Volume 12, Number 4 (August 2019) p. 790 – 811 • ISSN 1983-4195
http://dx.doi.org/10.1590/S1983-41952019000400005

IBRACON

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS
IBRACON STRUCTURES AND MATERIALS JOURNAL

Statistical analysis of mechanical properties of mortars with fly ash and waste tire rubber

Análise estatística de propriedades mecânicas de argamassas com cinza volante e resíduo de borracha de pneus





A. PCZIECZEK [a]
adriane_sbs@hotmail.com
https://orcid.org/0000-0003-1349-9480

C. EFFTING [a]
carmeane.effting@udesc.br
https://orcid.org/0000-0001-5457-5457

I. R. GOMES [a]
itamar.gomes@udesc.br
https://orcid.org/0000-0002-2663-9123

A. SCHACKOW [a]
adilson.schackow@udesc.br
https://orcid.org/0000-0003-2561-5231

E. HENNING [b]
elisa.henning@udesc.br
https://orcid.org/0000-0002-7754-9451

Abstract

This article aims to perform statistical analysis on the inclusion effects of waste tire rubber and fly ash from thermoelectric plants as mortar components for coating buildings. Reference mortars and mortars containing 5% and 10% rubber with a maximum grain size of 0.71 mm and mortars containing fly ash particles with a diameter of 45 µm were produced. Mortars containing rubber replaced 5% and 10% of the fine aggregate mass by this material and fly ash was added in 10% and 20% proportions compared to the cement volume. A 3^2 factorial experiment was performed on the mechanical properties of the compressive strength of mortars, applying analysis of variance (ANOVA) and surface response. The rubber waste material contributed to the decrease in compressive strength of the mortar and that factor displayed the highest significance in the response variable.

Keywords: coating mortar, waste tire rubber, fly ash, compressive strength, statistical analysis.

Resumo

Este artigo tem como objetivo efetuar a análise estatística dos efeitos da inclusão da borracha de pneus inservíveis e cinza volante oriunda de usinas termelétricas como componentes da argamassa para revestimento de edificações. Foram produzidas argamassas de referência e argamassas contendo borracha com dimensão máxima dos grãos de 0,71 mm e cinza volante com granulometria de 45 µm. As argamassas contendo borracha tiveram 5% e 10% da massa do agregado miúdo substituído por esse material e a cinza volante adicionada em proporções de 10% e 20% em relação ao volume de cimento. Foi realizado um projeto fatorial 3^2 para os resultados referentes à propriedade mecânica de resistência à compressão das argamassas, aplicando a análise da variância (ANOVA) e de superfície de resposta. O resíduo de borracha contribuiu para a diminuição da resistência à compressão das argamassas e foi o fator que apresentou maior significância na variável resposta.

Palavras-chave: argamassa de revestimento, resíduo de pneus, cinza volante, resistência mecânica à compressão, análise estatística.

[a] *Santa Catarina State University, Technology Science Center, Civil Engineering Department, Joinville, SC, Brazil;*
[b] *Santa Catarina State University, Technological Science Center, Mathematics Department, Joinville, SC, Brazil.*

Received: 06 Feb 2018 • Accepted: 08 Aug 2018 • Available Online: 08 Aug 2019

1. Introduction

The accumulation of solid wastes has been the subject of research on the exploitation of those wastes, as alternative materials, due to increasing urban development. The search for sustainability, besides being an environmental concern, is economic as well, providing the development of new technologies and financial savings. Regarding this aspect, civil construction is one of the sectors that have absorbed large quantities of solid recycled waste products as building components [1].

One of the great concerns of cities is inadequate disposal of useless tires, as they are non-biodegradable and products that remain for a long time. Besides that, when stored improperly, they serve as insect and rodent breeders. According to [2], there have been some alternative proposals for resolving the disposal problem of useless tires, as they can be used for making river embankments and sea breakwater worksites. Another manner for recycling waste tire rubber is by cutting or scraping them, as this reused material can be used in a great number of industest areas and in asphaltic pavements as bonding material for roadway purposes. Research studies have been done by [3] and [4] in the field of civil construction and they have shown the possibility of utilizing waste tire rubber in concrete applications, without any structural functionality, and display good thermal and acoustic performance. The effect of incorporating rubber powder in mortar for coating was confirmed by [5] and [6]; according to their performed research studies, mortar containing this waste rubber displays lower incidences of visible fissures and increases water absorption through capillarity. According to [7], using 30% proportions of recycled tire rubber to substitute sand in high-strength mortars contributed to decreasing traction strength in flexion and compression; the presence of irregular and spheroid pores in the morphology was verified.

On the other hand, the increasing usage of thermoelectric power plants and the consumption of coal as fuel have generated considerable amounts of waste products as light or fly ash and heavy or bottom ash. These wastes are formed due to incomplete combustion of coal [8]. High storage cost and concern for proper disposal of these waste products have encouraged the generation of alternative solutions in waste management in diverse applications, such as manufacturing pozzolanic cement, in concrete and mortar mixtures, as well as others [9].

There is great diversity in mineralogy of ashes, as this varies according to the composition of coal, calcination conditions, and storage environment. The surface of fly ash, variation of particle dimension, and morphology considerably affect the workability and speed in developing cement mass strength [10].

Research studies performed by [11], [12] and [13] have shown that fly ash features advantageous pozzolanic characteristics when added to cement, assuring increased compressive strength, impermeability, and durability of mortars and concrete structures, as well as economic and environmental advantages.

Therefore, the overall objective of this work consists in analyzing statistically the physical and mechanical properties on compressive strength results of mortars for coating walls, applying analysis of variance (ANOVA) and response surface methods. Mortars containing the addition of fly ash and waste tires rubber to partially substitute fine aggregate were produced. The effect of the presence of these two waste products in the same mortar was studied in this research, contrary to previous research studies, whereas analyses were performed using these waste products separately.

