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CAMPUS: **PESQUEIRA**	COORDENAÇÃO Edificações	
PROFESSOR: **Ruan Landolfo da Silva Ferreira**	GRUPO **I**	REGIME DE TRABALHO: ( ) 20h ( ) 40h (**X**) DE

TODAS AS ATIVIDADES DESENVOLVIDAS DEVERÃO SER COMPROVADOS (ART. 21)

ATIVIDADES DE ENSINO

COMPONENTES CURRICULARES	CURSO	C.H. TOTAL DO COMPONENTE	C.H. SEMANAL	C.H. de PREPARAÇÃO DE AULAS
A12-PS.104 – MANUTENÇÃO PREDIAL	Edificações Médio Integrado	27	1,5	1,5
A12-PS.083 – MATERIAIS DE CONSTRUÇÃO II	Edificações Médio Integrado	40,5	2,25	2,25
A2005 – TÉCNICAS DE CONSTRUÇÃO I	Edificações Subsequente	54	3,0	3,0
A2022 – TÉCNICAS DE MANUTENÇÃO	Edificações Subsequente	72	4,0	4,0
A201401 - MATERIAIS DE CONSTRUÇÃO	Edificações Subsequente	72	4,0	4,0
SUBTOTAL		265,5	14,75	14,75

ATIVIDADE	C.H. Semanal
PARTICIPAÇÃO EM REUNIÕES SEMANAIS DE PLANEJAMENTO PEDAGÓGICO	1,0
ORIENTAÇÃO DE ESTÁGIO – ALUNO(A)S: BRUNO CÉZAR SANTOS BATISTA E MARIA JANAINY MELO SILVA	4,0

ATIVIDADES DE PESQUISA

ATIVIDADE	C.H. Semanal
PUBLICAÇÃO DE ARTIGOS CIENTÍFICOS EM REVISTAS INDEXADAS - *Ferreira, R. L.*, Anjos, M. A., Maia, C., Pinto, L., de Azevedo, A. R., & de Brito, J. (2021). Long-term analysis of the physical properties of the mixed recycled aggregate and their effect on the properties of mortars. *Construction and Building Materials*, 274, 121796.	4,0

ATIVIDADES DE EXTENSÃO

ATIVIDADES ADMINISTRATIVO-PEDAGÓGICAS

ATIVIDADE	C.H. Semanal
COMISSÃO DE REESTRUTURAÇÃO PPC EDFICIAÇÕES MÉDIO INTEGRADO E SUBSEQUENTE. DECLARAÇÃO CACC/DENS/IFPE – PESQUEIRA. PORTARIA Nº 057/2014 - DGCP05/2020	1,5

COMPLEMENTO / OBSERVAÇÕES

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AULAS	PREPARAÇÃO DE AULAS	APOIO AO ENSINO	PESQUISA	EXTENSÃO	ADMINISTRATIVO PEDAGÓGICO	TOTAL/SOMA
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DECLARAÇÃO

Declaramos para fins de direito que o professor **Ruan Landoufo da Silva Ferreira**, **Siape 3087909**, exerceu a função de orientador de estágio no curso Técnico em Edificações desta Instituição de Ensino no semestre de 2020.2 nos seguintes termos:

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Pesqueira, 21 de Fevereiro de 2021.

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Long-term analysis of the physical properties of the mixed recycled aggregate and their effect on the properties of mortars

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HIGHLIGHTS

- The use of MRA for the production of cementitious materials is still limited.
- First phase showed that there were no statistically differences in the physical properties of MRA over a year.
- Feasibility of using MRA for the production of cementitious materials is correlated to the quality control of CDW.
- The use of CDW is possible in eco-friendly mortars in buildings.

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ABSTRACT

The use of mixed recycled aggregates (MRA) for the production of cementitious materials is still limited due to the high heterogeneity of the rubble sources and the lack of specific regulations, which contributes to maintaining the problems associated with the management of construction and demolition waste (CDW) in recycling plants. Therefore, this paper investigates the influence and effects of the use of MRA, collected over time, on the physical and mechanical properties of cement and lime-based mortars, based on a statistical modelling using Machine Learning algorithms. For this purpose, an extensive experimental programme with three stages was developed, intending to evaluate the variability of the MRA produced. The first phase consisted of the physical characterization tests of 36 samples of MRA. The second phase intended to perform technological tests to select the best volumetric ratio of cement: hydrated-lime: MRA (1:1:6, 1:1:7 or 1:2:9) to be used with 100% MRA (modified mortars). Finally, the third experimental phase investigated the physical and mechanical properties of the modified mortars produced with the volume ratio selected in the previous phase and using MRA collected at different periods of time. The results obtained were analysed using a T hypothesis test, a joint analysis of all variables using a Robust Principal Components Analysis (ROBPCA) and a partner recognition model based on data driven and ROBPCA (Data Driven Soft Independent Modelling of Class Analogy - DD-SIMCA). From the results, it was noticed that MRA 1:1:6 mortars presented a better performance in terms of mechanical strengths and water absorption by capillary, due to the filler effect of the MRA. As a matter of fact, the statistical tests have proven that no statistically significant differences were found in the physical properties of the 36 MRA samples and among the physical and mechanical properties of mortars in these periods investigated, which demonstrates the potentially reproducibility of CDW. Therefore, it was found that a proper selection and processing of CDW, as well as a definition of efficient mixing ratios can minimize the effects from the high heterogeneity of these wastes and enable the effective use of MRA in mortars.

1. Introduction

Concerns about the management of construction and demolition waste (CDW) by the construction industry have increased.

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The sector is responsible for approximately 30% of the total waste generated worldwide [1]. Several strategies have been developed to reduce, reuse and recycle CDW. In order to set aside the disposal in landfills, more efficient alternatives ways to manage the waste have been pushed forward [2]. One of the most current, spread and successful practices is the use of recycled aggregates (RA) obtained from CDW in cementitious materials as replacement of natural aggregates (NA).

There is also another positive factor in the use of RA in mortars, linked to a cleaner production of cementitious materials, due to the non-extraction of natural raw material to make the cementitious matrix, which in the case of mortars in Brazil uses natural sand from river, a limited natural resource [3]. Thus, the use of RA will support the reduction of the mortar's environmental impact, contributing to a clean production [4].

After being processed by certified recycling facilities, the CDW gives rise to three main types of RA: recycled concrete aggregates (RCA), recycled masonry aggregate (RMA) and recycled mixed aggregate (MRA) [5,6]. Usually there are small amount of contaminants, such as wood, plastic, plaster, Styrofoam, asphalt, glass, etc. The applications of RA are diverse, from the sub-base layer to the production of concrete and mortars [7]. Currently, RCA is the most used type of RA in construction, which has driven the development of specifications in many countries, including its use in structural concrete.

Notwithstanding the several works regarding the use of RA in constructions products, studies on the variability of RA properties are urgently needed. RA from CDW recycling plants present a wide variation of their composition due to many factors that influence their production [8], processing and treatment. The quality of the RA needs to be assessed, since they may exhibit different properties [9]. The variability in quality depends on the stage, typology and origin of the construction and/or demolition. Another factor is the different quantities of each waste that have been processed. Therefore, RA present a high heterogeneity of their composition, which will influence the final product. The type of RA affects differently the performance of the materials, as well as the amount of contaminants present and the amount of old mortar adhered to the particle.. Furthermore, the RA present lower mechanical strength and higher water absorption relative to NA.

These RA characteristics results on the final properties of the mortars. In general, the replacement of natural aggregates reduces the workability of the mortars. The consistency of fresh mortar decreases due to the absorption of RA of part of the mixing water. This effect reflects as well on the mechanical properties, since the cement particles do not hydrate, which reduces the compressive strength of the modified mortars. The reduction is also attributed to the adhered mortar and porosity of the particles. Previous studies that analysed mortars with 100% of MRA have reported that the flexural strength decreased due to the lower mechanical properties of the particles. Nonetheless, works with very fine RA found an increase in mechanical strengths of the mortars [10–12]. This could be explained by a filler effect or potential pozzolanic reactions.

