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Factor Analysis of the Physical–Mechanical Properties for Geopolymers Based on Brick Dust and Biomass Bottom Ash as Eco-Friendly Building Materials

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Abstract: The production of building materials is unavoidable if the well-being and development of society are to be maintained. However, in manufacturing these materials, significant greenhouse gas emissions and environmental effects are produced. For this reason, and with the aim of reducing the impact of the manufacture of these materials, this work developed a geopolymeric material made up solely of wastes, brick dust and biomass bottom ashes which replaced the traditional ceramic materials. To evaluate the quality of this sustainable geopolymeric material, different groups of specimens were formed with different percentages of both residues, subsequently determining the physical properties of the new-formed geopolymers and guaranteeing they accomplish the prescriptions of the ceramic regulations for construction. In addition, the results of the geopolymer characterisation tests were statistically analysed using factor analysis, with the sole purpose of establishing connections and interdependence between the variables that influence the geopolymerisation process. Thus, it was possible to demonstrate that the combination of brick dust and biomass bottom ashes produced geopolymers with adequate qualities to replace traditional ceramics, as well as that the different combinations of both residues produced feasible materials to be used as ceramics with various characteristics, with two main factors determined by factorial analysis that governed the physical properties of the geopolymer obtained: the percentage of brick dust and the theoretical porosity.

Keywords: circular mining; wastes; ceramic; geopolymer; construction materials; factorial analysis; data mining; structures

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1. Introduction

The construction sector is an essential sector for the maintenance and development of the population's well-being [1]. However, this sector produces significant greenhouse gas pollution [2]. This fact is mainly due to large construction materials production, the high extraction of raw materials and also the development [3], in most cases, of poorly optimised industrial processes [4]. More specifically, a high percentage of ceramic materials are consumed in construction, causing a scarcity of clay as the essential raw material for the shaping of these products [5]. In addition, in the sintering process developed for the manufacturing of traditional ceramic materials, high temperatures are reached, thus conditioning the use of large percentages of energy [6]. Various authors have confirmed that energy consumption for construction and the manufacturing of new materials accounts for 40% of the total energy consumed in Europe.

Consequently, in order to develop more sustainable materials with a lower carbon footprint within the framework of a new Circular Economy [7], numerous research studies have been carried out based on the use of mining and industrial waste as raw materials for building materials [8]. In this way, the extraction of new raw materials is reduced, and landfilling these wastes is avoided [9]. This means that with the use of waste in building materials, the economic and ecological material flows are much more closed, framed in an increasingly globalised Circular Economy perspective oriented, in this case, to the mining and construction sectors [10].

More specifically, in the field of ceramic materials for construction, high CO_2 emissions are produced [11]. As mentioned before, this fact is mainly due to the high amounts of energy consumed in the raw material extraction process and in the sintering process, once it is necessary to reach average temperatures of 950 °C for shaping [12]. Consequently, it is not only necessary to reduce the extraction of virgin materials, but also to use new materials with similar characteristics to the traditional ones but with much more optimised production processes, such as geopolymers [13].

Geopolymer is a material that is currently being studied in various scientific investigations. However, it is not a new material, as it was Joseph Davidovits in 1978 [14] who discovered the potential of this material [15]. Nevertheless, and due to its manufacturing process, in which a source of aluminosilicates reacts with an alkaline solution [16] to obtain a product of adequate strength [17] without the need to use cement or sintering processes, this material is a sustainable, environmentally friendly and promising solution that will replace traditional construction materials [18].

For this reason, and as mentioned above, the use of geopolymer has been evaluated in various research projects, mainly as a cement substitute for the development of concrete or mortar [19], as well as to replace traditional ceramic materials [20]. In addition, geopolymeric material has a very important environmental advantage, which is the possible use of waste from other industries for its development [21]. This is feasible as long as the waste is a potential source of aluminosilicates, such as coal fly ash [22], slag from metallurgical processes [23], metakaolin [24], glass waste [25], bagasse [26] and even hazardous [27]. In turn, these aluminosilicates must be alkaline activated, using, in most investigations, sodium hydroxide [28] or potassium hydroxide [29] solutions in the appropriate proportions.