When one wishes to study the effect of the influence from two or more variables, in any given experiment, factorial planning is the most recommended technique. In each attempt or replica, all possible combinations of the levels from each variable are investigated. If the effect of a variable depends on the level from other variables, one can say there is interaction among them [14].

According to [15], analysis of variance, or ANOVA, consists in an adequate statistical procedure for the evaluation of quantitative

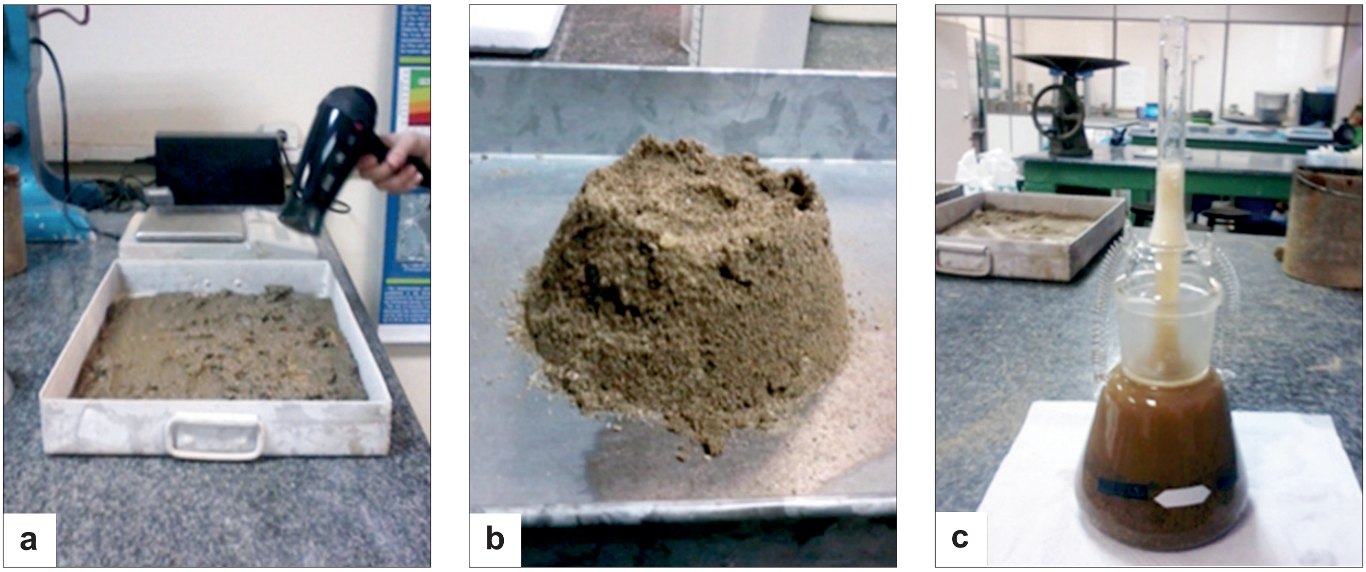


Figure 1
Test for determining the specific mass of the sand, (a) drying material by blowing air; (b) dry surface saturated condition; (c) calibrated flask with the sample after removing air bubbles

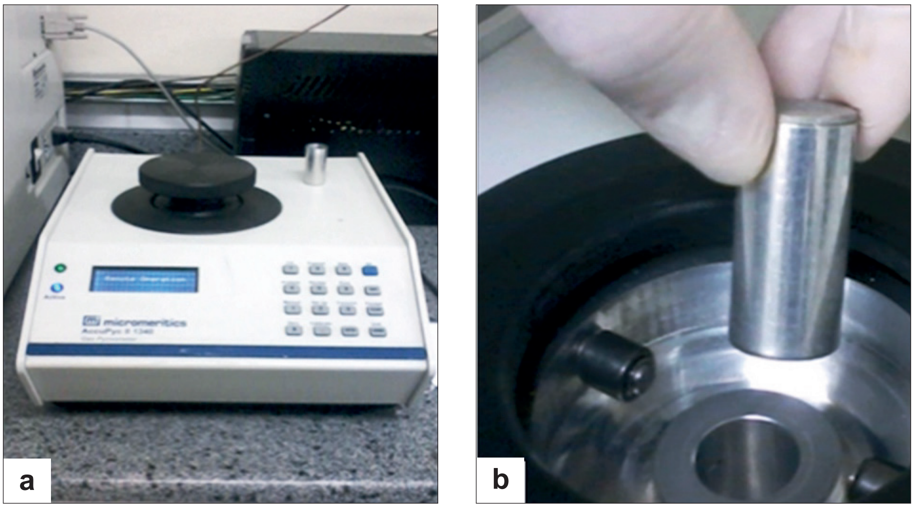


Figure 2
Helium gas pycnometer (a) equipment used; (b) sample chamber

answers in planned experiments. ANOVA is used for accepting or rejecting investigated hypotheses of an experiment, whereas the objective is to analyze the average variation of test results and identify what the factors are that really produce significant effects in the answers from any given experiment.
Linear regression analysis is also used a great deal in planned experiments including continuous level factors. In this case, analysis of variance is used to identify significant factors and, afterwards, regression analysis is used to construct a model incorporating these factors. Dual-level factorial planning, complete and fractional make it possible to estimate the main effects and interactions, while triple-level complete factorial designs make it possible to estimate the degree of curvature in a response variable [16].