Researches concerning the reliability of RA have been developed [13–15]. However, the studies on the variability of RA properties is focused on analysing recycled aggregate concrete (RAC), mainly composed of cementitious waste, for structural uses. Studies on the variability of MRA and their use in rendering mortars are lacking. Even though several works have shown the feasibility to produce modified mortars with MRA as a replacement of NA [16–20]. There is a lack of studies with in depth analysis of the RA's properties, considering the differences between the recycling plants and seasonal effects. Therefore, researches in order to establish parameters that could provide a greater reliability of their use are required. The knowledge of the variability of RA may increase the confidence in the quality of these materials and promote specific regulations and standards to achieve a better and effective CDW management.

This work intends to investigate the variability of physical properties of MRA and its effect on the physical–mechanical properties of cement and hydrated-lime mortar in substitution of 100% of NA. An extensive experimental program was carried out, divided into three stages. Initially, the MRA was collected in different periods of the year, totalling 36 samples. Subsequently, three different volumetric ratios of modified mortars were produced, namely 1:1:6, 1:1:7 and 1:2:9 (cement: hydrated-lime: aggregate). After technical characterization and statistical analysis, the modified mortar with the best performance was chosen to be produced 11 times per year with MRA from the same recycling plant. The analysis of the final properties of the selected mortar was related to the characteristics of RA used over time. The results obtained in each experimental phase were submitted to a robust statistical analysis based on artificial intelligence methods.

2. Materials and methods

2.1. Materials

The mixed recycled aggregate (MRA) used in this investigation was obtained from a recycling plant located in São José do Mipibú (Brazil) - *Duarte Usina de Reciclagem*. The MRA was produced from the crushing of construction and demolition waste (CDW) resulting basically from leftover concrete/plaster (~70%), rocks with small amount of mortar adhered (~17%), ceramic materials (~9%) and other materials (~4%, gypsum particles, Styrofoam, wood, paper, etc.). After crushing, the MRA produced had a particle size below 6.3 mm. Thus, a total of 36 samples of MRA were collected between the months of February and December 2019. The MRA were collected from the production stacks, i.e. directly from the MRA volumes that formed immediately after crushing the CDW and specifically the midpoint of the pile, as seen in Fig. 1. For this reason, in some months, more than one MRA sample was collected (See Table S1). The sampling and reduction of the MRA collected was performed according to the Brazilian standards NBR NM 26:2001 and NBR NM 27:2001, respectively.

After collection, the samples were sieved in the laboratory to remove the coarse particles (>4.75 mm) and then dried in an oven (100 ± 5 °C) for a period of about 24 h, or until they reached consistency of mass, and stored in separate containers for subsequent physical characterization tests. To preserve the inherent characteristics of the selection and crushing process of CDW, no further processing was carried out.

Fig. 1. Pile where the MRA was collected. Source: authorship of the authors.

For the production of eco-friendly mortars, pozzolanic Portland cement (PC) (similar to ASTM C 595), hydrated-lime (HL) type CH-I (similar to ASTM C207-6) and 100% MRA were used. The type of cement used in this study was recommended by other authors [15,18,19]. The use of HL is justified due to the benefits provided for the mortars properties, mainly workability and water retention, and for the environment due to the fixation of CO_2, which contributes to a cleaner production [9,18,20,21]. To produce the reference mortars, 100% natural silica sand (NA) from a river was used.

2.2. Methods

The experimental programme was divided into three phases:

- *First phase:* Physical characterization of the constituents of the mortars, in particular NA and the 36 MRA samples, as indicated in Table 1. In this phase, a statistical analysis was performed to evaluate the physical properties over time;
- *Second phase:* Technological characterization tests of mortars produced with 100% MRA (modified mortars) and with different volumetric ratios, as indicated in Table 1. The MRA used in this phase consisted of a mixture in equal mass proportions of the 36 samples of the previous experimental phase. Three volumetric ratios commonly used in rendering mortars in local construction were applied for this investigation: 1:1:6 (M1), 1:1:7 (M2), and 1:2:9 (M3) (cement: hydrated-lime: MRA). A detailed example of mix design can be seen in a previous study [16]. A technical and statistical analysis was conducted in order to select the best proportion of materials to compose the modified mortar (M1, M2 or M3) used in the final experimental phase;
- *Third phase:* Using 100% of the MRA collected in different months (February-December) and with the mortar previous selected in the "second phase", new modified mortars were produced. Therefore, new technological and statistical tests were performed to characterize the fresh and hardened properties of modified mortars. In this phase, the aim was to produce mortars with 100% MRA, in order to provide information from the technological point of view (characteristics and properties) and demonstrate the degree of variability of MRA mortars produced in different months of the year. In addition, it was sought to promote the use of MRA in mortars and consequently contribute to their acceptance in the construction industry towards a cleaner and more sustainable production [22,23].

The methods used to perform the tests in each experimental phase are shown in Table 1.

The mortars were produced in two different environments. In the second experimental phase, they were produced in a construction site (real scale), located in the city of Parnamirim - Brazil, using a mechanical mixer with capacity for 400 L. In the third experimental phase, the modified mortars were produced at a laboratory scale using a planetary mechanical mixer with a capacity of 5 L. The mixing procedure in both phases was performed based on the Brazilian prescriptions (NBR 16541:2016) and as in a previous study [12]. In addition, the amount of water was experimentally adjusted so that all mortars presented a diameter within 255–265 mm on the consistency table, according to the Brazilian standard NBR 13276:2016 (similar to ASTM C1329). The dynamic modulus of elasticity (E_d) of the mortars was determined based on non-destructive tests and using the ultrasonic dynamic methodology. For this purpose, tests were performed to determine the dry density of the hardened mortar (ρ_h) (as per NBR 13280:2005 - equivalent to EN 1015–10:1999) and the ultrasonic speed of the specimens (υ) (as per NBR 8802:2013 - equivalent to ASTM C 597–16). The Poisson coefficient was assumed to be constant for the different types of mortars and equal to 0.20.

Table 2 shows the consumption of materials needed to produce 1 m^3 of modified mortars for the 2nd experimental phase. The content of MRA grows as the consumption of HL increases, resulting in increasing the w/c ratio of the mixes. This occurs due to the high porosity and, therefore, higher absorption of MRA [12].

After mixing, the mortars were submitted to the characterization tests shown in Table 1. All tests were performed in the laboratory, except the bond strength test, which was performed at an ambient temperature of 25 ± 5 °C. For this purpose, coatings with an area of approximately 1 m^2 and a thickness of 2.00 cm were produced. The substrate used was made of concrete blocks.

In the laboratory, all samples remained for two days in the prismatic specimens (4x4x16 cm) for an initial curing of hardening, with their surface protected by a glass plate. After this period, demoulding was performed, keeping the samples with all their faces exposed to the environment, with a controlled relative humidity of 95 ± 5% and local temperature of 20 ± 5° C until the ages established for each test (Table 1).

2.3. Statistical analysis

The statistical analyses were carried out according to the information present in each of the three stages:

- In the first stage, the physical characteristics of the aggregates were analysed; it was expected that all samples showed the same variation for all measured properties. A t hypothesis test

Table 1
Aggregate and mortar characterization tests.

