



ORIGINAL ARTICLE

Assessment of the impact of adding fly ash and coal bottom ash to an advanced cement-based composite matrix

Análise do impacto do uso de cinza volante e cinza pesada de carvão em matrizes de compósitos cimentícios avançados

Mariana Vieira^a 
 Guilherme Pereira^a 
 Fernanda Pacheco^b 
 Maria Luísa da Silva Marques^a 
 Roberto Christ^c 
 Regina Celia Espinosa Modolo^d 



^aUniversidade do Vale do Rio do Sinos – UNISINOS, Graduação em Engenharia Civil, São Leopoldo, RS, Brasil

^bUniversidade do Vale do Rio do Sinos – UNISINOS, Performance e Graduação em Engenharia Civil, São Leopoldo, RS, Brasil

^cUniversidad de La Costa, Departamento de Ingeniería Civil e Ambiental, Barranquilla, Colombia

^dUniversidade do Vale do Rio do Sinos – UNISINOS, Escola Politécnica, Programas de Pós-Graduação em Engenharia Civil e Engenharia Mecânica, São Leopoldo, RS, Brasil

Received 31 March 2021

Accepted 15 February 2022

Abstract: To reduce environmental impact and hydration heat from high cement consumption in advanced cement-based composites, this study proposes the partial cement substitution by fly ash (FA) and coal bottom ash (CBA) in rates of 15% by mass (7.5% FA and 7.5% CBA) and 30% by mass (15% FA and 15% CBA). Matrixes were assessed for their physical and mechanical characteristics through the tests of compressive strength, capillary water absorption and ultrasonic pulse velocity, added to the analysis of images generated by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). Results indicated better performance of fly ash due to its particle size, shape and texture, especially for the rate of 15%. In terms of compressive strength, mixture RFA15 yielded the highest strength. The capillary water absorption results were linear and with low variations of about 1% and 5% between 28 and 56 days.

Keywords: cement-based composites, fly ash, coal bottom ash.

Resumo: A fim de mitigar os impactos ambientais e o calor de hidratação do consumo elevado de cimento em compósitos cimentícios avançados, o presente estudo propõe a substituição parcial de cimento por cinzas volantes (CV) e cinzas pesadas de carvão mineral (CPC) nas proporções de 15% em massa (7,5% de CV e 7,5% de CPC) e 30% em massa (15% de CV e 15% de CPC). As matrizes foram avaliadas em relação às suas características físicas e mecânicas através dos ensaios de resistência mecânica à compressão, absorção de água por capilaridade, velocidade de propagação de ondas ultrassônicas, somados à análise de imagens geradas pela microscopia eletrônica de varredura (MEV) e ensaio de espectrometria por dispersão de energia de raios-x (EDS). Os resultados indicam um comportamento superior da cinza volante devido à sua granulometria, forma e textura, destacando-se o traço no teor de 15%. Em termos de resistência mecânica à compressão, o traço TCV15 apresentou maior resistência em relação aos outros traços. Quanto à absorção por capilaridade, verificou-se linearidade nos valores encontrados e pequenas variações na ordem de 1% a 5% entre 28 e 56 dias.

Palavras-chave: compósitos cimentícios, cinza volante, cinza pesada de carvão.

How to cite: M. Vieira, G. Pereira, F. Pacheco, M. L. S. Marques, R. Christ, and R. C. E. Modolo, "Assessment of the impact of adding fly ash and coal bottom ash to an advanced cement-based composite matrix," *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 5, e15506, 2022, <https://doi.org/10.1590/S1983-41952022000500006>

Corresponding author: Regina Célia Espinosa Modolo. E-mail: reginaem@unisinis.br

Financial support: The authors would like to thank Unisinos, Performance Technological Institute a(itt) and CNPq for the financial support granted to Regina Célia Espinosa Modolo with the Productivity Research Scholarship (Process 307755 / 2018-5).

Conflict of interest: Nothing to declare.

Data Availability: The data that support the findings of this study are available from the corresponding author, [FP], upon reasonable request.



This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1 INTRODUCTION

The properties of conventional concrete are widely known by the scientific community, as this material has an annual global production of about 12 billion cubic meters [1]. Modern concretes surpass the ones used a few decades ago, especially when comparing the mechanical strengths of each one, since concrete compressive strength is firmly connected to the particle-size distribution of the materials used in their making [2], which has considerably progressed in current mix design methods, including the use of software tools to define particle packing, for instance [3].

Concrete evolution was a result of the need for a high slenderness ratio for structural pieces of buildings due to the porosity of the outcoming material, increasing the chances of current structures having a shorter lifespan. Such scenario, added to the evolution of structural calculations, makes conventional concrete unable to meet the modern requirements for concrete, thereby demanding the use of concretes with higher performance, such as advanced cement-based composites [4]–[7]. The advances of admixtures, mineral additions and fiber reinforcements, along with execution techniques like curing at high temperatures and pressures, have allowed for higher load-bearing capacity and durability, except for minimized and safe structures [8]–[12]. These materials are called advanced cement-based composites [13]–[15].

Such materials are characterized by being made of particles with less than 2 mm of maximum diameter [16], basically fines (quartz sand, common cement, quartz powder and silica fume). They also have very high mechanical properties and durability. Owing to the lower water-cement ratio and the use of very fine aggregates, the composite attains excellent compactness and particle packing [17], [18]. Packing, in turn, is directly connected to the performance of the matrix, so it is essential to study the particles, their shape, dimension and distribution. Many studies used this variable as the most relevant, seeking to optimize mix ratios and improve mechanical properties [19]–[22].

According to Deboucha et al. [23]–[26], cement content can be reduced by up to 30% by mass by replacing it with another material with pozzolanic reaction, resulting in higher or equivalent compressive strength when compared to the reference mixture. This behavior can be explained by the reaction of cement with the pozzolanic material, i.e., it reacts with the C-H in the cement matrix and transforms into C-S-H, a component that is responsible for the strength of the concrete being developed [27]–[31].

Based on these facts, this study focuses on the partial replacement of cement for fly ash and coal bottom ash, to reduce its environmental impact. For that purpose, the properties of compressive strength and particle-size distribution of fly ash and coal bottom ash were assessed, along with the reduction in the water absorption of concrete. Thus, the analysis relied on the SEM and EDS techniques.

2 CEMENT-BASED COMPOSITES AND THE USE OF ASHES

Advanced cement-based composites are an evolution of high-performance concrete (HPC) called ultra-high performance concrete (UHPC). It consists of a concrete with no coarse aggregate, replaced by very fine particles with reduced size [32], [33], requiring a higher amount of mineral additions in its composition, in addition to a packing between particle sizes [34]. This particle packing is a key factor for the characteristics of concrete density and porosity. Packing is optimized with the use of submicron particles that widen the size range of the particles, resulting, though discontinuous particle-size distribution, in an efficient filling of the porosity of the cement particle packing [35]. Furthermore, the reduced water content in the mixture favors this higher compactness.