Figure 3
Specimens for pozzolanic activity

2. Materials and experimental program

The following materials were used for preparing the mortars: fine washed river sand, Portland CP II Z-32 cement, CH-III type hydrated lime, and water supplied from the local concessionaire. The waste rubber was obtained from the rubber tires by shredding useless rubber tires. The fly ash consists of a waste product from thermoelectric power plants using coal as fuel. Initially, tests were performed containing ash before performing any grinding process. New mortars were produced and tests were performed containing ground fly ash in their compositions, whereas there was a ten-minute period for grinding in a ball mill.
The manufacturer supplied the physical characteristics of the Portland CP II Z-32 cement and the CH-III hydrated lime products. The Portland CP II Z-32 cement was chosen as it is commonly used in civil construction and as it provides diverse application possibilities. Although, this type of cement already contains 6 to 15% of pozzolan in its composition, the addition of fly ash was justified, as it is an abundant material in the state of Santa Catarina, especially due to the large-scale thermoelectric plant facilities in the southern region of the country.
The physical characteristics of the fine aggregate (Figure 1) were determined as stated in NBR NM 52 [17] and NBR NM 248 [18]. According to experimental tests, the fineness module of the fine aggregate was 2.09 in this research; the maximum diameter of grains was 2.36 mm, and a specific mass of 2.55 g/cm³. The maximum size of the waste rubber grains was 0.71 mm and specific mass of 1,1953 g/cm³. These values were determined through a sieve analysis test, utilizing a set of standard series of sieves and helium gas pycnometry (Figure 2). The fly ash, without performing any grinding process, presents as characteristic a specific mass of the 2.1680 g/cm³, 45 μm granulometry and a 75.2% pozzolan activity performance rate. The fly ash, after grinding, has a 77.6% pozzolan activity performance rate for ground ash, as stated in the recommendations of NBR 12653 [19], displayed in Figure 3. The fly ash, after grinding, displayed a 2.5% increase in the pozzolan

Table 1
Fresh-state mortar properties

Materials	Specific mass (g/cm³)	Unit mass	Maximum diameter of grains (mm)
Portland cement CP II Z-32	2.98	1.08	<0.074
Hydrated lime CH III	2.40	0.75	0.074
Ground aggregate	2.55	1.43	2.36
Rubber	1.19	0.36	0.71
Fly ash	2.17	0.90	0.045

activity index in the material. This increase occurred due to the decrease in the ash size as the specific surface area increased, making greater contact among the reactive elements of the mixture. The results from the test regarding the physical characteristics of the materials are found on Table 1.
The chemical composition of the waste products was analyzed using an Energy Dispersive Spectroscope (EDS). Points 1 and 2 are displayed in figures 4 and 5 that are selected for the application of EDS rubber and fly ash analyses and, in Tables 2 and 3 the semi-quantitative chemical analysis results on waste products are displayed. The analyzed points are obtained by EDS spectra in (Figure 4), it is possible to observe that the rubber is mainly composed of carbon (C), oxygen (O), zinc (Zn), sodium (Na) and sulphur (S). The fly ash (Figure 5) display the greatest concentrations of carbon (C), oxygen (O), silicon (Si) and chemical compounds of silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3) and lime (CaO) in its composition.
The reference mortar was produced using cement, lime, and sand in a 1:1:6 proportion (in volume). The mortars containing rubber

Table 2
Chemical composition of rubber

Chemicals	Mass concentration (%)
C	72.77
O	20.81
S	0.55
Zn	5.87

Table 3
Chemical composition of fly ash

Chemicals	Mass concentration (%)	Chemicals	Composition (%)
C	40.93	C	40.93
O	25.58	O	0.00
Mg	0.90	MgO	1.50
Al	5.50	Al_2O_3	10.39
Si	12.83	SiO_2	27.45
K	1.48	K_2O	1.78
Ca	10.42	CaO	14.58
Fe	2.35	Fe_2O_3	3.36