Experimental phases	Properties	No. of samples and size	Brazilian standard	Specimens	Curing time (days)
1st phase	Particle size distribution	36	NBR 248[1]:2003	Aggregates	–
1st phase	Fineness modulus	36	NBR 248[1]:2003	Aggregates	–
1st phase	Powder content (<75 μm)	36	NBR NM 46[2]:2003	Aggregates	–
1st phase	Bulk density	36	NBR NM 45[3]:2006	Aggregates	–
1st phase	Specific gravity	36	NBR NM 52[4]:2009	Aggregates	–
2nd and 3rd phases	Flexural strength	6 prismatic (40 × 40 × 160 mm)	NBR 13279[5]:2005	Hardened mortar	28 and 91
2nd and 3rd phases	Compressive strength	6 prismatic (40 × 40 × 80 mm)	NBR 13279[5]:2005	Hardened mortar	28 and 91
2nd and 3rd phases	Dynamic modulus of elasticity	6 Prismatic (40 × 40 × 160 mm)	NBR 15630[6]:2009	Hardened mortar	28
2nd phase	Adherence strength	6 cylindrical (50 × 10 mm)	NBR 13528[7]:2010	Hardened mortar	56
2nd phase	Water absorption by immersion	6 prismatic (40 × 40 × 160 mm)	NBR 9778[8]:2009	Hardened mortar	28
2nd and 3rd phases	Capillary water absorption	6 prismatic (40 × 40 × 160 mm)	NBR 15259[9]:2005	Hardened mortar	28
3rd phase	Consistence by flow table	6	NBR 13276[10]:2016	Fresh mortar	–
3rd phase	Bulk density	6	NBR 13278[11]:2005	Fresh mortar	–
3rd phase	Air content	6	NBR 13278[12]:2005	Fresh mortar	–

[1] Equivalent to EN 13,139 (2002); [2]Equivalent to ASTM C117 (2017); [3,4]Equivalent to NP EN 1097–6 (2003); [5]Equivalent to EN 1015–11 (1999) and ASTM C1314 (2016); [6]Equivalent to ASTM C597 (2009) and EN 12504–4 (2004); [7]Equivalent to EN 1015–12 (2000) and ASTM C952 (2012); [8]Equivalent to EN 1936 (2007) and ASTM C642 (2013); [9]Equivalent to EN 1015-18 (2002); [10] Equivalent to EN 1015-3 (1999) and ASTM C1329 (2016); [11]Equivalent to EN 1015–6 (1998); [12]Equivalent to EN 1015-7 (1998).

Table 2
Mix design of the modified mortars in the 2nd phase.

Mix designation(volumetric ratios)	Composition (kg/m^3)					
	PC	HL	NA	MRA	Water	w/c
R1(1:1:6)	231.1	93.3	1503.5	–	316.6	1.37
R2 (1:1:7)	207.5	83.8	1575.4	–	300.9	1.45
R3 (1:2:9)	170.2	137.5	1661.1	–	257.0	1.51
M1(1:1:6)	210.6	85.1	–	1409.1	337.0	1.60
M2 (1:1:7)	189.7	76.6	–	1481.0	318.8	1.68
M3 (1:2:9)	157.2	127.0	–	1577.7	268.8	1.71

R1, R2 and R3 = Reference mortars (100% of NA); M1, M2 and M3 = Modified mortars (100% of MRA).

was performed to assess whether each sample was statistically similar to the mean value for a given property at a given time. However, the statistical tools used in this work allow the joint analysis of all variables (Robust Principal Components Analysis - ROBPCA) and then a data driven based algorithm uses the Principal Components Analysis (PCA) and hypothesis test was used to evaluate whether all samples presented the same variation when all variables were jointly evaluated (Data Drive Soft Independent Modelling of Class Analogy - DD-SIMCA). Initially, a ROBPCA was performed to identify the presence of anomalous samples, i.e. any sample that for some reason differed anomalously from the others [25]. Then, the Data Driven strategy, where the information present in the data guides the modelling, was applied together with SIMCA (DD-SIMCA) to evaluate whether all the samples were statistically similar [26]. This will inform in whether the distribution of the physical properties of the aggregates remained statistically constant over the months analysed;

- In the second stage, the mechanical properties of seven specimens prepared according to the three proportions at 28 and 91 days of curing were analysed. In this stage, some mechanical information was lost because some specimens could not be analysed. These analyses were not possible on some specimens due to failure during casting and/or incoherent results when the tests were performed. For this reason, before performing the PCA analyses, the missing data were filled with the imputation strategy based on the K nearest neighbour (KNN) a machine learning algorithm [27]. The PCA jointly evaluates all the properties and indicates which proportion of materials and time is needed to achieve the best physical and mechanical characteristics of the mortars using the scores and loadings graphics. The scores indicate the similarity and differences between the analysed samples and the loadings graphic highlight which properties influence the distance between the samples presented in the score graphics, so the interpretation of the PCA uses both scores and loadings graphics jointly;
- In the third phase, the optimized conditions in the second phase were used to produce modified mortars separately. It was analysed whether there was a significant variation between the prepared specimens with the RA of each month regarding the physical and mechanical properties of the produced mortars. For the same reason of the second phase, some specimens were not analysed, which required estimating their values previously to filling and the missing data. The analysis had the same objectives as in the first phase. A robust principal component analysis was performed to identify whether there were any anomalous samples and a DD-SIMCA model was used to evaluate whether all samples were statistically similar. The physical and mechanical properties that varied and the order of magnitude of this variation was determined in the various mixes.

3. Results and analysis

3.1. First experimental phase

Fig. 2 shows the particle size distribution of the studied aggregates, determined according to the Brazilian standard NBR NM 248:2003 (similar to ASTM C136). It was observed that both the mean values of MRA and the lower and upper deviations are within the ranges prescribed in the Brazilian (NBR 7211:2009) and American (ASTM C144) standards for aggregates used in concrete and mortars. These results revealed that the samples collected from MRA in this recycling plant have a particle size distribution compatible with the limits established in standards and better behaviour when compared to NA.

Fig. 3a, b, c, and d show the micrographs, obtained by scanning electron microscopy (SEM), of NA and MRA, respectively. It could be seen that the shape of both aggregates is irregular; however, the MRA particles are more angular, with well-defined edges and vertices, which can be positive in terms of filling the cement matrix.

The surface texture of MRA is extremely porous and rough (Fig. 3b, c and d), which may contribute to an increase of the surface area related to the aggregate-step interface. An analysis of energy dispersive spectroscopy (EDS) of the surface of MRA (Fig. 4) indicated the prevailing presence of silicon (35.39%), calcium (31.57%), and aluminium (17.06%). This could be attributed to the presence of an old mortar layer attached to the RA particles. These observations are consistent with previous studies [9,16], bearing in mind that the presence of old mortar attached to the

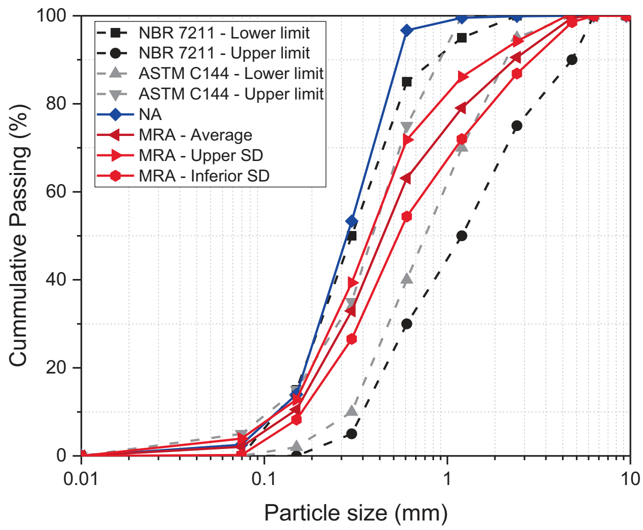

Fig. 2. Particle size distribution of MRA and NA.