Maximum aggregate size is directly related to the performance of the material, which improves as size decreases [36]. According to Mehta and Monteiro [27], this relation occurs because the greater the maximum aggregate size, the smaller its surface area per unit of volume covered by cement paste. The reduced area brings about weak links that have little cohesion and tend to produce microcracks in the interfacial transition zone [37].

Apart from the packing, Hiremath and Yaragal [38] observed that an optimized mix method and a significant mixing speed and duration lead to the formation of a dense microstructure and a strong interfacial transition zone between the fine aggregate and the cement paste.

With the combustion of coal at high temperatures of approximately 1300°C in an oxidizing medium, two types of ash are formed, namely bottom ash and fly ash [39]. As per Calvanese et al. [40] and Singh and Siddique [41], by pulverizing coal in boilers, approximately 80% remains unburned, and the ashes from the burning process, recovered by filters from the exhaust and gas ducts, make up fly ash. The remaining 20% are characterized as bottom ash.

Many studies have already demonstrated that adding coal ashes to advanced cement-based composites decreases cement content, increases compressive strength and workability, decreases porosity and consequently increases the durability of the composite, and so on [42].

According to Isaia et al. [43], each type and mixture of pozzolanic materials act differently depending on the fineness, the chemical and/or physical activity and the amount added to the mixture, given the interaction with the paste.

The binary mixture, that is, one with two pozzolans in the composite, causes hybrid and synergistic effect between hydration and pozzolanic reactions, along with physical effects of obstruction and refinement of pores due to the presence of smaller particles.

Coal ash is waste derived from inorganic and organic matter during the incineration and combustion of coal. The main composition of the ashes from power plants consists of crystalline, vitreous and organic matter [44]. Osterreicher-Cunha et al. [45] stress that fly ash, in physical terms, is normally characterized by its silty particle size, with particle specific gravity varying between 2050 kg/m³ and 2200 kg/m³.

Fly ash has been broadly used as a supplementary cementation material in technological concretes as it contributes to the workability of fresh concrete and the formation of the microstructure, as well as mechanical properties and long-term durability. The proportion of fly ash in binding agents is usually adapted to different engineering applications and curing conditions [46].

According to Lenormand et al. [47], the durability and environmental efficiency of pozzolanic materials derived from coal incineration are one of the most decisive points regarding their use as construction materials. Both fly ash and bottom ash can reduce hydration heat and autogenous shrinkage of high-strength concrete, in addition to providing more workability and viscosity to the fresh mixture. The size of fly ash particles is usually within the same range as that of cement [48].

When pozzolanic materials are used, the most important effects on the microstructure of the cement paste are the changes in pore structure, which comprises the reduction of particle size caused by pozzolanic reactions, and the obstruction of pores and voids by the action of finer particles, hence improving the density of the composite. The pozzolanic effect is maximized in binary mixtures [49], i.e., a mixture made with two materials, as is the case in this study, cement and fly ash.

Using a binary mixture may also allow for a benefic effect of pore refinement, generating greater resistance to chlorate mitigation and to concrete corrosion, thus increasing overall durability. Such pore refinement leads directly to a reduction in capillary water absorption, which takes place because of size, distribution, shape, tortuosity and continuity of their pores [50].

It is believed that composites with ternary mixtures can be optimized so that the synergistic effect lets the components compensate for their mutual defects, meaning that individual properties are improved. Results showed that using ternary mixtures improves compressive strength and flexural strength overall. Durability is also improved, along with the resistance to sulfate, acid and chloride ion penetration [51].

Studies have revealed that synergetic action in a ternary mixture greatly improves fresh concrete workability and produces a more uniform mixture, a denser microstructure and grants better performance to hardened concrete [52].

Thus, this research aims to present the analyze of the impact of fly ash and coal bottom ash addition on the properties of ultra-high-performance concrete, considering mechanical and physical properties.

3 EXPERIMENTAL PROCEDURES

3.1 Materials

The materials used to craft the advanced cement-based composite were: Brazilian type CPV-ARI cement, quartz dust, sand and fly ash and coal bottom ash as a partial substitute for cement. These materials presented the particle-size distribution of Figure 1, along with the characteristic diameters of Table 1. In addition to laser particle size to characterize FA and CBA, the technologies of scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used as well. The sand used has specific weight of 2623,4 kg/m³ and its particle size distribution is presented in Figure 2.

Table 1 - Particle size distribution

Material	Size (µm)			Maximum particle size
	D10	D50	D90	
Type V Portland cement	3.67	11.89	21.77	12.02
Quartz dust	3.24	21.44	46.21	21.98
Fly ash	2.09	5.19	14.41	6.56
Coal bottom ash	14.68	49.17	103.5	52.63

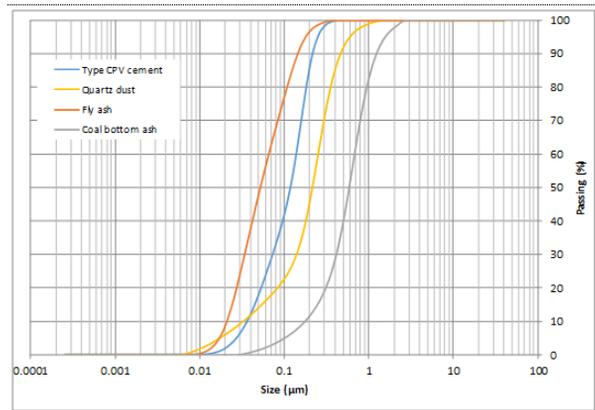


Figure 1. Particle-size distribution

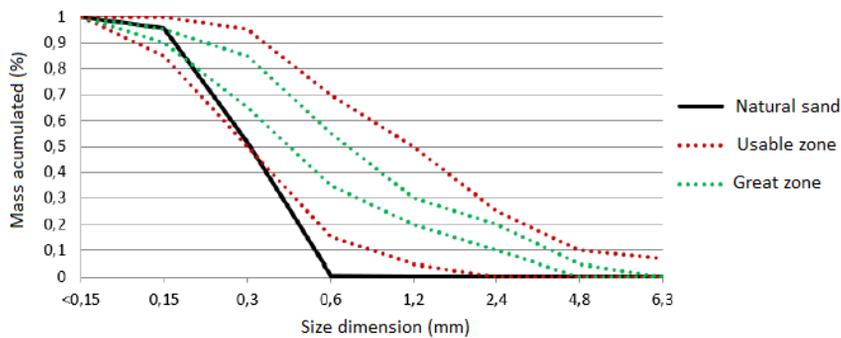


Figure 2. Sand Particle-size distribution

Regarding the materials particle size distribution is important to notice that Li et al. [53] uses ashes with D50 between 15,94 and 22,05 and in this study, the range is between 5,19 and 49,17, due to fly ash, as expected. Is also important to notice that the difference between coal bottom ash and cement are higher than with the use of fly ash, which has similar values to the cement in all characteristic diameters.