In addition, the properties of geopolymers are diverse, including high-temperature stability [30], fire resistance [31], piezoelectric properties [32], good behaviour in contact with steel [33], interesting porosity characteristics [34], etc. Therefore, they make this material a sustainable solution for construction and highly functional [15].

Therefore, the manufacture of geopolymers as substitutes for traditional ceramics made from waste deletes from input all the economical, energetic and environmental costs related to the previous tasks to the extraction of clay, cleaning and cutting of trees, movement of land, classification, storage and different treatments of waste management, etc., [35]. On the other hand, in addition to the savings derived from these costs, an industrial or mining liability is transformed into economic activity, thereby contributing to the recycling of raw materials from a circular economy perspective [36]. Finally, a much more optimised production process is developed that is perfectly adaptable to any traditional ceramic industry, since the sintering phase is not necessary because the geopolymer is formed at low temperatures [37].

Based on the above, and with the aim of developing more sustainable geopolymeric materials as substitutes for traditional ceramic building bricks, brick dust from the ceramic industry was used as a source of aluminosilicates in this stowage [38]. In turn, as an alkali activator, and with the aim of developing a 100% waste-based material, biomass bottom ash was used instead of sodium hydroxide or potassium hydroxide. These ashes, currently unused, have a high potassium percentage as they are derived from the combustion of almond shells and "alperujo". Alperujo is a residue from the agri-food oil industry that is produced in considerable quantities [39].

The brick dust used in this research, belonging to one of the most important wastes from the ceramics industry, has significant percentages of silicon and Aluminium, making it an excellent source of aluminosilicates. So much so, that several researchers have used it for the formation of geopolymers, activating this waste with sodium hydroxide solutions [40]. In contrast, in this research, geopolymer materials composed of 100% waste are developed using biomass bottom ash as an alkaline activator.

Biomass bottom ash is a waste produced in large quantities by the electric power generation industry [41]. This residue, like biomass fly ash, has a very different chemical composition depending on the biomass used for incineration. However, it can be stated that due to the production process of this residue, it usually has a very low content of organic matter [42] and a high percentage of oxides, calcium, potassium, iron, etc. For this reason, this material can be used as an alkaline activator, due to the high pH it provides in contact with water. The waste can be classified as non-hazardous according to European legislation [43] and has been used in some research with some success [44].

Consequently, the aim of this research is the statistical analysis of the results of the physical and mechanical properties of geopolymeric material made of 100% waste, biomass bottom ash and brick dust. Obtaining an adequate statistical model that allows for the correlation of physical and mechanical properties and the main variables from which the formation of the optimum geopolymer is derived.

With this objective, different families of specimens were formed with the combination of both residues (brick dust and biomass bottom ash) and, finally, the results of the characterisation tests of the samples were analysed by means of statistical methods using factorial analysis [45] with the sole purpose of establishing connections and interdependence reasons between the variables that influence the geopolymerisation process. In this way, a new material is defined that is more sustainable than traditional ceramics composed of 100% waste, and the possible combinations of waste that can provide interesting properties for commercial purposes are statistically detailed.

2. Materials and Methods

The materials and methodology used in this research are detailed in the following parts:

2.1. Materials

The materials used are entirely industrial by-products. On the one hand, as an aluminosilicate source, brick dust was used. In turn, biomass bottom ashes from the combustion of almond shells and "alperujo" for energy production were used as alkaline activators, hereinafter named BBA.

2.1.1. Brick Dust

Brick dust is an inherent industrial by-product of ceramic production. In this specific case, samples of brick dust belonging to ceramic companies located in the south of Spain were used. These samples showed a similarity over time in terms of their chemical composition and physical properties, as detailed below.

It should be noted that the waste known as brick dust comes from the crushing of ceramic materials intended for construction that, for various reasons, are not marketable, either because they have fractured or have inadequate shapes. This material, usually produced in the ceramics industry, is usually crushed to reduce its size and deposited in a landfill, as its uses are very limited, and it has no economic value.

However, it should be noted that this waste comes from a ceramic material, i.e., it is already sintered, and therefore has very attractive properties for the formation of geopolymers, unlike the clay from which it comes. In addition, and due to the milling process that the residue undergoes, its particle size is very small, so its use in geopolymeric materials is direct, without the need for previous processes.

