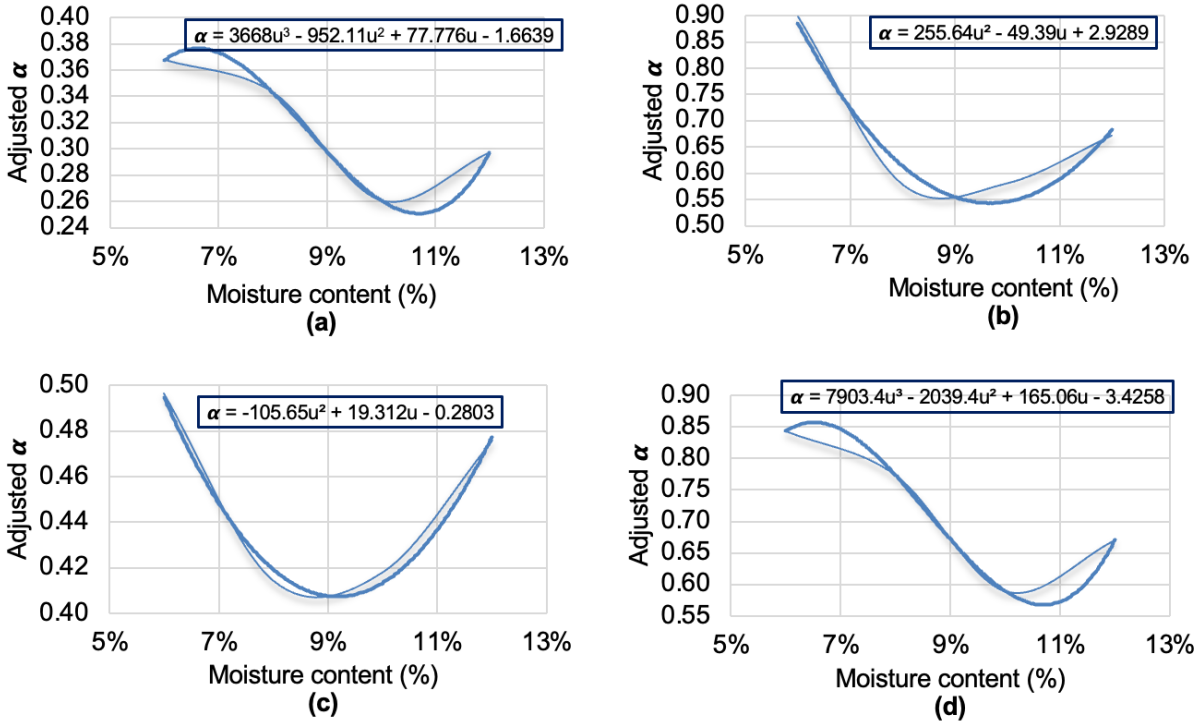


Figure 1. Adjustment of the α coefficient for correlation between axial compressive strengths and moisture contents: (a) natural aggregates; (b) recycled aggregates; (c) natural fine aggregate and recycled coarse aggregate; (d) recycled fine aggregate and natural coarse aggregate

3.2 Reliability analysis

Goodness-of-Fit tests indicate that data follows the Gaussian distribution. Figure 2 shows the statistical characterization of the sample, indicating that it is close to a normal distribution, through histograms and cumulative curves, showing satisfactory adherence to the assumption of normality.

The first reliability analysis consisted of assuming S as a constant equal to 3 MPa, the minimum regulatory requirement for concrete blocks to be classified as standard market products, according to ABNT NBR 6136 [9]. In this stage, the random variable α was treated as deterministic. Thus, the results indicated that the highest probability of failure occurred in the samples of blocks composed of AMN+AGN, while the highest reliability index was obtained in the group of blocks composed of AMR+AGN. The compositions of AMR + AGR and AMR+AGN presented the lowest failure probabilities. In contrast, the groups of blocks composed of AMN+AGR and AMN+AGN presented failure probabilities greater than 50%, significantly increasing the failure risk associated with parameter α, as shown in Figure 3(a).