3.2 Methods

The mix ratios used in this experimental program are presented in Table 2. After determining the reference ratio, the partial replacement by mass of cement by fly ash (FA) and coal bottom ash (CBA) was carried out. The materials were mixed in a dual speed mortar mixer. The materials were added in the same order as in Christ [3]. After mixing, the samples were cured under standard conditions according to NBR 5738:2015 [54] until the testing age. The relation water/cement was 0,3 for all mixtures. The materials order in mixture was cement and FA or CBA, sand, superplasticizer and quartz dust.

Table 2 - Mix ratios developed according to their mass

Mixtures	Cement	Sand	Quartz dust	Fly ash	Bottom ash
RR Reference mix ratio	1.00	1.78	1.11	-	-
RFA15 Mix ratio replacing cement by 15% FA	0,85	1.78	1.11	0.13	-
RFA30 Mix ratio replacing cement by 30% FA	0,70	1.78	1.11	0.31	-
RFA7.5BA7.5 Mix ratio replacing cement by 7.5 FA and 7.5 CBA	0,85	1.78	1.11	0.06	0.07
RFA15BA15 Mix ratio replacing cement by 15% FA and 15% CBA	0,70	1.78	1.11	0.15	0.16

The samples were cured in humidity chamber until the age of the tests.

3.3 Characterization Parameters

The tests performed during this experimental program are described as follows, along with their respective standards.

a) Characterization of Ashes – Scanning Electron Microscopy (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDS)

To perform the SEM analysis, the sample was previously dried in an oven for approximately 24 hours at a temperature of 45°C. Magnifications of 1000 and 5000 times were used for the analysis. The EDS test, which aims to characterize materials in indicative terms of chemical composition, was performed on each ash. The determination of the percentages of each constituting element of the ashes relied on the mean of the results obtained from eight different observation points.

b) Ultrasonic Pulse Velocity

The ultrasonic pulse velocity test abided by NBR 8802:2013 [55], searching for a quality indicator for the different concretes (density, void presence). For this test, specimens of 50 mm x 100 mm were analyzed at 7, 28 and 56 days of curing, three specimens per mix ratio developed, which were the same ones used for the compressive strength test. During the test, a thin layer of solid petroleum jelly was added to the surface of the transmitter and receiver device to ensure the perfect coupling between the magnetic wave devices and the specimens. The direct method was used with devices on opposite longitudinal faces.

c) Axial Compressive Strength

The compressive strength test was performed as per NBR 5739:2007 [56]. Cylindrical specimens with dimensions of 500 mm x 100 mm were molded and then fractured at 7, 28 and 56 days, considering three specimens per mixing ratio developed, at each age.

d) Capillary Water Absorption

The test for determination of capillary water absorption was performed according to RILEM TC 116-PCD [57]. In this test, specimens with diameter of 50 mm and thickness of 50 mm were used, which were the lower half of cylindrical specimens with dimensions of 50 mm x 100 mm. The analyses took place at 28 and 56 days of curing, considering three specimens per mix ratio developed. The samples had to be dried in an oven at 100°C until constant mass was obtained, which was measured by weighing twice a day. Next, the specimens were wrapped with a balloon on the top face and with tape on the sides, promoting the impermeability of concrete on the external faces, and a 3-mm water layer was maintained on the bottom face. The weighing was done at 10 min, 1h, 4h and 24h.

4 RESULTS AND DISCUSSIONS

4.1 Scanning Electron Microscopy (SEM)

The SEM images are presented in Figures 3 and 4, considering magnifications of 1000 times (a) and 5000 times (b) respectively.

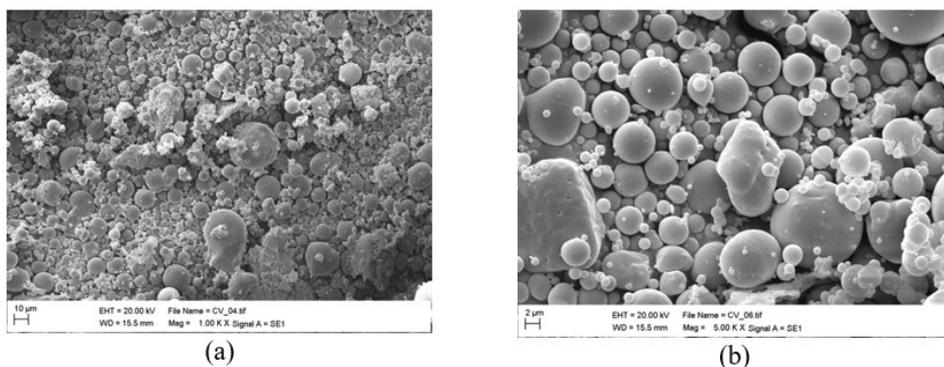


Figure 3 – Shape of the fly ash used in this study, assessed by scanning electron microscopy

In Figure 3, most of the fly ash grains were uniformly distributed, spherical and with regular shape. Furthermore, in Figure 2(a), the dimension of some spherical grains varied between 0.67 and 44.56 μm , with average diameter of 7.61 μm between measured particles, which was close the characteristic average diameter of 6.56 μm obtained in the laser particle size test. Kutchko and Kim [58] found average particle size varying between 16 and 64 μm , bearing in

mind that bigger particles usually correspond to higher unburned carbon concentrations. Rafieizonooz et al. [59] reported the spherical and regular shape of fly ash, which presented smaller particles than the coal bottom ash, also assessed by these authors. Coal bottom ash had an irregular shape with apparent grain porosity.

Figure 4 depicts the irregular shape with porous and rough texture of coal bottom ash. In Figure 4(a), the dimension of some grains varied from 3.67 to 89.59 μm , with average diameter of 42.16 between measured particles, which is somewhat different from the characteristic average diameter of 56.62 μm obtained in the laser particle size test. Such difference is understandable, because in SEM only a small portion of grains gets identified, while the particle-size test uses broader sampling. Thus, the values obtained comply with the particle-size distribution.

Concerning Rafieizonooz et al. [59], the ashes in this study turned out to be physically compatible with their result, seeing that they reported porosity and irregular shape of coal bottom ash grains. As per Mangulkar and Jamkar [60], it is very important to not only observe the size of the particles but also the predominance of their shape. From the ashes assessment, it was noted that FA had less laminar particles, what can favor particle packing.

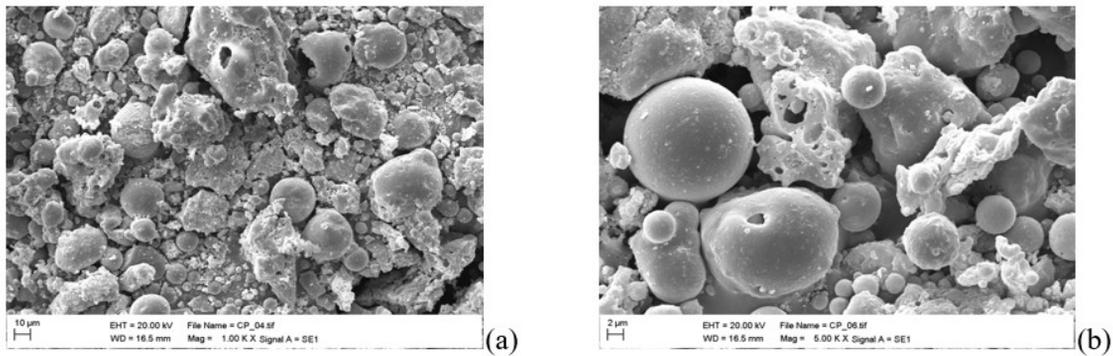


Figure 4 – Shape of the coal bottom ash used in this study, assessed by scanning electron microscopy

4.2. Energy-Dispersive X-Ray Spectroscopy (EDS)

Analyzing the EDS test results (Table 3 and Table 4), the elements in greater proportion in the composition of fly ash were, on average, silicon (53.75%), aluminum (25.85%), calcium (18.21%) and iron (4.67%), along with lower amounts of potassium and titanium.