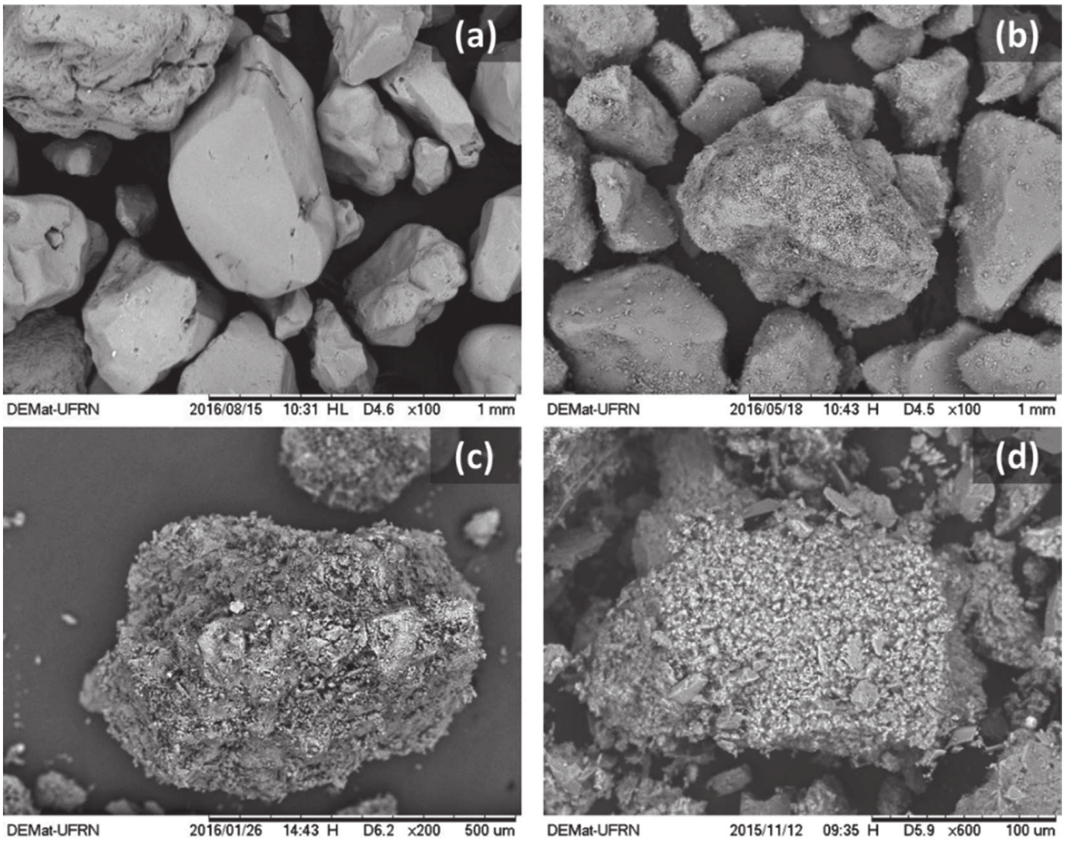

Fig. 3. Micrographics SEM: (a) natural aggregates (NA); (b), (c) and (d) recycled mixed aggregate (MRA).

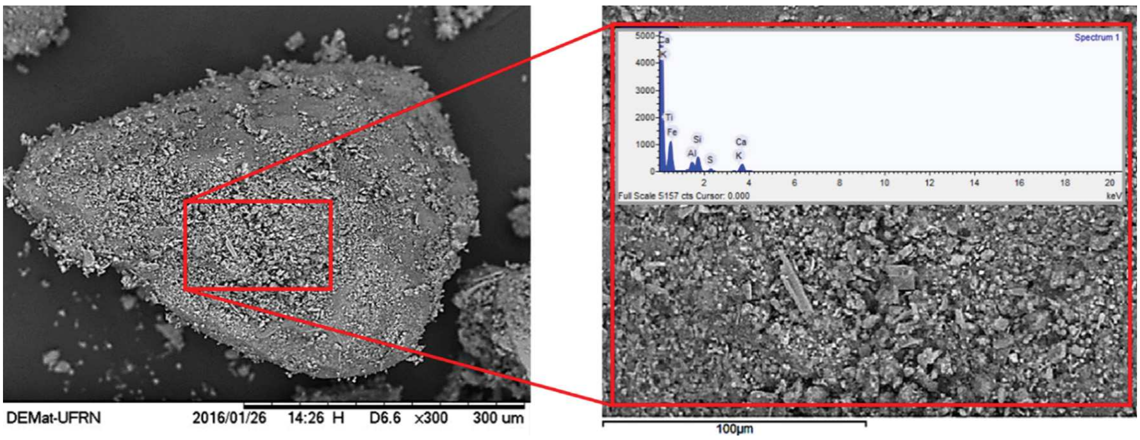

Fig. 4. Analysis of the surface texture of MRA.

Table 3
Physical properties of the studied aggregates.

Physical properties	NA		MRA			
	Average	CI	Average	CI	CI_{min}	CI_{max}
Fineness modulus	1.36	0.13	2.21	0.07	2.13	2.28
Powder content (<75 μm)	2.20	2.54	7.29	0.54	6.76	7.83
Bulk density	1.50	0.0	1.38	0.01	1.36	1.40
Specific gravity	2.64	0.13	2.52	0.02	2.51	2.54

CI = confidence intervals; CI_{min} and CI_{max} = Minimum and maximum confidence intervals, respectively, obtained by the T-test, with a reliability level equal to 95%.

particles of the aggregate affects negatively the mechanical behaviour and durability of concrete and mortars [16,26–28].

Table 3 shows the results from the aggregate's physical characterization tests. The MRA has some differences from NA, namely a lower specific gravity and higher powder content (<75 μm). The heterogeneity of raw materials present in the original CDW, the higher degree of friability and the crushing process explain these results. On the other hand, although the MRA has a high powder content, the obtained value (7.29 ± 0.54%) is below the limits established by the Brazilian (NBR 15116: 2004) and European (UNE-EN 13139: 2002) standards for the use of RA in non-structural concrete (≤20%) and mortars (≤8%), respectively [29,30].

The MRA fineness module identifies an aggregate with a particle size larger than the NA's. The results of the MRA bulk density were statistically different from those of NA, considering the confidence intervals (CI at 95% confidence). The lower bulk density is probably due to the irregular shape of the MRA inherent to the crushing process and intrinsic to the characteristics of the original CDW. At first, this behaviour may indicate a worse filling effect of the voids. However, higher NA density may increase the weight of the final product without increasing the mortar's strength, as reported by Amaral et al. [31].

In order to verify that the individual values of each property differ from their respective average and NA average values, a 95% confidence test was conducted. As expected, there are statistically significant differences between the MRA and NA. However, analysing all the results obtained (see supplementary information in Table S1), it was found that there were no significant differences between mean and NA values for specific gravity. Regarding the specific gravity, it is important to point out that considering the CI_{max} and CI_{min} (2.54–2.50 g/cm^3, respectively), the results obtained show the good quality of the MRA produced throughout the investigation period. This observation is consistent with a previous study [32] that showed that RA with specific gravity above 2.50 g/cm^3 are predominantly made up of natural rocks, surrounded by a layer of hardened cement paste, and that the hardened paste content is relatively low. Although the specific gravity results of the MRA studied are higher than the values found in the literature, it is important to note that these aggregates consist of a larger amount of waste with a higher specific gravity, such as concrete and mortar debris (~70%). However, the specific gravity values of the MRA studied are consistent with similar studies [12,16,19,33].

To investigate the dispersion of the results in the other properties, all data were submitted to Robust Principal Component Analysis (ROBPCA), which can be seen in Fig. 5.

The biplot presented in Fig. 5 consist on the scores (blue circles) and loading values (red circles with line). The principal components (PCs) are representation of the original variables on the transformed variables called PCs. The interpretation depends on three characteristics: (1) the explained variance of each PC, (2) the magnitude and direction of the lodgings and (3) the dispersion of the scores. The loadings values are normalized up to length 1 as maximum value. The direction of the loadings indicates the samples where the values of that variable are higher and the explained variance indicate the importance of the variation of the variables described by each PC. Analysing Fig. 5, one can see that the bulk density and the specific gravity do not show a relevant variation between the samples. On the other side, the fineness module and powder content show maximum value of loadings; since the explained variance is higher for PC1, it is possible to say that the variation of the powder content is higher than the fineness module on the analysed samples. In terms of the scores, sample #3 presents the lowest value of powder content, sample #9 the highest, sample #27 the lowest value of fineness module, and sample

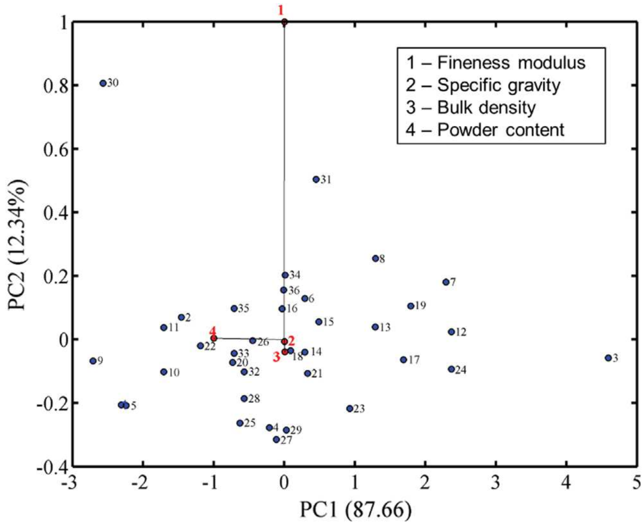

Fig. 5. Biplot for all properties obtained from the 36 samples of MRA.