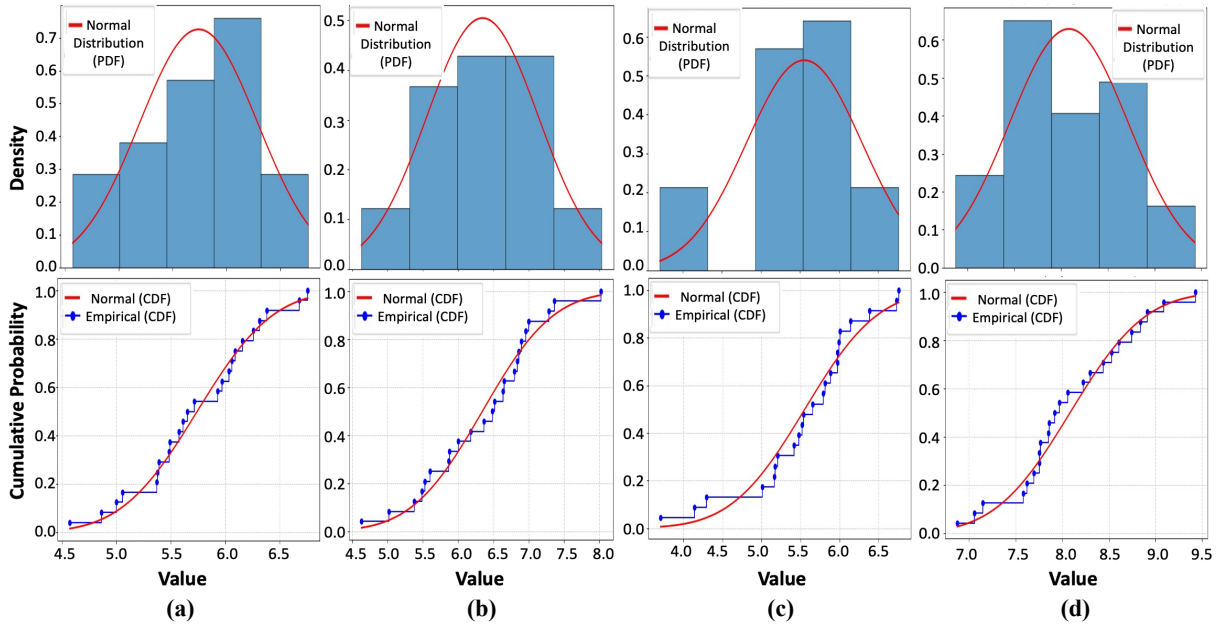


Figure 2. Histogram and Normal Distribution (PDF) and Cumulative Probability vs. Normal CDF: (a) natural aggregates; (b) recycled aggregates; (c) natural fine aggregate and recycled coarse aggregate; (d) recycled fine aggregate and natural coarse aggregate

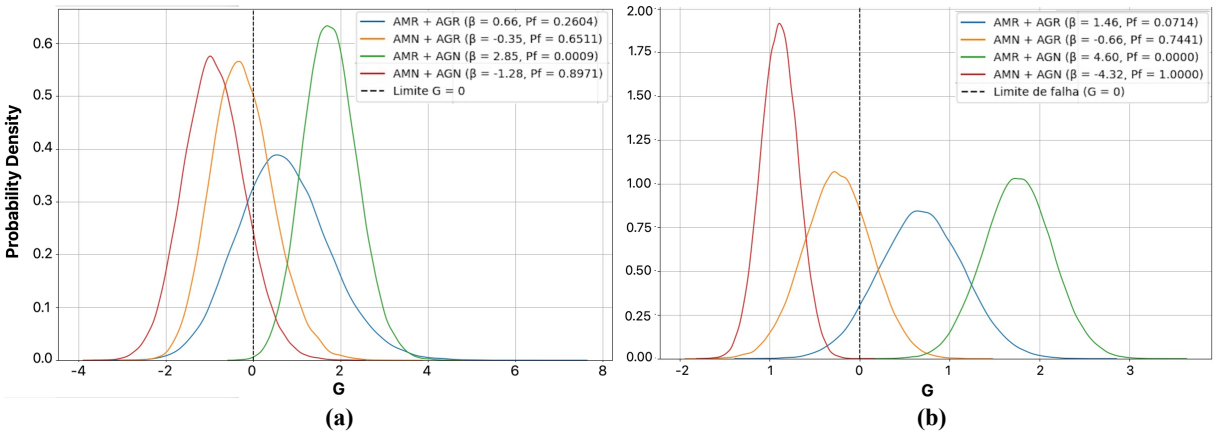


Figure 3. Monte Carlo-Limit State Distribution G: (a) Fixed $S = 3$ and variable α; (b) Fixed $S = 3$