Table 3 - Chemical composition of fly ash obtained by EDS

Fly ash chemical composition (%)							
Spectrum	Al (Al ₂ O ₃)	Si (SiO ₂)	Fe (Fe ₂ O ₃)	K (K ₂ O)	Ti (TiO ₂)	Ca (CaO)	Na (Na ₂ O)
Sum spectrum	27.68	57.90	4.60	2.78	1.64	5.40	-
Spectrum 2	20.35	61.29	5.08	3.89	2.98	6.41	-
Spectrum 3	4.05	5.20	-	-	-	90.74	-
Spectrum 4	20.65	73.84	1.10	2.41	0.63	0.74	0.63
Spectrum 5	36.67	54.51	4.36	1.97	-	2.49	-
Spectrum 6	28.30	52.24	8.98	3.77	3.24	3.47	-
Spectrum 7	36.84	57.29	3.89	1.98	-	-	-
Spectrum 8	32.24	67.76	-	-	-	-	-

Table 4 – Chemical composition of coal bottom ash obtained by EDS

Coal bottom ash composition (%)							
Spectrum	Al (Al ₂ O ₃)	Si (SiO ₂)	Fe (Fe ₂ O ₃)	K (K ₂ O)	Ti (TiO ₂)	Ca (CaO)	
Sum spectrum	25.52	56.94	11.34	2.30	1.31	2.59	
Spectrum 2	40.77	54.47	4.75	-	-	-	
Spectrum 3	36.11	53.63	5.27	4.99	-	-	
Spectrum 4	17.60	74.85	4.02	3.53	-	-	
Spectrum 5	29.52	61.45	3.94	3.47	1.61	-	
Spectrum 6	29.53	35.51	34.96	-	-	-	
Spectrum 7	39.76	56.98	3.26	-	-	-	
Spectrum 8	30.18	57.19	5.54	3.22	2.38	1.49	

Still on the topic of chemical composition, the fly ash used in this study had a total percentage of SiO₂, Al₂O₃ and Fe₂O₃ equals to 84.27%. As described in ASTM C618-15 [61], the percentage sum of these elements falls into category C or F if above 50% and, above 70%, into class N, which require other variables for classification, such as loss on ignition (LOI), as it represents the mass of moisture and volatile materials in a sample. The chemical analysis performed by Rafeizonooz et al. [59] indicated that the fly ash used was composed mostly of silica, iron and alumina, and the percentage sum of SiO₂, Al₂O₃ and Fe₂O₃ was about 78.82%, therefore making it a class F ash according to ASTM C618-15 [61].

Regarding the EDS test results for coal bottom ash, the elements that make up most of this waste were, on average, silicon (56.38%), aluminum (31.12%) and iron (9.13%), along with small amounts of potassium, titanium and calcium. The percentage sum of SiO₂, Al₂O₃ and Fe₂O₃ of the ash used in this study was equals to 96.63%. Nonetheless, the limits of ASTM C618-15 [61] apply to fly ash and natural pozzolans only.

The chemical analysis of coal bottom ash performed by Rafeizonooz et al. [59] revealed that it was composed mostly of silica, iron and alumina, with small amounts of sulfate, magnesium and calcium. The percentage sum of SiO₂, Al₂O₃ and Fe₂O₃ was equals to 83.24% in their study. It should be noted that the chemical characterization values obtained are based on a semi-quantitative technique, which explains the great variation from the energy-dispersive X-ray test and the reduced reliability [62].

4.3. Compressive Strength

The compressive strength tests were carried out at 7, 28 and 58 days of specimen curing, and the average test results were summarized in Table 5. Three samples were tested for each trace, and the result presented is the medium. Figure 5 allows a comparison between the average strength of each mixture at each testing age.

Table 5- Compressive strength test results

Mixture	7 days (MPa)	28 days (MPa)	56 days (MPa)
RR	70.5	75.3	64.8
RFA15	43.8	70.5	83
RFA30	49.6	59.4	74.8
RFA7.5BA7.5	57.1	68.9	62.2
RFA15BA15	40.4	31	48

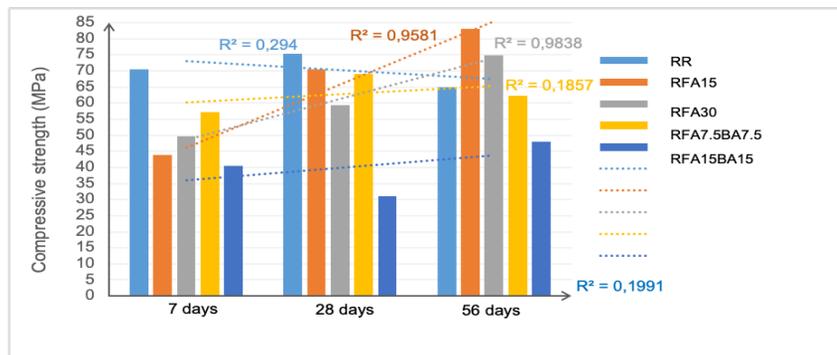


Figure 5 – Compressive strength test results

From these tests, it was concluded that the binary mixture with 15% fly ash (RFA15) yielded higher 28-day strength than the binary mixture with 30% fly ash (RFA30) and the other ternary mixtures, and its strength was just 6.8% lower than that of the reference mixture (RR). Mixture RFA15 presented the highest 56-day strength, which was approximately 28% higher than that of RR.

Among the ternary mixtures, the one with lower pozzolanic replacement content yielded the best compressive strength, what may be caused by the particle size distribution and format. Moreover, mixtures RR, RFA7.5BA7.5 and RFA15BA15 did not achieve the linearity that was expected of them, seeing that RR and RFA7.5BA7.5 demonstrated lower values at 28 days and RFA15BA15 at 56 days, what can be noted by curves and correlation coefficients.

Mixture RR achieved the best compressive performance at 7 and 28 days, but due to the pozzolanic activity that occurs at more advanced ages, mixture RFA15 had a very similar performance at 28 days and superior at 56 days of curing. Mixture RFA30 presented an increase of approximately 16% compared to RR at 56 days.

Some results still produced great variability. It was related to the susceptibility of reactive powder concrete to the procedures of mixing, molding and curing, during which any variation can generate significant changes in the results.