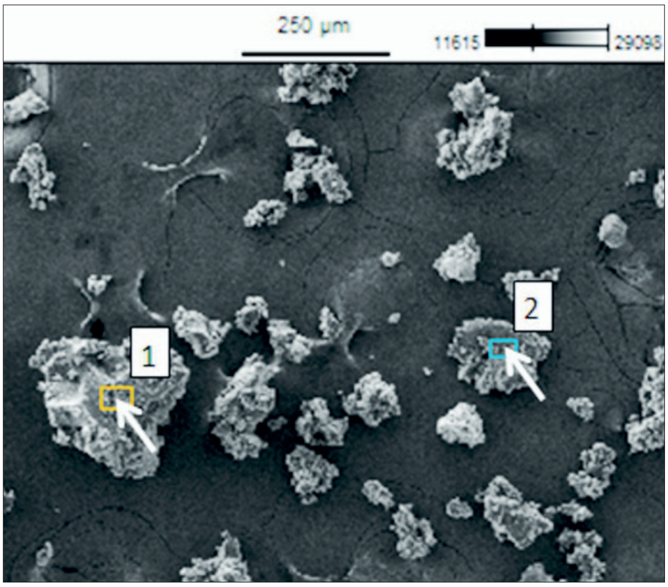


Figure 4
MEB image of the rubber powder and selected places for applying EDS

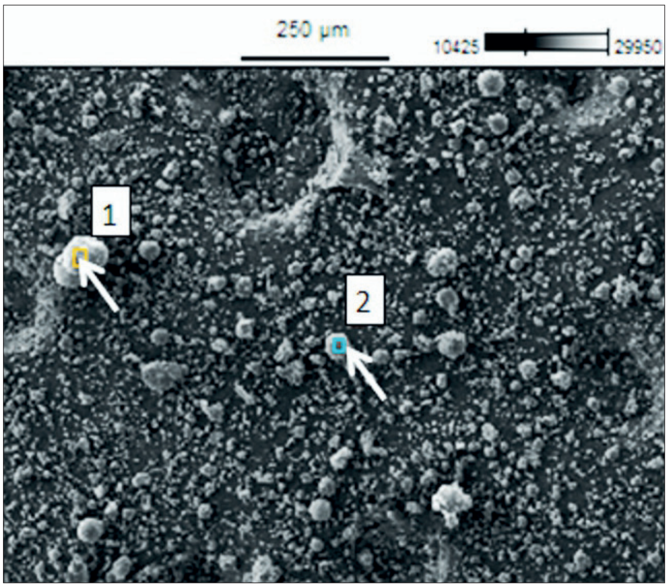


Figure 5
MEV image of fly ash and selected places for applying EDS

Table 4
Fresh-State mortar properties

Mixture	Mortar components (*) (g)						Consistency index (mm)
	Cement	Ash	Lime	Sand	Rubber	Water	
REF	720	–	496	5720	–	1468	253
B5	720	–	496	5434	71.6	1392	255
B10	720	–	496	5148	143.2	1320	250
C10	720	60	496	5720	–	1468	263
C10B5	720	60	496	5434	71.6	1392	258
C10B10	720	60	496	5148	143.2	1320	250
C20	720	120	496	5720	–	1480	257
C20B5	720	120	496	5434	71.6	1400	260
C20B10	720	120	496	5148	143.2	1340	251

Note: (*) For the preparation of the same volume of mortar (3.33 cm^3 or 12 specimens 40 x 40 x 160 mm)

had 5% and 10% of the fine aggregate mass substituted by waste rubber and, the mortars containing 10% and 20% fly ash were added to the mixture compared to the cement volume. The mortar compositions are displayed on Table 4, thus REF is the reference mortar. B5 and B10 contain 5% and 10% rubber in the Mortar. C10 and C20 contain 10% Ash in the Mortar and 20% Ash in the Mortar. C10B5 and C10B10 contain 10% Ash + 5% Rubber in the Mortar, and contain 10% Ash + 10% Rubber in the Mortar. C20B5 and C20B10 contain 20% Ash + 5% Rubber in the Mortar and 20% Ash + 10% Rubber in the Mortar. Mortars containing ground fly ash were produced using the same composition of mortar that obtained the best performance using two waste products in its composition. The consistency of mortars was evaluated as stated in NBR 13276 [20] that made it possible to characterize the conferred workability of each mixture and identify its adequacy for utilization as a coating. Water retention was also analyzed as stated in NBR 13277 [21], the specific mass, and incorporated air content in mortars as stated in NBR 13278 [22].
The compressive strength of the mortars was evaluated after 28 days of curing, in prismatic specimens measuring 40x40x160 mm, as stated in NBR 13279 [23].
The results were submitted to statistical tests to verify the influence from rubber and fly ash factors on compressive strength, using the STATISTICA 13.0 software program [24]. A complete 3^2 factorial experiment was performed for this study, using six replicas, considering the rubber and fly ash factors on three different levels for each factor, thereby resulting in a project including 54 experiments.
The analysis of variance (ANOVA) is a statistical test used for testing the equality of treatment effects, making it possible to identify if there is any significant difference among averages and if the factors (independent variables) exert any influence on the dependent variable [16]. The proposed factors can be quantitative or qualitative, which is the case in this research work. The variable answer must be a continual quantitative. It is necessary to verify one's assumptions to validate the conclusions inferring ANOVA, which means, the residuals from this model must be independent, with constant variance and normally distributed [16]. In this study, the Bartlett test was applied to analyze the variance homogeneity and a normal probability graph to verify the normality of residuals.
The magnitude of the differences among the averages was evaluated by performing a multiple comparison test, the Tukey Test. That test is necessary when there is a significant difference among averages, as it completes the ANOVA, comparing the results from all the average pairs. The Pareto charts and effects complement the analysis. These charts make it possible to visualize the magnitude and the importance of the effects. The contour plot, results from the application of the response surface methodology will aid in determining the factorial conditions (percentage of ashes and tires) to achieve an optimal value for the response variable (compressive strength).
A 5% (α) significance level was adopted for statistical analysis in all performed tests.

3. Results and discussions

The results on tests performed on fresh-state mortars are shown on Table 5. A specific mass reduction was verified as the quantity of rubber increased in the mortar. This fact is due to a low unit

Table 5
Mortar composition

Mortar	Water/ Cement ratio	Consistency index (mm)	Specific mass (g/cm^3)	Incorporated air content (%)	Water retention (%)
REF	2.04	253	1.995	2	80
B5	1.93	255	1.920	5	81
B10	1.83	250	1.805	10	82
C10	2.04	263	1.982	2	79
C10B5	1.93	258	1.879	7	82
C10B10	1.83	250	1.785	11	84
C20	2.06	257	2.008	1	82
C20B5	1.94	260	1.954	3	83
C20B10	1.86	251	1.859	10	85
CM20	2.05	265	1.993	1	80
CM20B5	1.94	262	1.920	5	81

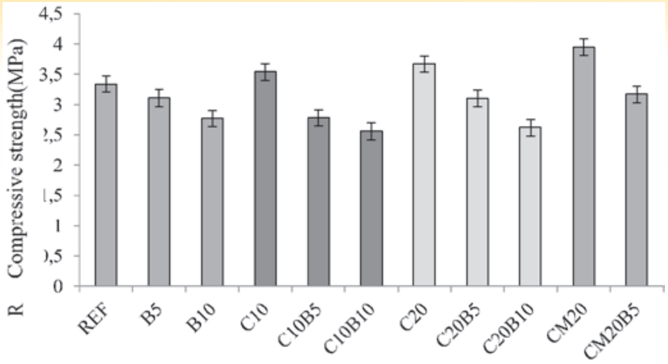


Figure 6
Average compressive strength of mortars

mass function and the specific mass of the waste products used. Mortars containing 10% of rubber exhibit increased incorporated air content, whose values do not exceed 11%, which also contributes to the workability of the mortar. Mortars containing lime must exhibit 14% maximum incorporated air content as stated in ASTM C 270 [25], if not, this can reduce the traction adherence strength in the substrate. The addition of rubber also contributed to increasing water retention in mortars, probably caused by the increase in the incorporated air concentration. Water retention in mortars must not be less than 75% as stated in ASTM C 270 [25], as accelerated loss of water reduces strength, adhesion, and the capability to absorb deformations, as well as decreased durability and impermeability of the mortar. Presently, all the mortars studied exhibited over 80% of water retention; this demonstrates that mortars containing rubber maintain their workability longer, when subject to influences that bring about water loss from mixing.