The essential physical properties of the brick powder were a density of 2.54 t/m^3 and a grain size between 40 and 200 μm. On the other hand, its chemical composition lacked elements of lower atomic weight, such as Carbon, Hydrogen, Nitrogen and Sulphur, reflecting the inexistence of carbonated compounds and organic matter. The chemical composition of the residue under study showed a reduced loss due to calcination of around 1.74%, as well as a chemical composition mainly of Silicon, Aluminium, Calcium, Iron, Potassium and Magnesium. Consequently, this chemical composition makes this material ideal for use as an aluminosilicate source in geopolymers once the percentage of silicon is 27.32% and Aluminium is 8.16%, according to the X-ray fluorescence test.

2.1.2. Biomass Bottom Ashes Comming from Almond Shells Combustion and "Alperujo"

The ashes used in the present study, hereinafter BBA, are a by-product generated in the combustion of almond shells and "alperujo" used for electrical energy generation. These ashes were obtained from the energy industry located in the south of Spain, like brick dust, and were analysed in different production batches. However, it should be mentioned that when using biomass for such specific combustion, it creates a by-product with similar physical and chemical properties over time, so the analysis of samples at different time periods indicates that the ashes' properties were very similar.

These biomass bottom ashes particles had a density of 2.65 t/m^3. These particles' size was between 10 and 200 μm. Consequently, it can be stated that both density and particle size favour the mixing of both materials without segregations production. On the other hand, it should be noted that the biomass bottom ash produced by the combustion of "alperujo" and almond shells reflected a chemical composition, as expected, formed mainly by oxides of Potassium, Silicon, Calcium, Phosphorus, Magnesium, Aluminium and Iron, with 8.16% of loss by calcination and a higher percentage of Carbon than brick dust, due to the biomass not burnt during the energy production process. Consequently, it can be stated that the chemical composition of this waste is suitable for use as an alkaline activator for the formation of geopolymers.

2.2. Methodology

The methodology followed in this study is based on the development of geopolymers with brick dust and biomass bottom ashes, as well as the study of the physical properties of the different families of geopolymers formed by statistical methods of factor analysis. In this way, it is possible to choose among the different combinations of residues that provide the most appropriate physical characteristics to the specific case in which they will be used.

Therefore, firstly, the methodology for the shaping of the different families of geopolymer specimens is presented and, later, the methodology used for the statistical factorial analysis.

2.2.1. Conformation of Specimens and Determination of Physical-Chemical Properties

The geopolymer specimens were made with the use of wastes only; on the one hand, brick dust as a source of aluminosilicates, and on the other hand, biomass bottom ash as an alkaline activator.

Since the chemical composition of the waste is complex and the aim of this research is to study the dependence of the combination of both wastes in order to obtain a geopolymer with optimal mechanical and physical characteristics, both wastes (ashes and brick dust) were combined in varying proportions. For this purpose, different families of specimens were formed, each consisting of six specimens in order to obtain statistically reliable results, and with varying percentages of ash and brick dust.

The first family was composed solely of brick dust, even though it was known that this family would never be able to develop a geopolymeric structure. However, it served the main purpose of comparing strength results and indirectly proving that the combination of ash and brick dust was capable of executing a geopolymeric structure with higher strength. The second family, named B, was composed of 90% brick dust and 10% biomass bottom ash, while family C was composed of 80% brick dust and 20% ash. The percentage of ash was then increased in 10% increments up to family J, which consisted of 10% brick dust and 90% ash. In this way, it was possible to cover the whole possible field of combinations of both wastes and to study the physical–mechanical properties of the different families, with the main purpose of evaluating the dependence between the physical and mechanical variables of the geopolymers with the proportion of incorporation of both wastes.

Therefore, the families that were manufactured are summarised in Table 1 below.

Table 1. Combination percentages of brick dust and biomass bottom ash for the different families of shaped specimens.

Samples Families	% Brick Dust	% BBA
Family A	100	0
Family B	90	10
Family C	80	20
Family D	70	30
Family E	60	40
Family F	50	50
Family G	40	60
Family H	30	70
Family I	20	80
Family J	10	90

The specimens of the different families were formed in the same way, making a total of 6 specimens for each family detailed. For this, the manufacturing process consisted of mixing the brick dust and the biomass bottom ash in the corresponding proportion according to the family to which it corresponded. Once both residues were mixed, 20% water was added to the total mass of the sample. The percentage of water added is similar to that used in industry, thus ensuring that the subsequent compaction process is maximised and that geopolymerisation reactions take place. For compaction, the mixture of brick dust, ashes and water mixed in the appropriate proportions was poured into a metal matrix measuring 60 mm long by 30 mm wide and then pressurised to 30 MPa with the aid of a metal rammer of identical dimensions. The use of this forming pressure is used in order to replicate the general conditions that occur in the ceramic industry. Finally, the specimen was removed after the compaction process.