Lawrence et al. [63] stated that finer dusts tend to yield better cement hydration, although some dusts reduce the hydration rate, what can lead to a delay in configuration and then affect the development of short-term compressive strength, an effect that is especially linked to fly ashes and silica fume. According to Mehta and Monteiro [27] apud Duarte et al. [64], the reduction of compressive strength owing to the increased rate of substitution of cement by ashes is a result of the generation of low-density secondary hydration products, mostly calcium silicates formed from the reaction of calcium hydroxide with ash particles. Calcium silicates Hydrated calcium silicates are also cement hydration products, although they have high density.

Such delay can be observed in the results since the compressive strength reached values that are lower than the usual for reactive powder concretes, indicating that the ashes used changed the setting time of the composite [6].

Kreuz [65] reported that compressive strength decreases as the rate of substitution of cement by bottom ash increases, though there were cases with 10% of substitution in which the strength remained equals to or even greater than the reference mixture.

The reduction in the value of strength of the reference concrete to 56 days, and the 28 days of the RFA15BA15 was also observed. This variation may result from the molding and sample-making processes, or from the greater heterogeneity that is expected when concretes with a higher strength class are developed [66], [67].

Still related to the results and with the characterization of pozzolans, it is worth pointing out that, according to Lee et al. [68] smaller particles tend to have greater efficiency in the development of resistance resulting from the generation of secondary products.

4.4. Ultrasonic Pulse Velocity

According to IS 13311-92 [69], which regards the classification of the quality of concrete with respect to the ultrasonic pulse velocity, all mixing ratios analyzed at 7, 28 and 56 days fit the maximum quality class, graded as excellent (Figure 6). The reference mixture RR yielded the highest ultrasonic pulse velocity at all testing ages, despite not presenting a linear behavior.

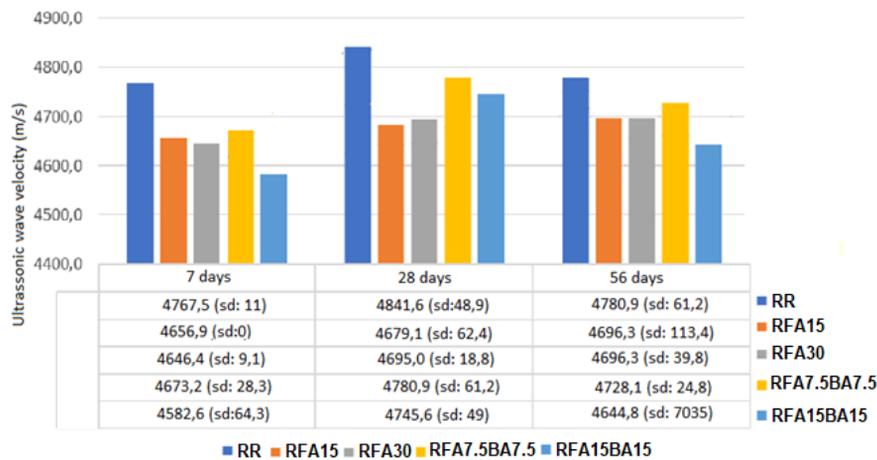


Figure 6 – Ultrasonic pulse velocity test results

The assessment at 7 days of curing revealed no linearity between the values of the ternary mixtures RFA7.BA7.5 and RFA15BA15, but the binary mixtures RFA15 and RFA30 displayed a difference of less than 1% in the results. Mixtures RFA15 and RFA30 remained close and only mixture RFA15BA15 was different from the others, and mixture RFA7.5BA7.5 presented the highest ultrasonic wave velocity after RR. In the next assessment, at 28 days of curing, both binary and ternary mixtures obtained linear results compared to each other. However, the value of mixture RFA15BA15 was 3.5% higher than that of 7 days. At 56 days of curing, the results were like those from the 7 days of curing, considering the proportioning between the mixtures, and in both ages the lowest result was obtained in mixtures with 30% of pozzolanic materials in agreement with other studies [66], [70]

Therefore, all mixtures, except for the binary ones, reached higher ultrasonic pulse velocities at 28 days of curing, compared to 7 and 56 days of curing, and the result at 56 days was higher than that at 7 days, except for mixture RR.

The decrease of permeable pore space in ash concrete mixtures results in higher ultrasonic pulse velocities. The values from this test indicate the quality of the mixture in terms of density, homogeneity and uniformity [41] [58]. Yujing et al. [71] pointed that UPHC with pozzolanic materials promotes a pore medium size reduction, and thus, the material is denser than conventional concretes and UPHC with lower pozzolanic materials content.

Finally, the ultrasonic pulse test results were not linear, considering that only RFA15 presented progressive results, and RFA30 remained the same at 28 and 56 days.

Analyzing the results obtained for compressive strength and propagation velocity of ultrasonic waves comparatively, it is worth noting that the expectation brought by Godinho et al. [72] was not verified, since an equivalent relationship between the variables was not perceived. While in the compressive strength the sample with the best performance at 56 days was the RFA15, in the ultrasonic speed there was a superiority of the reference sample.

4.5. Capillary Water Absorption

The capillary water absorption test results show that all mixtures presented slight variations between 28 and 56 days, except for mixture RFA30, which at 56 days presented an increase of 32% in absorption at the end of 24 hours, as observed in Figures 7 and 8.

Moreover, the resulting values had great variation, most likely due to the presence of voids in the materials. Capillary pores are reduced by the formation of secondary C-S-H gel from the pozzolanic reaction, therefore reducing concrete capillary water absorption [50].

The results obtained in 28 and 56 days are very similar. Probably, due to the type of cement applied, which has hydration and strength development occurring in first ages. However, it may be pointed out that the mixtures with the use of pozzolanic materials has reached almost the same values of reference mixture at the age of 56 days, showing its contribution for the mixture [73].

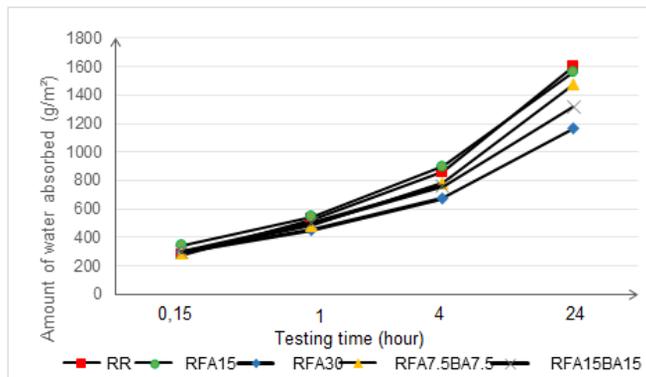


Figure 7 – 28-day capillary water absorption test results

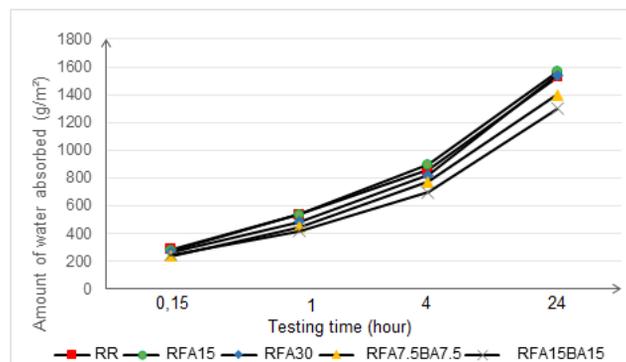


Figure 8 – 56-day capillary water absorption test results

5 CONCLUSIONS

From the ashes assessment, it was noted that fly ash presented better results in the tests of compressive strength and capillary water absorption, which can be linked to particle size, shape, texture and pozzolanic activity. Chemically, both coal ashes were similar as the fly ash contained silicon, aluminum, calcium and iron, in addition to small amounts of potassium, titanium and sodium, whereas the bottom ash contained silicon, aluminum and iron along with small amounts of potassium, titanium and calcium.