The average compressive strength of mortars after 28 days is displayed in Figure 6. The addition of 20% ground fly ash (CM20) proved to increase the average compressive strength after curing the mortar for 28 days, compared to the reference mortar that increased about 18%. Related to mortar containing 20% of unground fly ash (CM20) the average compressive strength increased about 7%. This proves that fly ash, when submitted to a grinding process, increases the pozzolanic activity of the material due to the increased specific surface area. Besides that, the grinding of the waste product did not change other mortar properties, such as water retention and incorporated air content.

The increase of the compressive strength in mortars containing fly ash can be linked to the pozzolanic activity of the ash,

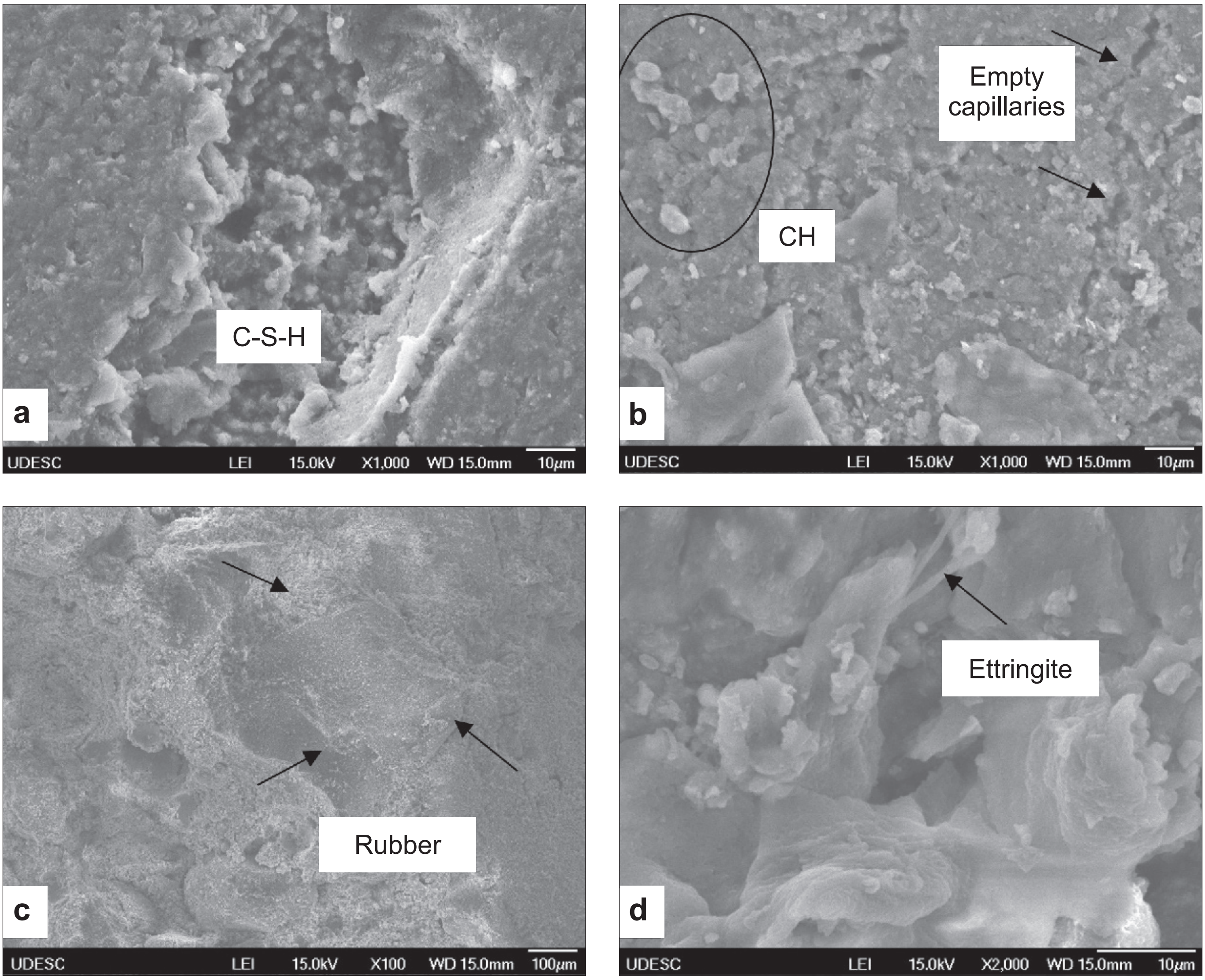
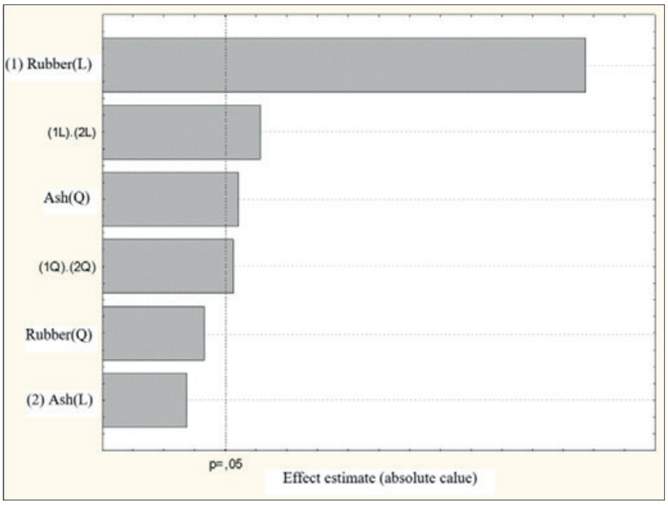