The fabricated specimens were left at an ambient temperature of 20 ± 2 °C for 24 h in order to achieve the geopolymerisation process. Subsequently, all the specimens were dried at a temperature of 90 ± 2 °C for 24 h, thus eliminating the water that had not reacted in the geopolymerisation process. At the end of this process, the geometric dimensions of the specimens and their mass were measured. At the same time, and in order to eliminate possible inert compounds that are not part of the geopolymer and do not contribute special characteristics to the material, the specimens were subjected to a water bath at a temperature of 20 ± 2 °C for 24 h with continuous recirculation of water. Finally, the specimens were dried again at a temperature of 90 ± 2 °C, and their mass and geometry were measured. In this way, the possible linear shrinkage experienced by the material after the water bath with continuous water recirculation and the variation of the mass could be observed.

The specimens formed according to the detailed procedure of the different families were subjected to various tests to determine their physical and mechanical properties, to obtain a relationship between properties with the subsequent statistical analysis and, in turn, to demonstrate the feasibility of using geopolymers made from biomass bottom ash and brick dust as substitutes for traditional ceramic material. For this purpose, the tests carried out were those of linear shrinkage and weight loss according to UNE-EN 772-16, capillary water absorption according to UNE-EN 772-11, cold water absorption according to UNE-EN 772-21, boiling water absorption according to UNE-EN 772-7 and determination of open porosity and apparent density according to UNE-EN 772-4. In addition, since this geopolymeric material is intended to replace the traditional ceramic materials used for brick manufacture, it is essential to study the mechanical properties of the material. More specifically, this research evaluates the compressive strength of all the specimens of the different families according to the UNE-EN 772-1 standard.

Figure 1 shows the forming process of the geopolymeric specimens made of brick dust and biomass bottom ash in schematic form, detailing with images the performance of the tests described.

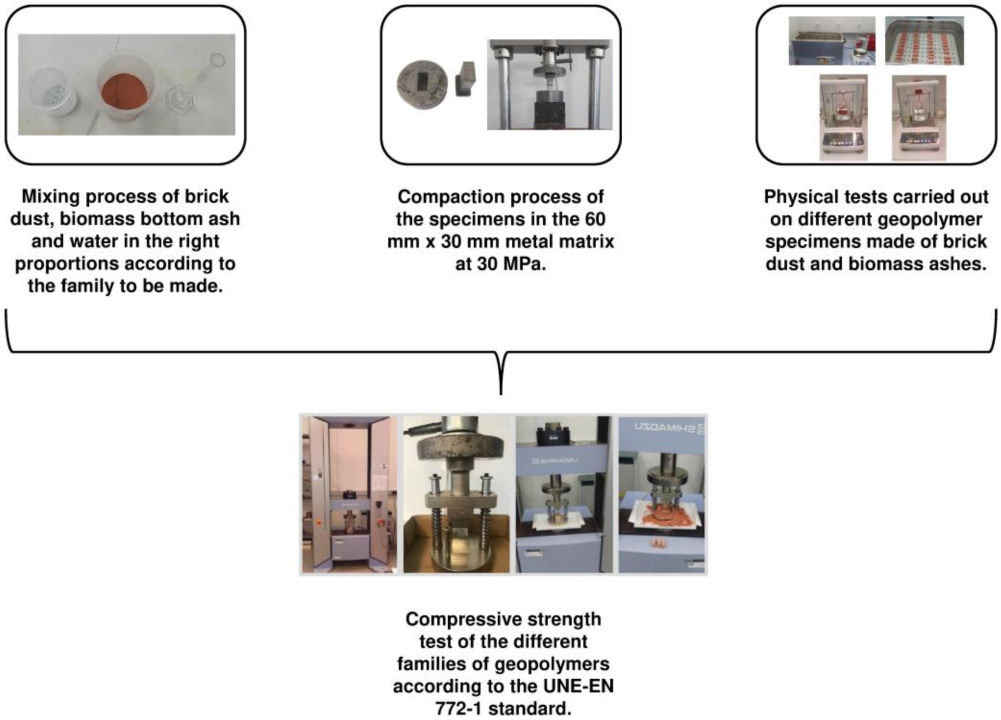

Figure 1. Images of the forming process of the different families of geopolymers, as well as of the tests carried out.