Regarding the test mixtures, the binary mixture with 15% fly ash performed better, considering that its results maintained linearity and progression in the tests of compressive strength and ultrasonic pulse velocity. As for the capillary water absorption test, the results were identical between the samples analyzed. The binary mixture with 30% fly ash was also efficient as it performed better than the reference concrete. There seems to be a need for in-depth analysis of the interaction between ashes, especially due to the nonuniform particle size of coal bottom ash.

Considering the results obtained through this study, the authors recommend that future studies may evaluate different proportions between coal and bottom ash, considering the satisfactory behavior obtained by the tests of ultrasonic velocity and compressive strength.

ACKNOWLEDGEMENTS

The authors would like to thank Unisinos, Performance Technological Institute (itt) and CNPq for the financial support granted to Regina Célia Espinosa Modolo with the Productivity Research Scholarship (Process 307755 / 2018-5).

REFERENCES

- [1] S. Sangadji et al., "The use of alkaliphilic bacteria-based repair solution for porous network concrete healing mechanism," *Procedia Eng.*, vol. 171, pp. 606–613, 2017, <http://dx.doi.org/10.1016/j.proeng.2017.01.387>.
- [2] C. Shi et al., "A review on mixture design methods for self-compacting concrete," *Constr. Build. Mater.*, vol. 84, pp. 387–398, Jun 2017, <http://dx.doi.org/10.1016/j.conbuildmat.2015.03.079>.
- [3] R. Christ "Desenvolvimento de compósitos cimentícios avançados à base de pós-reativos com misturas híbridas de fibras e reduzido impacto Ambiental," M.S. Thesis, Civil Engineering, Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, RS, Brazil, 2014.
- [4] A. N. Mohameed et al., "Improving the engineering and fluid transport properties of ultra-high strength concrete utilizing ultrafine palm oil fuel ash," *J. Adv. Concr. Technol.*, vol. 12, pp. 127–137, Apr 2014, <http://dx.doi.org/10.3151/jact.12.127>.
- [5] I. S. Agwa et al., "Effects of using rice straw and cotton stalk ashes on the properties of lightweight self-compacting concrete," *Constr. Build. Mater.*, vol. 235, pp. 1–12, 2020, <http://dx.doi.org/10.1016/j.conbuildmat.2019.117541>.
- [6] A. M. Zeyad et al., "Workability, setting time and strength of high-strength concrete containing high volume of palm oil fuel ash," *Open Civ. Eng. J.*, vol. 12, pp. 35–46, 2018, <http://dx.doi.org/10.2174/1874149501812010035>.
- [7] A. M. Zeyad, A. F. Khan, and B. A. Tayeh, "Durability and strength characteristics of high-strength concrete incorporated with volcanic pumice powder and polypropylene fibers," *J. Mater. Res. Technol.*, vol. 9, no. 1, pp. 806–818, Jan 2020., <http://dx.doi.org/10.1016/j.jmrt.2019.11.021>.
- [8] B. F. Tutikian, G. C. Isaia, and P. Helene "Concreto de alto e ultra-alto desempenho concreto: ciência e tecnologia," in *CONCRETO: Ciência e Tecnologia*, G. C. Isaia, Ed. São Paulo, Brazil: IBRACON: 2011, ch. 36, vol. 2.
- [9] D. M. Al Saffar, A. K. L. Al Saad and B. A. Tayeh. "Effect of internal curing on behavior of high performance concrete: an overview," *Case stud. construction mater.*, vol. 10, pp. e00229, 2019.
- [10] A. M. Zeyad et al., "The effect of steam curing regimes on the chloride resistance and pore size of high-strength green concrete," *Constr. Build. Mater.*, vol. 280, pp. 1–20, Apr 2021., <http://dx.doi.org/10.1016/j.conbuildmat.2021.122409>.
- [11] A. M. Zeyad et al., "Influence of steam curing regimes on the properties of ultrafine POFA based high strength green concrete," *J. Build. Eng.*, vol. 38, pp. 1–21, Jun 2021., <http://dx.doi.org/10.1016/j.job.2021.102204>.
- [12] J. H. Haido et al., "Effect of high temperature on the mechanical properties of basalt fibre self-compacting concrete as an overlay material," *Constr. Build. Mater.*, vol. 268, pp. 1–19, 2021, <http://dx.doi.org/10.1016/j.conbuildmat.2020.121725>.
- [13] A. Bahari et al., "Experimental studies on rheological, mechanical, and microstructure properties of self-compacting concrete containing perovskite nanomaterial," *Struct. Concr.*, 2021, <http://dx.doi.org/10.1002/suco.202000548>.
- [14] A. S. Nik et al., "Nanostructural properties of cement – matrix composite," *J. Basic Appl. Sci. Res.*, vol. 11, pp. 2167–2173, 2011.
- [15] M. Askarian et al., "A comprehensive experimental study on the performance of pumice powder in self-compacting concrete (SCC)," *J. Sustain. Cement-Based Mater.*, vol. 7, no. 6, pp. 340–356, 2018.
- [16] N. A. Soliman and A. Tagnit-Hamou, "Development of ultra-high-performance concrete using glass powder – Towards ecofriendly concrete," *Constr. Build. Mater.*, vol. 125, pp. 600–612, Oct 2016., <http://dx.doi.org/10.1016/j.conbuildmat.2016.08.073>.