Figure 7
Mortar micrography, (a) formation of C-S-H, (c) formation of calcium hydroxide (CH), (c) rubber particles, (d) formation of late ettringite crystals (C_6ASH_{31})



Notes
Factor 1 – Rubber; Factor 2 – Ash; L – linear term: 1L (x_1) and 2L (x_2); Q – quadratic term: 1Q (x_1^2) and 2Q (x_2^2)

Figure 8
Pareto Chart for the rubber and fly ash effects

as this provides greater quantities of hydrated calcium silicates (C-S-H). These are the main responsible items for increasing compressive strength in concretes and mortars, contrary to the transition zone, whereas, there is the presence of ettringite (C_6ASH_{31}) calcium hydroxide (CH), as can be observed by the image obtained from the scanning electron microscope (SEM) in Figures 7 (a), (b), and (d). Yet in mortars containing rubber, they displayed decreased compressive strength. This reduction can be related to the increase in the incorporated air content in the fresh state and because the waste products displayed low specific mass, as this situation was also witnessed by [5] and [26]. Besides that, the decrease in compressive strength in mortars is related to the absence of adherence between the rubber and the cement paste matrix, as this can be observed in Figure 7 (c); this fact was also witnessed by [25].

ASTM C 270 [25] defines minimum strength ratings for some types of mortars. According to the standard, mortar strength must be over 2.40 MPa after 28 days. According to the obtained results, all the studied mortars exhibited values over 2.40 MPa, but the performance of the best mortar containing two waste products in its composition was the mortar with 20% ground ash + 5% rubber (CM20B5), exhibited average compressive strength of 3.17±0.25 MPa.

According to the defined experimental project, Table 6 displays the results on compressive strength of the studied mortars, including replicas of the mixtures containing varied concentrations of rubber and fly ash.

The effect of the rubber and fly ash factors on compressive strength was analyzed by means of a Pareto chart (Figure 8) and by the graph on main effects and interactions (Figures 9 and 10). The Pareto chart defines the magnitude and the importance of the effects, thus, rubber exhibits the most significant effect, as its value exceeds the reference line for the 5% significance level. Since the graph on main effects graphically displays the averages for each group, being that, the more the line is sloped, the greater the magnitude of the main effect is. Presently, the rubber displayed a greater effect on compressive strength compared to fly ash. The effect of interaction among

Table 6
Mixtures of 3² factorial project compressive strength of mortars

Mixture	Rubber (%)	Fly ash (%)	Replica	Compressive strength (MPa)	Mixture	Rubber (%)	Fly ash (%)	Replica	Compressive strength (MPa)	Mixture	Rubber (%)	Fly ash (%)	Replica	Compressive strength (MPa)
1	0	0	1	3.56±0.15	19	0	0	3	3.25±0.14	37	0	0	5	3.45±0.35
2	0	10	1	3.80±0.29	20	0	10	3	3.66±0.07	38	0	10	5	3.30±0.14
3	0	20	1	3.86±0.07	21	0	20	3	3.45±0.07	39	0	20	5	3.86±0.22
4	5	0	1	2.74±0.26	22	5	0	3	3.35±0.14	40	5	0	5	2.95±0.07
5	5	10	1	2.74±0.07	23	5	10	3	3.10±0.18	41	5	10	5	2.74±0.07
6	5	20	1	2.95±0.14	24	5	20	3	3.25±0.14	42	5	20	5	3.25±0.21
7	10	0	1	2.95±0.22	25	10	0	3	3.00±0.25	43	10	0	5	2.54±0.07
8	10	10	1	2.74±0.21	26	10	10	3	2.84±0.21	44	10	10	5	2.44±0.07
9	10	20	1	2.54±0.07	27	10	20	3	2.54±0.14	45	10	20	5	2.84±0.21
10	0	0	2	3.35±0.07	28	0	0	4	3.45±0.08	46	0	0	6	2.95±0.21
11	0	10	2	3.45±0.15	29	0	10	4	3.56±0.22	47	0	10	6	3.45±0.07
12	0	20	2	3.76±0.22	30	0	20	4	3.55±0.15	48	0	20	6	3.45±0.07
13	5	0	2	3.25±0.07	31	5	0	4	3.15±0.14	49	5	0	6	3.25±0.21
14	5	10	2	2.64±0.14	32	5	10	4	2.84±0.07	50	5	10	6	2.64±0.14
15	5	20	2	3.15±0.07	33	5	20	4	3.05±0.14	51	5	20	6	2.95±0.07
16	10	0	2	2.64±0.03	34	10	0	4	2.95±0.08	52	10	0	6	2.54±0.14
17	10	10	2	2.44±0.28	35	10	10	4	2.44±0.07	53	10	10	6	2.44±0.07
18	10	20	2	2.44±0.07	36	10	20	4	2.54±0.21	54	10	20	6	2.74±0.14