#30 the highest value of fineness module and the second highest value of powder content. All these conclusions can be seen in **Table S1**. The greatest advantage of PCA is that all the interpretation of the variables can be easily seen in a few graphics regardless of the number of samples and variables. For the present work, PCA makes it easier to perform statistical tests and evaluate whether the mortars and CDW present the same value and in what properties the sample differ.

An analysis using the DD-SIMCA uses the information of PCA and groups the samples that are similar with 95% confidence using a hypothesis test. Fig. 6 shows an acceptance plot graph with regular and extreme boundary curves for all investigated properties. Analysing these curves, it was perceived that sample #30 is an extreme sample, i.e. a sample whose properties differ from the other individual samples, as expected through the analysis of Fig. 5. As sample #30 is located between the green and red line, it is considered an extreme sample due to simultaneous high value of powder content and fineness modulus. To be considered an anomalous sample, it is necessary that the sample is located after the outlier boundary on 99% of confidence. Therefore, it is

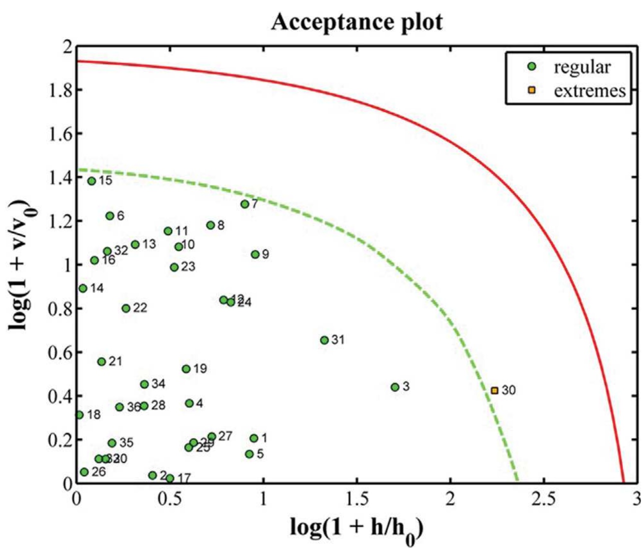

Fig. 6. DD-SIMCA acceptance plot.

concluded that all the samples are statistically similar when all the four properties analysed are taken into account.

As seen in **Table S1**, sample #30 shows a high value of powder content and fineness modulus but intermediate values of specific gravity and bulk density, but only a statistical test can present a reliable conclusion as to whether this sample significantly differs from the others. The DD-SIMCA results, shown in Fig. 6, are easy to interpret and make it possible to identify groups of samples that are similar or different from the target group, no matter the number of samples that are analysed.

Thus, the statistical tests used in this investigation found that the 36 MRA samples collected in different months have no statistically significant differences in relation to their physical properties. In the third step, it was be evaluated whether this is achieved when this MRA is used to prepare rendering mortars.

3.2. Second experimental phase

Table 4 shows the mean and the confidence interval (IC) results obtained in the tests performed in the second experimental phase. At 28 days, the modified mortars showed worse mechanical performance compared to conventional mortars (100% NA), for all three compositions studied.

The is due to the greater porosity of these aggregates, because of their larger specific surface, which demands a greater amount of water to produce the mixes [9,15,16,31–34] and, consequently, increases the w/c ratio. It should be noted that further comparisons between mortars with NA and modified mortars were beyond the scope of this phase, and therefore only the comparison for classification purposes between the results obtained in flexural and compression strength tests at 28 days of curing was performed. Further analyses were carried out in the third phase of this research (Section 3.3).

For mortars produced with 100% MRA (modified mortars), the best performance occurred for the one produced with a volumetric ratio of 1:1:6 (M1). In general, the reduction in cement and MRA consumption, with a probable reduction in the powder content of these aggregates (<0.15 mm), explained the worst mechanical performance of mortars M2 and M3 [35]. The importance of the ultra-fine particles of MRA is stressed since, despite contributing to a higher water demand, a higher content of these particles provided a more efficient filling of existing voids between the larger particles [12]. As a result, the mix becomes more compact and, therefore, better mechanical performances were observed.

The results of the substrate adherence test (f_a) showed that, regardless of the mixing ratio used, the incorporation of MRA resulted in modified mortars with performance above the minimum required by the Brazilian standard (0.20 MPa for indoor environment and ceiling) (NBR 13749: 2013). Among the modified mortars analysed, M1 showed the best behaviour in terms of adhesion to the substrate, which is related to a better mechanical performance and durability, due to the allowance of an even distribution of stress, avoiding the appearance of cracks and displacement of the coating [36]. The worst substrate adhesion performance of M2 and M3 is probably associated with the higher content of MRA and consequently the higher amount of ultrafine particles (0.075 mm) present in the same volume. As a result, adhesion is reduced due to filling the pores of the substrate with ultrafine particles of MRA instead of the hydrated products of Portland cement [7,9]. However, for all modified mortars failure was of the adhesive type, i.e. at the mortar-substrate's interface.

In terms of physical properties, the performance of the M1 mortar was also more satisfactory. The lower C_c and O_p percentages of M1 show that there was probably a refinement of the micro and macro pores of this mix due mainly to the filler effect caused by the higher powder content of the MRA used. Nevertheless, lower capillarity coefficients are favourable, as they indicate that the permeability of mortars is reduced [37] and, therefore, the entry of aggressive agents into their interior is hampered. The best performance of M1, relative to M2 and M3, occurred essentially due to the higher consumption of cement (which is bad from an environmental point of view) and, mainly, the lower consumption of MRA (Table 2).

Fig. 7 shows the two-dimensional distribution between the f_c and f_f of the modified mortars at 28 and 91 days. The modified mortars produced with a lower proportion of cement (M3) show less dispersion of the results, both at 28 and 91 days. On the other hand, M1 presented a better mechanical behaviour, which was previously reported and shows that M1 obtained statistically significant differences in comparison to the other mixes.

Naturally, with the increase of curing time (from 28 to 91 days), there is a gain of mechanical strength due to the evolution of the hydration reactions. However, the mechanical behaviour (f_c and f_f) of M1 at 28 and 91 days presented a statistically equal mean value according to a t hypothesis test at 95% confidence. This is attributed to the increase of dispersion of the results with the increase of curing time. In order to achieve more reliable results and with the same magnitude of mechanical strength, the tests of the following experimental phase were performed at 28 days.

All properties of the hardened mortars were analysed together using ROBPCA, for all modified mortars (Fig. 8).

The analyses of PCA are similar to the previous one: Fig. 8 shows that M1 is statistically different from the other modified mortars (M2 and M3). In addition, a lower dispersion of M1 was observed in terms of mortar properties (Fig. 8a), as seen in Table S2 and in the results of PCA in Fig. 8. The analysis also showed that M1 obtained higher values of f_a, f_{c28}, f_{f28} and E_d, and lower values of O_p and C_c (Fig. 8b), which can be concluded by the higher loadings' values of these properties on the projection on the PC1 axis. This indicates that the use of a mixing ratio of 1:1:6 with 100% MRA favours the mechanical performance and durability of modified mortars.

Table 5 shows the green shaded mortars with the best performance in all properties studied. It should be highlighted that f_{c28}

Table 4
Physical and mechanical properties of the mortars in the 2ª phase.