- [17] P. Richard and M. Cheyrez, "Composition of reactive powder concrete," *Cement Concr. Res.*, vol. 25, no. 7, pp. 1501–1511, Oct 1995., [http://dx.doi.org/10.1016/0008-8846\(95\)00144-2](http://dx.doi.org/10.1016/0008-8846(95)00144-2).
- [18] J. O. Lerch et al., "The effect of mixing on the performance of macro synthetic fibre reinforced concrete," *Cement Concr. Res.*, vol. 103, pp. 130–139, Jan 2018., <http://dx.doi.org/10.1016/j.cemconres.2017.10.010>.
- [19] E. Fehling, M. Schmidt, and S. Stuerwald, "Ultra-high performance concrete (UHPC)," in *Proc. 2nd Int. Symp. UHPC*, Kassel, Germany, 3-5 March 2008, pp.902–910.
- [20] E. Fehling, J. Schmidt, and J. Walraven, *Ultra-high Performance Concrete UHPC*. Berlin, Germany: Ernst and Sohn GmbH and Co. KG, 2014.
- [21] F. Toutlemonde and J. Replendino, *Designing and Building with UHPFRC*. Hoboken, NJ: John Wiley & Sons, Inc., 2013, 814 p.
- [22] S. A. Yildizel, B. A. Tayeh, and G. Calis, "Experimental and modelling study of mixture design optimisation of glass fibre-reinforced concrete with combined utilisation of Taguchi and Extreme Vertices Design Techniques," *J. Mater. Res. Technol.*, vol. 9, no. 2, pp. 2093–2106, 2020.
- [23] W. Deboucha et al., "Effect of incorporating blast furnace slag and natural pozzolana on compressive strength and capillary water absorption of concrete," *Procedia Eng.*, vol. 108, pp. 254–261, 2015, <http://dx.doi.org/10.1016/j.proeng.2015.06.145>.
- [24] B. A. Tayeh, "Effects of marble, timber and glass powder as partial replacements for cement," *J. Civil Eng. Construction*. vol. 7, no. 2, pp. 63-71, 2018.
- [25] M. Amin, B. A. Tayeh, and I. S. Agwa, "Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete," *J. Clean. Prod.*, vol. 273, 2020, <http://dx.doi.org/10.1016/j.jclepro.2020.123073>.
- [26] A. M. Zeyad et al., "Ultrafine palm oil fuel ash: from an agro-industry by-product into a highly efficient mineral admixture for high strength green concrete," *J. Eng. Appl. Sci. (Asian Res. Publ. Netw.)*, vol. 12, no. 7, 2017., <http://dx.doi.org/10.3923/jeasci.2017.8187.8196>.
- [27] P. K. Mehta and P. J. M. Monteiro, *Concreto, Estrutura, Propriedade e Materiais*. São Paulo: PINI, 1994. 573 p.
- [28] T. A. Tawfik et al., "Exploitation of the nanowaste ceramic incorporated with nano silica to improve concrete properties," *J. King Saud Univ. Eng. Sci.*, vol. 33, no. 8, pp. 581–588, 2020.
- [29] B. A. Tayeh et al., "Durability and mechanical properties of seashell partially-replaced cement," *J. Build. Eng.*, vol. 31, pp. 1–10, Sep 2020., <http://dx.doi.org/10.1016/j.jobte.2020.101328>.
- [30] B. A. Tayeh et al., "Sulphate resistance of cement mortar contains glass powder. *Journal of King Saud University -*," *Eng. Sci.*, vol. 32, no. 8, pp. 495–500, Dec 2020., <http://dx.doi.org/10.1016/j.jksues.2019.07.002>.
- [31] A. B. Tayeh, "Effect of incorporating pottery and bottom ash as partial replacement of cement," *Karbala Int. J. Mod. Sci.*, vol. 5, no. 4, pp. 270–279, 2019.
- [32] B. A. Tayeh et al. "Properties of ultra-high-performance fiber-reinforced concrete (UHPFRC): a review paper," in *AIP Conf. Proc.*, 2019, vol. 2157, no. 1, pp. 020040.
- [33] N. K. Baharuddin et al., "Potential use of ultra high-performance fibre-reinforced concrete as a repair material for fire-damaged concrete in terms of bond strength," *Int. J. Integr. Eng.*, vol. 12, no. 9, pp. 87–95, 2020.
- [34] E. C. Torregrosa, Dosage optimization and bolted connections for UHPFRC ties, Ph.D. dissertation, Polytechnic University of Valencia, Valencia, Spain, 2013.
- [35] O. Bonneau et al., "Characterization of the granular packing and percolation threshold of reactive powder concrete," *Cement Concr. Res.*, vol. 30, no. 12, pp. 1861–1867, 2000., [http://dx.doi.org/10.1016/S0008-8846\(00\)00300-8](http://dx.doi.org/10.1016/S0008-8846(00)00300-8).
- [36] B. F. Tutikian and P. Helene, "Dosagem dos concretos de Cimento Portland," in *Concreto: Ciência e Tecnologia*, G. C. Isaia, Ed. São Paulo: IBRACON, 2011. pp. 415–451. Vol. 1.
- [37] B. A. Tayeh, B. A. Bakar, and M. M. Johari, "Mechanical properties of old concrete —UHPFC interface," in *3rd Int. Conf. Concrete Repair, Rehabilitation and Retrofitting*, Cape Town, South Africa, 3-5 Sept. 2012, pp. 373.
- [38] P. N. Hiremath and S. C. Yaragal, "Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete," *Constr. Build. Mater.*, vol. 141, pp. 271–288, Jun 2017.
- [39] S. Sabedot et al. "Caracterização e aproveitamento de cinzas da combustão de carvão mineral geradas em usinas termelétricas," in: *III Congresso Brasileiro de Carvão Mineral*. Gramado, RS, 2011.
- [40] D. Calvanese, M. Lenzerini, and D. Nardi, "Description logics for conceptual data modeling," in *Logics for Databases and Information Systems*, Chomicki, J., & Saake, G., Eds., Norwell, MA, USA: Kluwer Academic Publisher, 1998, pp. 229–263.
- [41] M. Singh and R. Siddique, "Properties of concrete containing high volumes of coal bottom ash as fine aggregate," *J. Clean. Prod.*, vol. 91, pp. 269–278, Mar 2015, <http://dx.doi.org/10.1016/j.jclepro.2014.12.026>.
- [42] E. Baitem et al., "Physical and transfer properties of mortar containing coal bottom ash aggregates from Tefereyre (Niger)," *Constr. Build. Mater.*, vol. 125, pp. 919–926, Oct 2016, <http://dx.doi.org/10.1016/j.conbuildmat.2016.08.117>.
- [43] G. C. Isaia, P. Furquim, and A. L. G. Gastaldini, "A statistical approach of binary and ternary concrete mixtures with mineral additions," *Constr. Build. Mater.*, vol. 36, pp. 597–603, Nov 2012, <http://dx.doi.org/10.1016/j.conbuildmat.2012.06.026>.