The sample with the highest compressive strength value in the compressive strength test was analysed with Fourier transform infrared. In this way, it was possible to chemically verify that the geopolymer had been formed. To carry out this test, the geopolymer sample was initially crushed to a very small particle size of less than 0.063 mm. Subsequently, the sample was analysed with the Bruker Tensor20 spectrophotometer (Tensor20, Bruker, Billerica, MA, USA), obtaining the FTIR spectrum of the sample.

It should be noted that in this research, ceramic specimens were also made using traditional processes from red clay, that is, conventional ceramic material for bricks. The forming process of these ceramic specimens was similar to that detailed for the geopolymers, with the main difference being that these ceramic specimens were subjected to a sintering process at 950 °C. In this way, the differences between both materials, ceramics and geopolymers, could be appreciated with objective results.

2.2.2. Factorial Analysis

The quantitative analysis of the possible cause–effect relationships between the variables under study related to the processes and the results oriented to the modelling of the phenomenon was carried out by means of factorial analysis applied to all the physical properties and percentage fractions of the geopolymers previously formed with the combination of brick dust and biomass bottom ash. In this way, it is possible to know the origin of each element according to its level of association with the rest and to determine which factors directly influence the formation of geopolymers with different percentages of the treated waste. Consequently, it is possible to analyse the feasibility of the geopolymer formation with both materials, the correlation between the different physical properties, as well as the possible characteristics of the geopolymer formed with the combination of both residues.

In essence, it is a matter of defining two new variables called "factors", which were not measured during the experiment, but which govern the total performance once they carry all the information regarding the weight that each variable exerts on the system. In this way, the stress–strain phenomenon can be modelled from the initial variables measured in the study. This statistical tool has been widely used to model systems encompassing the mining–water environment trinomial, but has not previously been applied to modelling geopolymer stress–strain relationships.

Multivariate statistical calculations were used in the analysis to determine the relationship between the physical and mechanical properties of the formed geopolymers, as well as to obtain the main factors that conditioned the results of these properties. To attain this, initially, the correlation matrix of variables is obtained from all the data obtained from the test of all the properties. Subsequently, this matrix is analysed in detail, developing the matrix of factors from the r values of the previous matrix [46]. With the matrix of factors, the two main factors that condition the rest of the variables can be obtained, which are subsequently defined from the knowledge of the material and the methodology followed for the geopolymer forming.

In turn, for a better representation of the data, as well as for the optimisation of the statistical process, the factors can be rotated. This makes it easier to interpret the relationships established between the different physical and mechanical properties with the two main factors obtained. This is conducted thanks to the Varimax rotation, which consists of simplifying the factor matrix by moving its values closer to 0 or 1, i.e., to more dependent or less dependent.

Finally, all the variables are shown in graphs with two coordinate axes corresponding to the two main factors, representing graphically the lesser or greater dependence of the variables (in this case, physical and mechanical properties) on the main factors obtained in this statistical process. Therefore, the main advantage of using this factorial statistical method lies in the fact that it simplifies a considerable set of variables into two main factors, these being the ones that condition all the variables.

3. Results and Discussion

3.1. Physical Properties of the Different Families of Geopolymers Formed with Brick Dust and Biomass Bottom Ashes

The different families of geopolymer, ash and brick dust specimens, formed according to the methodology detailed above, are shown in Figure 2.

Figure 2. Image of the different families of prismatic specimens co-formed with brick dust and biomass ash. From left to right: Family A, Family B, Family C, Family D, Family E, Family F, Family G, Family H, Family I and Family J.

In turn, Table 2 shows the main physical properties of the different families of samples formed with increasing percentages of biomass bottom ashes and decreasing percentages of brick dust.