Mortars	Hardened properties							
	f_{c28} (MPa)	f_{f28} (MPa)	f_{c91} (MPa)	f_{f91} (MPa)	E_d (GPa)	f_a (MPa)	O_p (%)	C_c (g/dm^2.min$^{1/2}$)
R1(1:1:6)	8.61 ± 0.60	2.16 ± 0.52	–	–	–	–	–	–
R2 (1:1:7)	5.67 ± 0.86	1.75 ± 0.30	–	–	–	–	–	–
R3 (1:2:9)	3.21 ± 0.56	0.78 ± 0.39	–	–	–	–	–	–
M1(1:1:6)	3.91 ± 0.12	1.08 ± 0.13	4.09 ± 0.78	1.13 ± 0.70	7.77 ± 0.13	0.37 ± 0.11	35.54 ± 1.23	10.23 ± 1.49
M2 (1:1:7)	3.31 ± 0.33	0.96 ± 0.11	3.49 ± 0.50	1.02 ± 0.42	7.29 ± 0.64	0.35 ± 0.24	36.20 ± 0.92	10.53 ± 1.65
M3 (1:2:9)	3.22 ± 0.14	0.90 ± 0.07	3.36 ± 0.29	0.95 ± 0.28	7.12 ± 0.08	0.30 ± 0.22	36.50 ± 2.69	12.80 ± 1.13

f_{c28} and f_{c91} = Compressive strength at 28 and 91 days, respectively; f_{f28} and f_{f91} = Flexural strength at 28 and 91 days, respectively. E_d = Dynamic modulus of elasticity; f_a = Adhesion strength to the substrate; O_p = Open porosity by water absorption by immersion; C_c = Capillary coefficient by capillary water absorption.

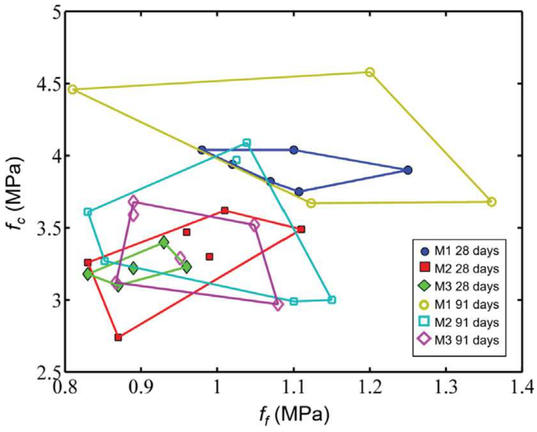

Fig. 7. 2D-plot of f_c and f_f variables of modified mortars at 28 and 91 days of curing.

was not taken into consideration in this analysis as it is not such a significant property for rendering mortars as f_a [6,38,39]. It was also observed in Table 5 that M1 is statistically equal to the others when analysing one property at a time. However, the difference in the mechanical properties of M1 can be better evidenced when all the properties were studied together in ROBPCA.

In addition to these factors, a visual analysis was performed to determine, after 56 days of curing, which mortars would present the greatest amount of visible cracks (Fig. 9).

Therefore, it was found that M1 had fewer visible cracks on its surface. Although this mortar has higher stiffness (higher f_c and E_d), the lower MRA content and, therefore, the lower w/c ratio used essentially explain the better performance of M1 in terms of cracking susceptibility. These observations corroborate the results of previous studies [15,39]. The latter authors found that the use of RA with higher amounts of powder (<0.075 mm) resulted in the appearance of a greater number of cracks in the mortars investigated.

Therefore, the modified mortar produced with a ratio of 1:1:6 (M1) was selected for the last phase of this investigation. The choice was made due to the best behaviour of this mortar both from a technological and statistical point of view, and mainly due to the higher adhesion strengths, lower capillarity coefficients and lower amount of visible cracks.

3.3. Third experimental phase

Table 6 shows the mean results obtained and the respective IC for all mortars studied. More details on the data analysed can be found in the supplementary material (Table S3).

In general, mortars with 100% of MRA presented lower performance than the reference mortar, which is consistent with previous studies, but is not a limiting factor for its use, since even lower performance mortars than the reference mortar can meet the minimum requirements required by the standard [7,14,31,40]. The main reason for the lower performance presented by some modified mortars is due to the higher porosity of their aggregates (Fig. 3). The higher porosity of MRA [9,14] results in a greater absorption of water and, therefore, explains the reduction in the physical, mechanical and durability performance of the mortars. This hypothesis is consistent with the very constitution of the CDW which, because it is highly heterogeneous, directly interferes in the properties of the cementitious materials made with it, resulting in different behaviours, even if the original source of the waste is the same [41].

In the fresh state, the modified mortars (with 100% MRA) obtained lower bulk density due to the lower apparent density of MRA compared to NA. This result is relevant because the weight of fresh mortar to be transported is lower, which contributes to increasing productivity. These results followed the same trend of previous studies that showed a decrease in bulk density in mortars produced with MRA [7,9,14,15,40]. In general, a greater content of air incorporated in the mortars with MRA may enhance their workability. On the other hand, the greater content of incorporated air directly affects the mechanical strength of the mortars due to the high porosity of the matrix [24]. These hypotheses were confirmed in this study, as the modified mortars with lower content of incorporated air had higher mechanical strength (M1-1, M1-2 and M1-3).

The dynamic modulus of elasticity (E_d) was significantly affected by the stiffness of the aggregates. RA presented lower stiffness than NA due to their higher porosity [6]. Thus, it was expected that the modified mortars would present lower E_d. These results are important because, as pointed out by Corinaldesi et al. [42], the lower stiffness of mortars produced with RA may contribute to a better adhesion of the mortar to the substrate. However, some modified mortars presented E_d similar to and even higher than that obtained by REF. This behaviour can be explained by the loading effect provided by the ultra-fine particles of MRA [12] and the late

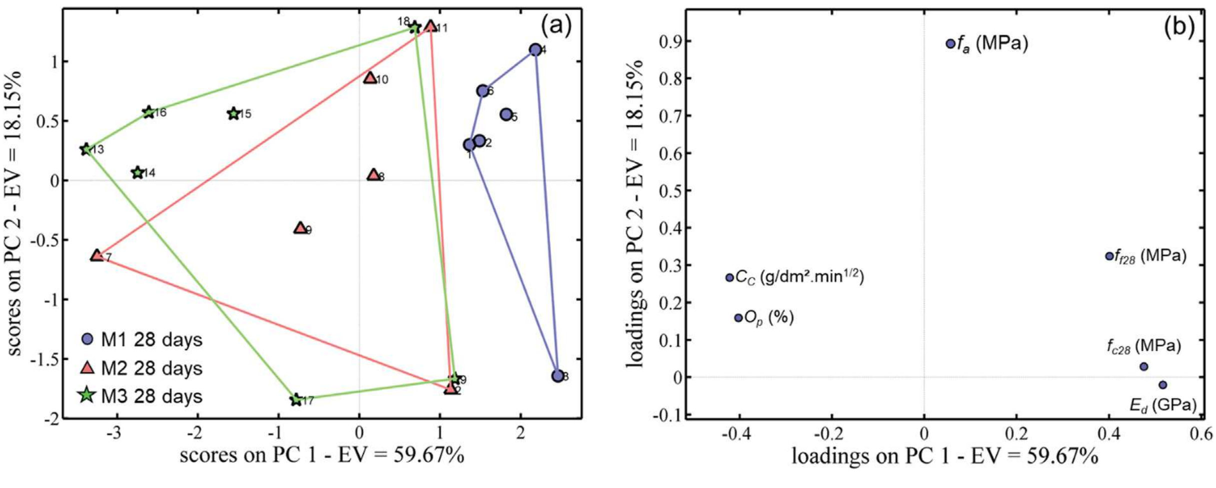

Fig. 8. (a) Score plot for all investigated properties and proportions and (b) loading plot of the modified mortar with the 1:1:6 ratio (M1).

Table 5
Analysis of 2nd phase results and selection of the best performing modified mortar.