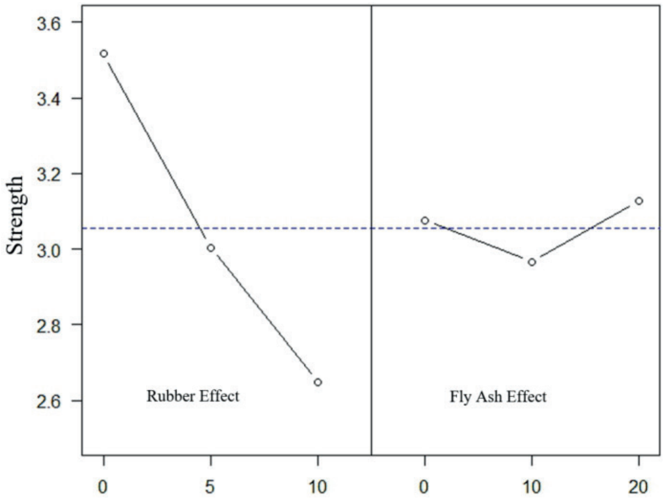


Figure 9
Graft of the main effects

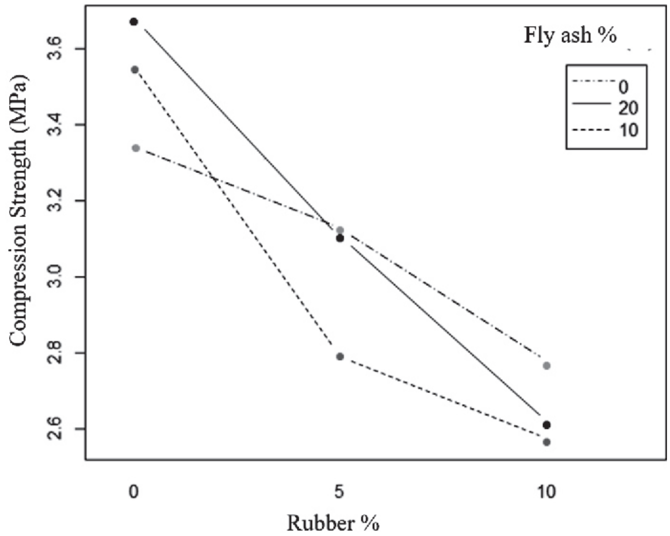


Figure 10
Graph on interaction effects

these factors is linked to the change in behavior of the rubber factor at different levels of the fly ash factor, proven by its effect on analyzed response variable.

The analysis of variance on compressive strength in factorial project mortars is displayed on Table 7. A 5% (α) significance level was adopted for statistical analysis in the hypothesis test, considering the null hypothesis for all response variable averages as being equal and for the alternative hypothesis considering that at least one of the factor level averages are different. Presently, the p-value < α to the null hypothesis must be rejected. It is also possible to determine which variables and what interaction among variables provide the greatest impact in strength variation through the "F Test", as the greater the value of this test is, the greater its significance is. Thus, the rubber and fly ash factors are significant. Rubber is the most effective in compressive strength in the studied mortars, as it exhibits a low p-value and the sum of the squared values is larger compared to other factors. The proportion of the variability of data is explained by the studied factors (rubber and fly ash) that was 0.81 (R^2), showing that the factors and their effects represent 81% of the variability of the measurements. The results show that the variability among replicas does not display any lack of adjustment considering the second order terms (quadratic function), as the p-value (0.346) > α (0.05), as this means the measurements are equal to the replicas.

Figure 11 exhibits the behavior of the residuals (the difference between the experimental values and those predicted by model) regarding distribution in normality and randomness. Presently, it is possible to confirm that the model is adequate for describing the behavior of compressive strength in mortars as a factor function in rubber and fly ash, as the residuals are approximately distributed along a straight line and randomly scattered.

According to the Bartlett test, errors due to the effects of rubber and fly ash factors exhibit constant variance. This specific test is characterized by the following hypotheses: the null hypothesis confirms that variances are constant and the alternative hypothesis confirms that variances do not display homogeneity. The p-value found (0.8115) for this test surpassed the 5% signifi-

Table 7
Analysis of variance on compressive strength of mortars

Factor	Squared sum	Freedom range	Squared average	F_0	F_c	p
Rubber (1L)	**6.7254**	**1**	**6.725378**	**188.5796**	4.06	**0.000000**
Rubber (1Q)	0.061633	1	0.061633	1.7282		0.195302
Ash (2L)	0.020069	1	0.020069	0.5627		0.457060
Ash (2Q)	**0.210675**	**1**	**0.210675**	**5.9073**		**0.019128**
(1L).(2L)	**0.350417**	**1**	**0.350417**	**9.8257**		**0.003028**
(1Q).(2Q)	**0.183750**	**1**	**0.183750**	**5.1524**		**0.028054**
Lack of adjustment	0.077511	2	0.038756	1.0867	3.20	0.346013
Pure error	1.604850	45	0.035663	–	–	–
Total	9.234283	53	–	–	–	–

Notes: L – Linear term: 1L (x_1) and 2L (x_2); Q – quadratic term: 1Q (x_1^2) and 2Q (x_2^2); F_0 – Calculated F; F_c – Critical F values for a 5% significance level obtained with the R software [29]. Statistically significant factors are shown in bold.