Table 2 shows how the weight loss is greater in the families of specimens with a higher percentage of biomass bottom ash. This fact is due to the process to which the specimens are subjected after finishing the geopolymerisation by submerging them with a continuous recirculation of water, since it is in this stage where those inert elements that do not react in the geopolymerisation process are eliminated. However, traditional ceramics made with red clay have a weight loss of 9.5%, so it can be stated that the values are in line between geopolymers and ceramics [47].

Table 2. Physical properties of the different families of specimens formed with increasing percentages of biomass bottom ashes and decreasing percentages of brick dust.

Family	Weight Loss, %	Linear Shrinkage, %	Capillary Water Absorption, g/m^2 min	Cold Water Absorption, %	Boiling Water Absorption, %	Open Porosity, %	Bulk Density, g/cm^3	Compression Strength, MPa
A	4.14	−0.06	4520	25	26.54	41.81	1.58	7.51
B	2.82	0.07	4768	24.36	25.83	40.53	1.57	10.51
C	3.21	0.12	4026	23.68	24.71	38.59	1.56	16.53
D	4.07	0.12	3475	21.37	22	35.12	1.6	23.98
E	4.66	0.11	3154	19.51	19.97	32.21	1.61	36.95
F	6.41	0.12	2130	17.16	16.17	27.22	1.68	46.1
G	7.66	0.14	1719	15.94	14.29	24.35	1.7	59.2
H	8.65	0.2	1774	15.25	12.4	21.32	1.72	57.19
I	10.45	0.3	1998	14.64	11.02	19.15	1.74	47.36
J	12.08	0.45	2103	14.61	10.43	17.98	1.72	29.68

On the other hand, it can be observed how the linear shrinkage of the specimens increases in line with the increase in the percentage of biomass bottom ash used, highlighting family A, which has a linear shrinkage percentage totally different from the other families as it does not contain ash. The results obtained are adequate, since the variation in dimensions is very small when compared to the linear shrinkage experienced by the family made with red clay, this linear shrinkage being 2.7% [48].

In turn, the capillary water absorption of the different families of geopolymers made with brick dust and biomass bottom ash decreases as the percentage of ash in the geopolymer increases. So much so, that a traditional ceramic obtains a capillary water absorption of 1700 g/m^2 min, very similar to that reflected in the family composed of 60% biomass bottom ash [49].

Consequently, this reduction in capillary water absorption reflects a much more closed geopolymer structure, i.e., with a lower percentage of interconnected voids. Therefore, the cold water absorption and boiling water absorption also decrease in line with the capillary water absorption due to the increased percentage of biomass bottom ash in the geopolymer and, therefore, obtaining a higher quality material [50].

The open porosity, as expected, decreases as the percentage of biomass bottom ash in the geopolymer increases, due to the formation of a much more closed structure with a lower number of pores. This decrease in porosity as the percentage of ash increases translates directly into an increase in the bulk density of the material, as is obvious [51].

Finally, it can be seen from Table 2 that the compressive strength increases as the percentage of biomass bottom ash increases. Therefore, it can be stated that a geopolymerisation process takes place and that the geopolymer is formed, as demonstrated by the subsequent chemical test. This fact is contrasted by observing the low strength of family A, composed only of brick dust and, therefore, not being a geopolymeric material. On the other hand, it should be noted that the strength increases up to family G, composed of 60% biomass bottom ash and 40% brick dust, after which the strength decreases. These results reflect that the combination of brick dust and ashes should be optimal, as a high percentage of ashes not only does not create a higher quality material but also impairs its strength [52].

In view of the above results, it can be stated that geopolymeric materials can be made with brick dust and biomass bottom ash that meet the requirements for brick ceramics, the optimum combination of both wastes being 60% biomass bottom ash and 40 % brick dust. However, it should be noted that there are different combinations of both materials that meet the requirements of the standard of 10 MPa (UNE-EN 772-1) minimum compressive strength and that provide very interesting characteristics of colour, water absorption, porosity, etc. Therefore, the subsequent statistical analysis will be indicated to relate such variables [53].

Therefore, the factorial analysis shown in the following section will be in charge of relating the different physical properties of the geopolymers based on the combination of both wastes, ash and brick dust, establishing the different possibilities of materials adaptable to different causes.

However, in order to clearly reflect that the geopolymer structure is produced by the combination of brick dust and biomass bottom ash, the sample detailed above that obtained the highest resistivity was analysed by infrared Fourier transform, showing the spectrum in Figure 3.