Mortars	Properties					
	f_{c28} (MPa)	f_{f28} (MPa)	E_d (GPa)	f_a (MPa)	O_p (%)	C_c (g/dm^2.min$^{1/2}$)
M1(1:1:6)	3.91 ± 0.12	1.08 ± 0.13	7.77 ± 0.13	0.37 ± 0.11	35.54 ± 1.23	10.23 ± 1.49
M2 (1:1:7)	3.31 ± 0.33	0.96 ± 0.11	7.29 ± 0.64	0.35 ± 0.24	36.20 ± 0.92	10.53 ± 1.65
M3 (1:2:9)	3.22 ± 0.14	0.90 ± 0.07	7.12 ± 0.08	0.30 ± 0.22	36.50 ± 2.69	12.80 ± 1.13

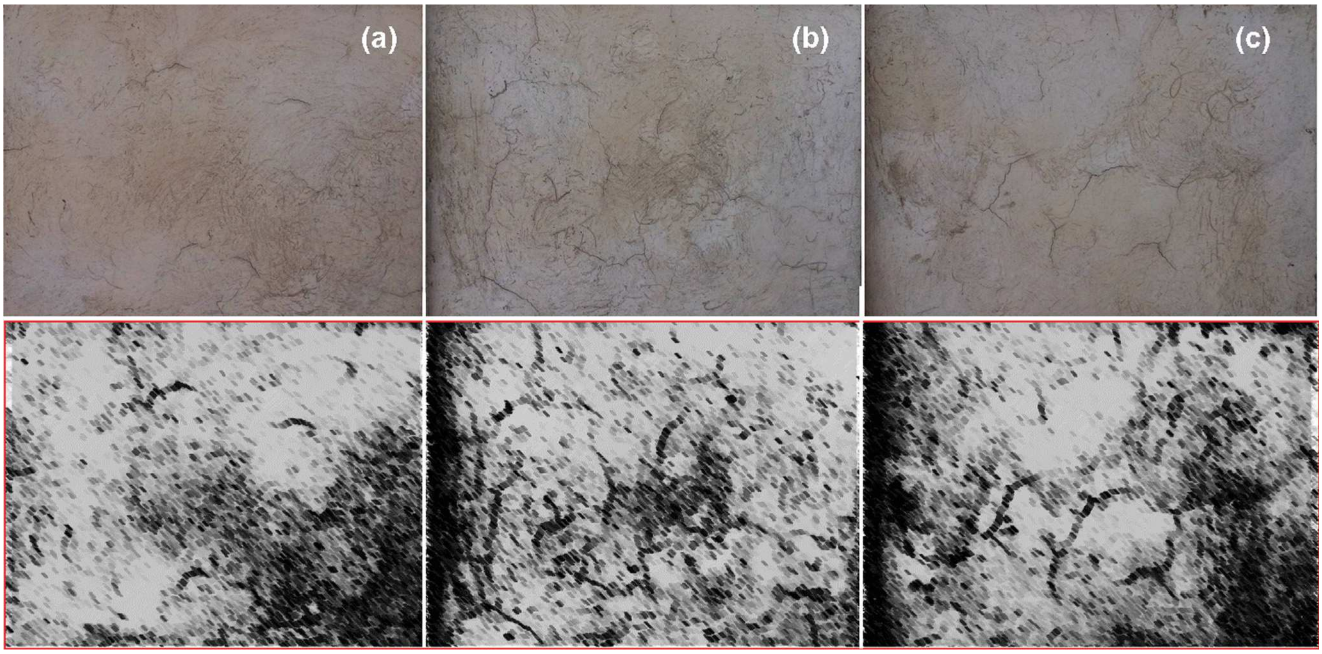

Fig. 9. Level of cracking of (a) M1, (b) M2 and (c) M3.

Table 6
Analysis of the 3rd phase results of the reference and modified mortars for different months of MRA collection.

Mortars	Fresh properties				Hardened properties					
	ρ_f(kg/dm^3)	A_c (%)	w/c	w/b	f_{c28} (MPa)	f_{f28} (MPa)	f_{f28}/f_{c28}	E_d (GPa)	C_c (g/dm^2.min$^{1/2}$)	w/c
REF	2042.37 ± 49.22	5.87 ± 2.27	1.43	1.02	7.01 ± 0.41	1.92 ± 0.13	0.28	12.44 ± 0.59	10.07 ± 0.52	1.37
M1-1	1989.68 ± 11.11	3.89 ± 0.54	1.67	1.19	8.47 ± 0.80	1.77 ± 0.29	0.20	12.25 ± 0.36	7.10 ± 2.12	1.67
M1-2	1996.11 ± 7.70	3.58 ± 0.37	1.68	1.21	8.61 ± 0.72	1.81 ± 0.35	0.21	12.85 ± 0.93	6.23 ± 0.64	1.62
M1-3	1838.32 ± 122.98	10.65 ± 6.61	1.71	1.22	7.77 ± 1.36	2.24 ± 0.28	0.28	11.84 ± 1.37	7.47 ± 1.30	1.71
M1-4	1789.16 ± 17.98	11.91 ± 0.89	1.96	1.40	5.80 ± 0.43	2.25 ± 0.23	0.38	11.15 ± 8.89	13.33 ± 0.80	1.96
M1-5	1769.40 ± 17.92	19.14 ± 0.82	1.98	1.41	5.68 ± 1.14	1.87 ± 0.08	0.34	10.82 ± 1.85	14.31 ± 2.74	1.98
M1-6	1801.14 ± 27.29	6.23 ± 1.42	2.15	1.53	4.89 ± 0.14	1.77 ± 0.23	0.37	11.17 ± 1.03	11.30 ± 2.79	2.15
M1-7	1799.78 ± 24.45	16.73 ± 1.13	1.85	1.32	6.14 ± 0.51	1.72 ± 0.12	0.28	12.80 ± 0.34	8.34 ± 3.32	1.85
M1-8	1820.86 ± 137.06	10.30 ± 6.75	2.02	1.44	5.44 ± 0.26	1.91 ± 0.31	0.35	11.21 ± 0.11	9.31 ± 1.36	2.02
M1-9	1806.27 ± 30.77	11.73 ± 1.50	2.01	1.43	5.66 ± 0.47	1.75 ± 0.41	0.31	10.49 ± 1.44	10.87 ± 2.24	2.01
M1-10	1783.71 ± 148.85	13.84 ± 7.19	1.92	1.37	5.86 ± 0.32	1.78 ± 0.64	0.30	12.89 ± 6.67	11.02 ± 1.94	1.92
M1-11	1904.03 ± 411.32	6.41 ± 20.22	1.82	1.29	6.56 ± 0.38	1.90 ± 0.13	0.29	12.60 ± 2.38	7.44 ± 1.37	1.82

ρ_f = Bulk density; A_c = Air content; w/c = water/cement ratio; w/b = water/binder ratio; REF = reference mortar (with 100% of NA); w/c = water/cement ratio (kg/kg); M1-X = Modified mortar with 1:1:6 ratio (defined in the 2nd phase) and "X" is the prefix that varies from 1 to 11, depending on the month of collection of MRA: February (1) to December (11).

hydration of non-hydrated cement adhered to the particles of MRA [10]. It is important to notice that the larger E_d may indicate a lower capacity to absorb deformations and, consequently, may have a greater susceptibility to the appearance of cracks.

In comparison with REF in some months, modified mortars showed higher compressive strength (M1-1, M1-2 and M1-3), higher flexural strength (M1-3 and M1-4) and lower capillary coefficients (M1-1, M1-2, M1-3, M1-7, M1-8 and M1-11). In general, these results are consistent with previous investigations [9,13] and contrary to other ones [4,7,14,15,31,40].