In the second Monte Carlo simulation (Figure 3(b)), both R and α were modeled as Gaussian random variables in order to more realistically represent the variability of the actual strength available under the design demand. The results obtained revealed a pattern similar to that identified in the first analysis. The compositions with AMN+AGR and AMN+AGN presented failure probabilities above 50%, evidencing a risk that, under the simultaneous influence of the variabilities of R and α, these compositions become more susceptible to unsatisfactory performance. On the other hand, compositions with AMR+AGN and AMR+AGR maintained failure probabilities below 50%, indicating that these compositions lead to a more feasible scenario, even when considering the uncertainties inherent to R and α.

Finally, the last reliability analysis focused on modeling uncertainties associated with S (Figure 4), by varying its standard deviation from 0.01 MPa up to 0.59 MPa. Thus, similarly, the groups composed of AMR + AGN and AMR + AGR were those with lower failure probabilities.

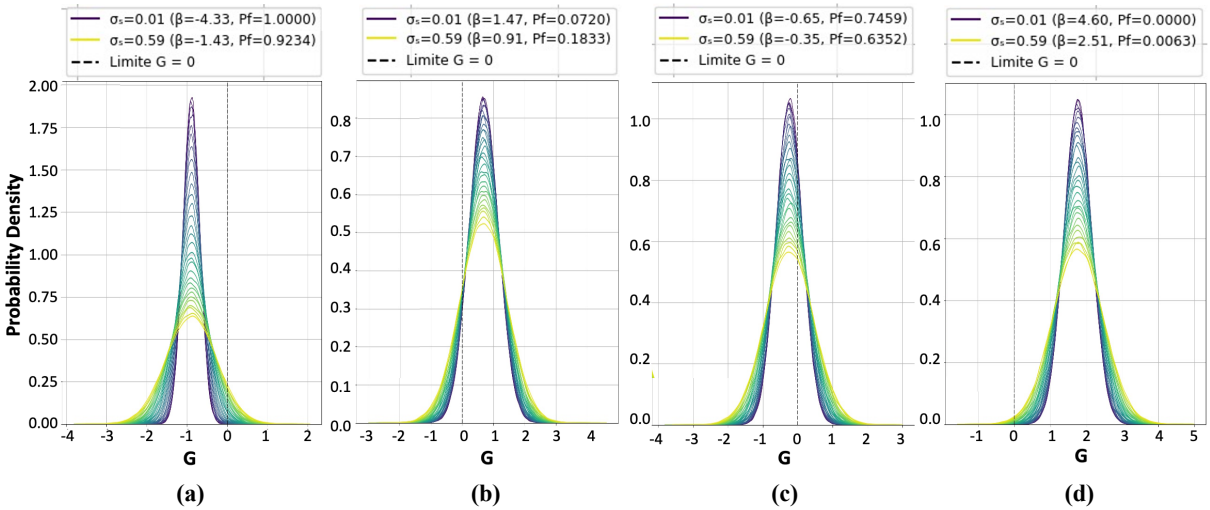


Figure 4. G Distribution: (a) natural aggregates; (b) recycled aggregates; (c) natural fine aggregate and recycled coarse aggregate; (d) recycled fine aggregate and natural coarse aggregate

Therefore, the compositions containing AMR were those that performed best in the situations analyzed.

4 Conclusions

This research aimed to correlate the experimental data on the compressive strength of SPs and concrete blocks using a parameter α, and to evaluate the uncertainties using Monte Carlo simulation models, covering three different scenarios.

The results indicated that the compositions with AMR+AGR and AMR+AGN presented average α values closer to 1, 0.58 and 0.59 respectively, evidencing a greater convergence between the compressive strength results obtained for the SPs and blocks. Given this, for this composition, the mechanical behavior of the SPs presented greater representativeness and consistency with those produced using the compressive rheometry technique.

The reliability analyses performed using Monte Carlo simulations showed that compositions with AMR performed better in the scenarios evaluated. Thus, the use of recycled sand proved to be safer and more consistent in the evaluations of this study.

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