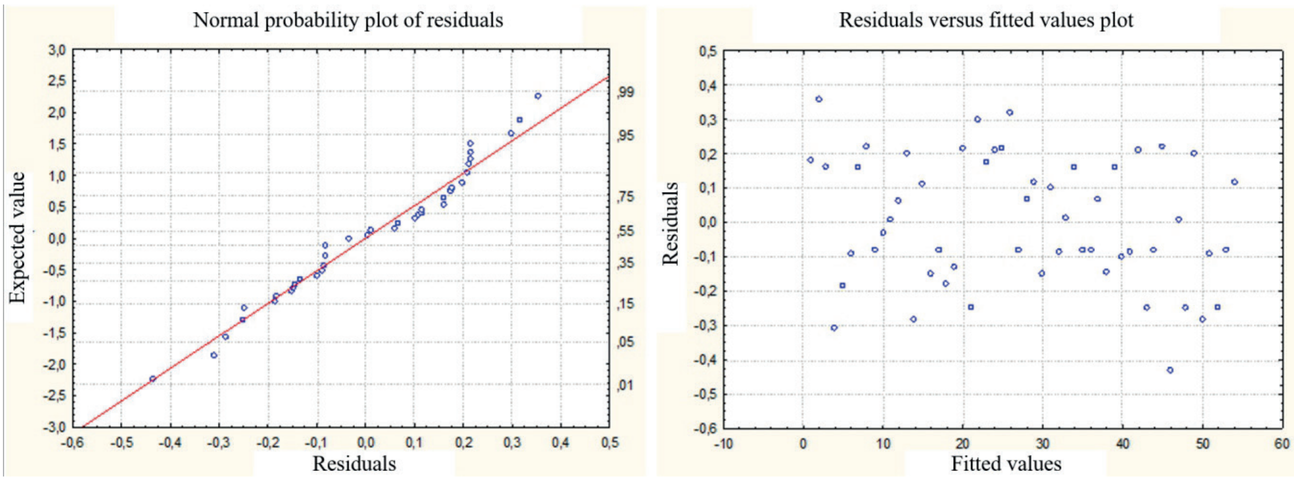


Figure 11
Normality and randomness of residuals charts

cance level; therefore, the supposition for homogeneity is valid. The magnitude of the differences among the averages was evaluated by the Tukey test. According to Table 8, it is possible to verify that the mortars containing only fly ash (Group a) are significantly different from the others, exhibiting higher averages in their compressive strength. The mortars containing 10% rubber (Group d) are considered as equal among one another; the same occurs in the mortar group containing 5% rubber (Group c).

A regression equation was obtained based on the measured results on the compressive strength of mortars to represent the factor effect (rubber and fly ash waste products) studied for this property. The final adjusted equation for compressive strength is expressed by Equation 1, whereas x_1 expresses the amount of the % of rubber in the mixture, x_2 the amount of the % of fly ash in the mixture, and Y the compressive strength of mortar in MPa.

$$Y = 3.340 - 0.0304x_1 + 0.0239x_2 - 0.0297x_1x_2 + 0.0013x_1x_1^2 \quad (1)$$

According to Equation 1, the rubber contributes to decreasing the compressive strength of mortars, while the fly ash factor contributes to increasing the value of this property.

The effect of the rubber and fly ash factors on compressive strength can also be analyzed using a contour graph, based on Eq. 1. It is possible to verify that the largest concentrations of rubber decrease compression strength as shown on Figure 12; however, fly ash contributes to increasing this property when added in largest amounts.

The results from this work agree with those found by [3] [5] and [26], that verify the reduction of compressive strength in mortars as the concentration of rubber increases, by applying other analysis approaches. Also according to research studies performed by [27] and [28], that revealed the presence of greater amounts of hydrated calcium silicate (C-S-H) in the cement paste matrix in composites containing fly ash, contrary to the transition zone, where there was the presence of ettringite and calcium hydroxide. They also abide by the results of [1]. In their work, the authors confirmed the addition of cementing components (cement, lime, and micro-silica) can explain the increased compressive strength, compensating for the decrease caused by the inclusion of waste rubber products. The decrease in compressive strength caused by the insertion of rubber was balanced by the presence of fly ash in this research work.

4. Conclusions

Table 8
Tukey test results for mortar compressive strength

Tukey group				Treatments		Averages
				Rubber (%)	Fly ash (%)	
a	–	–	–	0	20	3.66
a	–	–	–	0	10	3.54
a	b	–	–	0	0	3.34
–	b	c	–	5	0	3.11
–	b	c	–	5	20	3.10
–	–	c	d	5	10	2.78
–	–	c	d	10	0	2.76
–	–	–	d	10	20	2.61
–	–	–	d	10	10	2.56

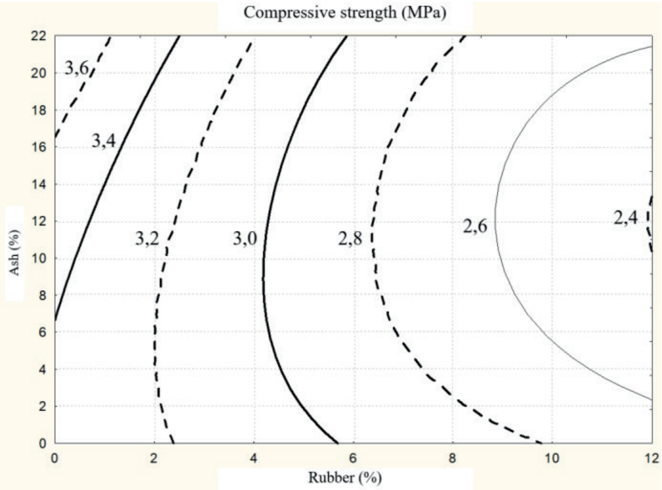


Figure 12
Contour plot on compressive strength in rubber and fly ash factor function

- The utilization of waste tire rubber to partially substitute fine aggregate and the addition of fly ash, originating from thermoelectric power plants, incorporated in coating mortar is a feasible alternative material for applications in civil construction;
- It was possible identify visually some rubber particles present in mortars, although in small amounts, and did not negatively affect the final aspect of the product;
- Compressive strength decreased as the rubber concentration increased in the mortar, especially because the waste rubber displayed little adhesion to the cement paste. However, the addition of ash in mortar increased compressive strength compared to the reference mortar, due to increased formation of hydrated calcium silicate (C-S-H);
- Fly ash, after grinding, displayed an increased rate of pozzolanic activity of the material. This increase occurred because of the decrease of ash particles that increased the specific surface area, making greater contact among the reactive elements of the mixture;
- Rubber as well as fly ash were verified as affecting the average compressive strength of mortars through statistical analysis, considering 5% as the significance level, although rubber is the factor that displayed a greater effect;
- The factorial project method made it possible to calculate a regression model, describing based on rubber and fly ash concentrations, compressive strength of mortars after 28 days of curing. Since, the contour graph made it possible to determine the necessary conditions for using the studied waste materials, in percentages to obtain an optimal value for compressive strength.

5. Acknowledgements

The authors wish to thank the Engisul Borrachas Ltda Company for supplying waste tire rubber and the Jorge Lacerda Thermoelectric Plant for supplying fly ash.

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