However, several factors can explain the better performance of these mortars, such as (i) the higher content of powder present in the respective MRA (see result of the 1st phase); due to its larger specific surface [32,40], it fills the voids between the larger particles and, therefore, increases the compaction of the mix and reduces the microstructural porosity; (ii) the better distribution of the particle size of MRA (Fig. 2), which contributes to densify the microstructure, providing more resistant and less permeable mortars; (iii) the improvement of the interfacial transition zone between the matrix and MRA, which, due to the porous texture

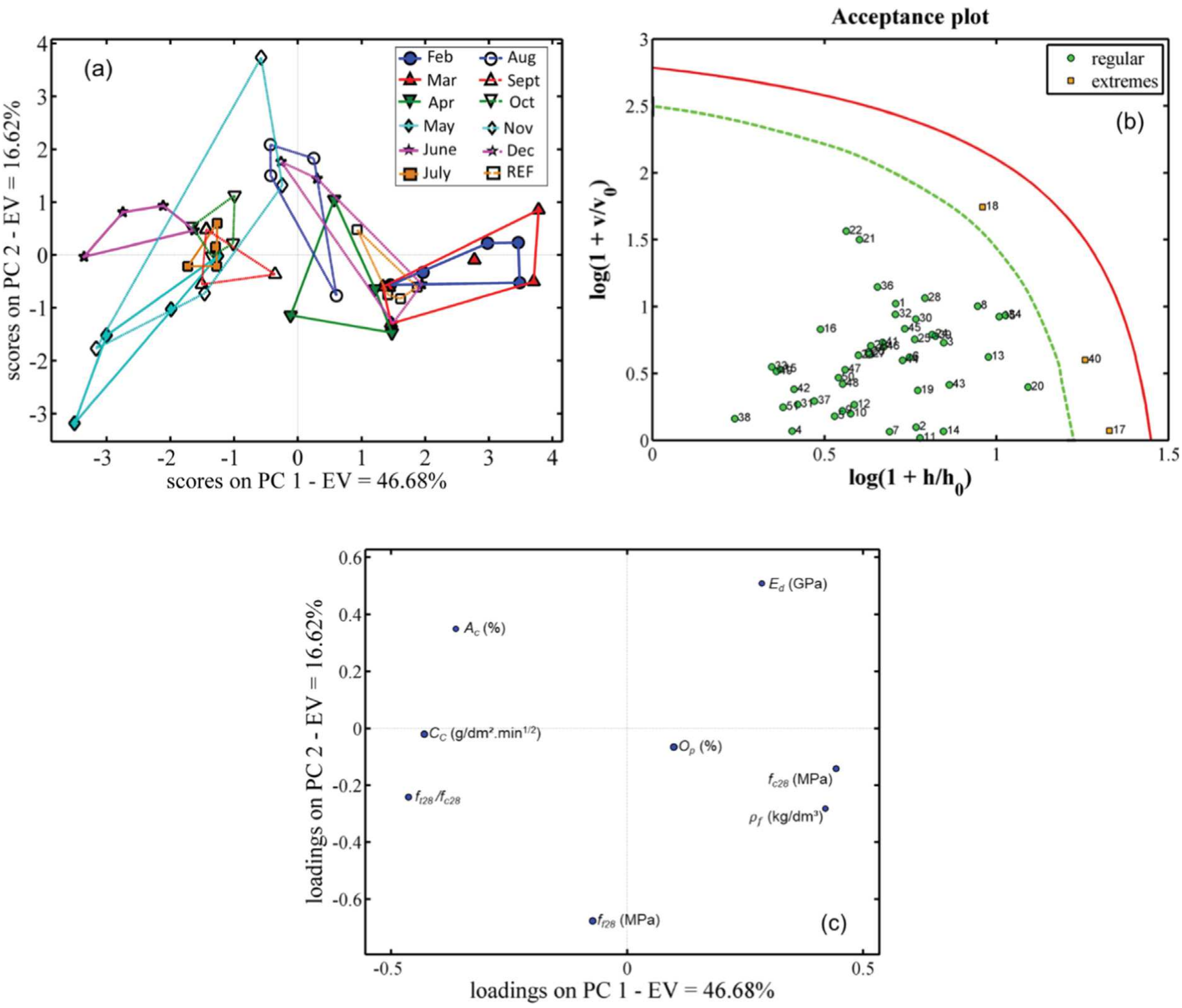

Fig. 10. (a) PC1 *versus* PC2 score ROBPCA plot, (b) PC1 *versus* PC2 loading ROBPCA plot (c) DD-SIMCA acceptance plot for all mechanical properties (fresh and hardened state) of the mortars.

and irregular shape of MRA, contributes to enhance the matrix-aggregate bond interface [33,37,42]; and, finally, (iv) the pozzolanic reactions between the various constituents of RA [13,43–45] and the carbonation of hydrated lime mortars produced with RA [12,21] may also justify the better performance presented.

These conclusions can be observed by analysing the results of each property individually. Some mortars with 100% MRA present better results than the reference mortar, so these properties were evaluated together using ROBPCA and DD-SIMCA. The results in Fig. 10a can be interpreted as for Figs. 5 and 6. They show that, taking into account all investigated properties (i.e. fresh and hardened state), all modified mortars presented similar results, even when compared with the reference mortar (samples #48, #49, #50 and #51, located between 1 and 2 in the PC1 scores) [46,47].

Although it was observed that in some months there was a greater dispersion of results (e.g. November), the analysis obtained by the DD-SIMCA method confirmed that all the analysed samples are similar (Fig. 10b), with 95% confidence. Only the modified samples produced in May and December presented values slightly higher than the mean value (#17, #18 and #40), which indicates that these samples present more extreme values for some properties (Table S3). However, these samples were not considered anomalous because they are within the outlier confidence region (99% of confidence) and, therefore, do not differ from each other and from the other analysed samples.

In the loadings graph (Fig. 10c), it is possible to perceive that the properties are distributed around the central region. Used together with the information from the scores, these results indicate that the properties vary in a non-biased way for the samples. It can be concluded that all the mortars produced (starting from different months and with the reference material) have similar physical and mechanical properties. By analysing the loadings graph, it is possible to identify that sample #17 has an E_d value lower than the mean of all mortars, sample 18 had an E_d value higher than the mean together with higher f_{t28} and f_{c28} values and sample #40 an air content value higher than the mean [46; 47]. This was evidenced when modelling only the hardened properties for 28 days.

4. Conclusions

The aim of this study was to evaluate the effects of the use of mixed recycled aggregates (MRA) obtained from construction and demolition waste (CDW) over time on the performance of rendering mortars. The following main conclusions can be drawn:

- The results from the first phase showed that there were no statistically significant differences in the physical properties of MRA collected over a year, which indicates an adequate reliability of the CDW used. Relative to NA, it was found that MRA presented a higher powder content (<0.075 mm) and higher porosity of the aggregates;
- From the volumetric ratios investigated in the second experimental phase, it was found that the M1 mortar at 1:1:6 (cement, hydrated-lime and MRA) showed higher adherence strength, lower capillary coefficient and less visible cracks. This was attributed to the lower water/cement ratio of M1. Therefore, M1 mortar was chosen to be produced with MRA collected over time. The results of the statistical analysis showed that at 91 days the mechanical strength presented greater dispersion and that there are no significant differences between the mean results obtained at 28 days, according to a 95% confidence T hypothesis test. In addition, the loading plot showed that, for all the properties analysed, mortar M1 is the one with the smallest dispersion of the results;
- In the third phase, the properties of the modified mortars produced with the M1 ratio and with MRA collected at different months were characterized in the fresh and hardened states. In the fresh state, the modified mortars (with 100% MRA) obtained lower bulk density and, in general, a lower incorporated air content. This is attributed to the lower apparent density of the MRA and the worse compaction effect of the fresh mortar. In the hardened state, different behaviours were observed. In general, there was also a reduction in physical and mechanical performance. However, in comparison with the mortar produced with 100% NA, the behaviour of modified mortars was better, mainly due to their higher compressive strength, higher flexural strength and lower capillarity coefficient. This is due to the filler effect provided by a greater amount of dust. These conclusions were drawn by analysing each property individually, but, taking into account the variation of all the properties together, no statistically significant differences were found both in the fresh and hardened states;

In conclusion, the results demonstrated that the feasibility of using MRA for the production of cementitious materials is strongly correlated to the quality control of CDW for the recycled aggregate production and to the proper mortar's volumetric ratio. The results found in this research encourage the use of alternative, low cost and low environmental impact materials and reduce the consumption of natural raw material.

CRediT authorship contribution statement

Ruan L. S. Ferreira: Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Marcos A. S. Anjos:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Cinthia Maia:** Supervision, Project administration. **Licarion Pinto:** Writing - original draft, Writing - review & editing, Supervision, Project administration. **Afonso R. G. Azevedo:** Writing - original draft, Writing - review & editing. **Jorge de Brito:** Writing - original draft, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2020.121796.

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COORDENAÇÃO DA ÁREA DE CONSTRUÇÃO CIVIL - CACC

DECLARAÇÃO

Declaro para comprovação junto ao IFPE que os professores citados na tabela abaixo, foram designados na continuidade emergencial da Portaria Nº 057/2014 – DGCP, visto uma demanda de caráter da PRODEN.

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Pesqueira, 13 de novembro de 2020.

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