- [44] G. Liu et al., "Petrological and mineralogical characterizations and chemical composition of coal ashes from power plants in Yanzhou mining district, China," *Fuel Process. Technol.*, vol. 85, no. 15, pp. 1635–1646, Sep 2004, <http://dx.doi.org/10.1016/j.fuproc.2003.10.028>.
- [45] P. Osterreicher-Cunha, A. F. B. Fernando, and M. D. T. Casagrande, "Effects of coal ash application on the microbial population of a tropical soil," in *Biomicroworld IV: Int. Conf.on Environmental*. Torremolinos, Spain, 14–16th September, 2011
- [46] Q. Zeng et al., "Determination of cement hydration and pozzolanic reaction extents for fly-ash cement pastes," *Constr. Build. Mater.*, vol. 27, no. 1, pp. 560–569, Feb 2012, <http://dx.doi.org/10.1016/j.conbuildmat.2011.07.007>.
- [47] T. Lenormand et al., "Incorporation of treated municipal solid waste incineration electrostatic precipitator fly ash as partial replacement of Portland cement: Effect on early age behaviour and mechanical properties," *Constr. Build. Mater.*, vol. 96, pp. 256–269, Oct 2015, <http://dx.doi.org/10.1016/j.conbuildmat.2015.07.171>.
- [48] H. Kim, "Utilization of sieved and ground coal bottom ash powders as a coarse binder in high-strength mortar to improve workability," *Constr. Build. Mater.*, vol. 91, pp. 57–64, Aug 2015, <http://dx.doi.org/10.1016/j.conbuildmat.2015.05.017>.
- [49] G. C. Isaia, A. L. G. Gastaldini, and R. Moraes, "Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete," *Cement Concr. Compos.*, vol. 25, no. 1, pp. 69–76, Jan 2003.
- [50] K. Celik et al., "High-volume natural volcanic pozzolan and limestone powder as partial replacements for Portland cement in self-compacting and sustainable concrete," *Cement Concr. Compos.*, vol. 45, pp. 136–147, Jan 2014., <http://dx.doi.org/10.1016/j.cemconcomp.2013.09.003>.
- [51] M. Ghrici, S. Kenai, and M. Said-Mansour. "Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements," *Cement Concr. Compos.*, vol. 29, no. 7, pp. 542–549, Aug 2007., <http://dx.doi.org/10.1016/j.cemconcomp.2007.04.009>.
- [52] S. Sujjavanich et al., "Synergistic effect of metakaolin and fly ash on properties of concrete," *Constr. Build. Mater.*, vol. 155, pp. 830–837, Nov 2017., <http://dx.doi.org/10.1016/j.conbuildmat.2017.08.072>.
- [53] X. Li et al., "Utilization of municipal solid waste incineration bottom ash in cellular concrete," *Constr. Build. Mater.*, vol. 178, pp. 175–182, 2018., <http://dx.doi.org/10.1016/j.conbuildmat.2018.05.147>.
- [54] Associação Brasileira de Normas Técnicas, *Concreto – Procedimento para moldagem e cura de corpos de prova*, ABNT NBR 5738, 2015.
- [55] Associação Brasileira de Normas Técnicas, *Concreto endurecido – Determinação da velocidade de propagação de onda ultrassônica*, ABNT NBR 8802, 2013.
- [56] Associação Brasileira de Normas Técnicas, *Concreto – Ensaio de compressão de corpos-de-prova cilíndricos*, ABNT NBR 5739, 2007.
- [57] RILEM TC 116-PCD. "Permeability of concrete as a criterion of its durability," *Mater. Struct.*, vol. 32, pp. 163–173, 1999.
- [58] B. G. Kutchlo and A. G. Kim. "Fly ash characterization by SEM–EDS," *Fuel*, vol. 85, no. 17, pp. 2537–2544, Dec 2006, <http://dx.doi.org/10.1016/j.fuel.2006.05.016>.
- [59] M. Rafieizonooz et al., "Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement," *Constr. Build. Mater.*, vol. 116, pp. 15–24, Jul 2016, <http://dx.doi.org/10.1016/j.conbuildmat.2016.04.080>.
- [60] M. N. Mangulkar and S. S. Jamkar, "Review of particle packing theories used for concrete mix proportioning," *Int. J. Engine Res.*, vol. 4, no. 5, pp. 143–148, May 2013.
- [61] American Society for testing and materials, *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*, ASTM C 618-15, 2015.
- [62] A. H. Batista et al., "Identification of heavy metals in crystals of sand and silt fractions of soils by scanning electron microscopy (SEM EDS/WD-EPMA)," *Rev. Bras. Ciênc. Solo*, vol. 42, pp. e0170174, 2018, <http://dx.doi.org/10.1590/18069657rbcs20170174>.
- [63] P. Lawrence, M. Cyr, and E. Ringot. "Mineral admixtures in mortars: Effect of inert materials on short-term hydration," *Cement Concr. Res.*, vol. 33, pp. 1939–1947, 2003, [http://dx.doi.org/10.1016/S0008-8846\(03\)00183-2](http://dx.doi.org/10.1016/S0008-8846(03)00183-2).
- [64] D. Duarte, F. Pelisser, and M. Peterson, "Propriedades do concreto com adição de cinza volante e cinza pesada," in *1º Congresso Internacional de Tecnologias para o Meio Ambiente*. Bento Gonçalves, Brazil, 2008.
- [65] A. L. Kreuz, Utilização de cinzas pesadas de termelétricas na substituição de cimento e areia na confecção de concretos, M.S. thesis, Federal University of Santa Catarina, Florianópolis, Brazil, 2002.
- [66] K. Ragalwar et al., "Significance of the particle size distribution modulus for strain-hardening-ultra-high performance concrete (SH-UHPC) matrix design," *Constr. Build. Mater.*, vol. 234, pp. 117423, 2020., <http://dx.doi.org/10.1016/j.conbuildmat.2019.117423>.
- [67] Y. Shi et al., "Design and preparation of ultra-high performance concrete with low environmental impact," *J. Clean. Prod.*, vol. 214, pp. 633–643, 2019., <http://dx.doi.org/10.1016/j.jclepro.2018.12.318>.
- [68] N. K. Lee et al., "Uncovering the role of micro silica in hydration of ultra-high performance concrete (UHPC)," *Cement Concr. Res.*, vol. 104, pp. 68–79, 2018.
- [69] Bureau of Indian Standards, *Method of Non-destructive testing of concrete - Part 1: Ultrasonic pulse velocity*, BIS IS 13311-1, 1992.
- [70] D. Qian et al., "A novel development of green ultra-high performance concrete (UHPC) based on appropriate application of recycled cementitious material," *J. Clean. Prod.*, vol. 261, pp. 121231, 2020, <http://dx.doi.org/10.1016/j.jclepro.2020.121231>.

- [71] L. Yuing et al., “Static mechanical properties and mechanism of C200 ultra-high performance concrete (UHPC) containing coarse aggregates,” *Sci. Eng. Compos. Mater.*, vol. 27, no. 1, pp. 186–195, 2020, <http://dx.doi.org/10.1515/secm-2020-0018>.
- [72] J. P. Godinho et al., “Factors influencing ultrasonic pulse velocity in concrete,” *Rev. IBRACON Estrut. Mater.*, vol. 13, pp. 222–247, Mar-Apr 2020.
- [73] R. Palod, S. V. Deo, and G. D. Ramtekkar, “Sustainable approach for linz-donawitz slag waste as a replacement of cement in concrete: mechanical, microstructural, and durability properties,” *Adv. Civ. Eng.*, vol. 2020, pp. 5691261, 2020.

Author contributions: MV: experimental procedure, materials characterization; GP: experimental procedure, materials characterization; FP: supervision, writing, revising; MLSM: writing, data curation; RC: supervision, revising; RCEM: supervision, revising, formal analysis, submission.

Editors: Edna Possan, Guilherme Aris Parsekian.