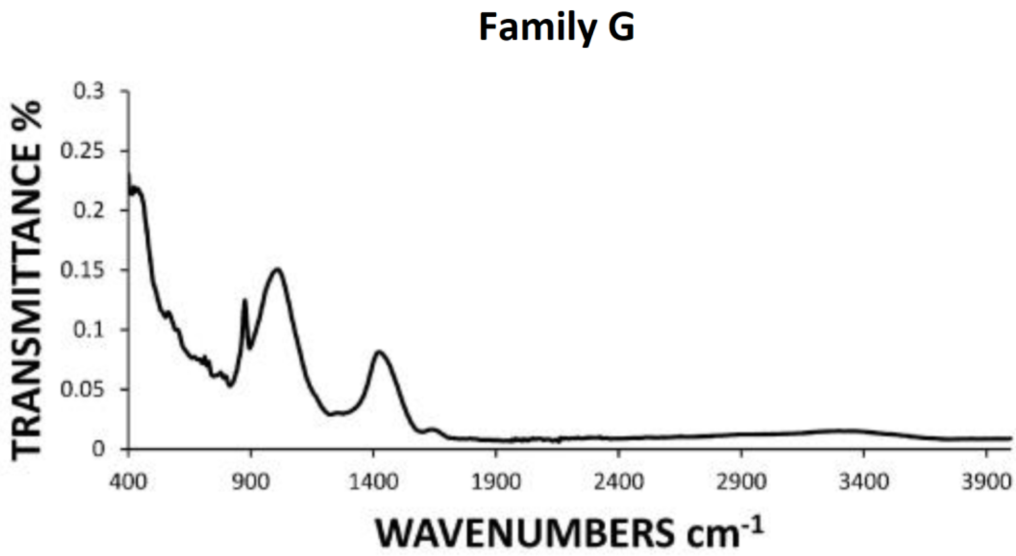

Figure 3. The spectrum obtained from the analysis of the geopolymeric sample made of ash and brick dust showed the highest mechanical resistance to compression.

The analysis of the spectrum obtained with the Fourier transform infrared shows that the bands in the 950–1150 cm^{-1} and 875 cm^{-1} zones have a significant intensity. This increase in intensity indicates an increase in the length of the chain and of the aluminosilicate gel formed, i.e., a complete geopolymerisation process. This corroborates the formation of the geopolymer.

3.2. Factorial Analysis

The physical properties of the formed geopolymers were carried out through factor analysis. The first of the elements obtained was the correlation matrix of all the physical properties measured for the various detailed families.

The Pearson proximity ratios (correlation coefficient "r") between the analysed variables are shown in the correlation matrix of Table 3. This matrix is the statistical base from which the factorial analysis was derived.

Table 3 shows high and very high levels of positive or negative correlation between the different physical properties of the geopolymers. As can be seen, all physical properties directly related to porosity and, therefore, to water absorption, whether boiling water, cold water or suction, have a high level of correlation. In turn, linear shrinkage, strength, apparent density and weight loss show significantly lower correlation values with the properties detailed above. This is to be expected considering the geopolymerisation process that has been developed by combining brick dust and ash, as well as the basis for each of the physical properties. It should be noted that the absorption of boiling water is proportional to the absorption of water by capillarity, the absorption of cold water and the open porosity, and inversely proportional to the other properties; on the other hand, the compressive strength is proportional to the linear shrinkage, the apparent density and the weight loss, being inversely proportional to the variables not mentioned. This is to be expected if one takes into account that the lower the porosity of the formed geopolymer, the less water it can absorb and, consequently, the higher its density. Therefore, all other things being equal, a higher density will lead to a higher compressive strength.

Table 3. Correlation matrix of the different physical properties of the shaped geopolymers.

Boiling Water Absorption	1							
Capillary water absorption	0.9474	1						
Cold water absorption	0.9851	0.9639	1					
Linear Shrinkage	−0.8200	−0.6528	−0.7685	1				
Bulk density	−0.9183	−0.8686	−0.8941	0.6797	1			
Weight loss	−0.9419	−0.8217	−0.8966	0.8609	0.8750	1		
Open porosity	0.9968	0.9380	0.9820	−0.8363	−0.9144	0.9473	1	
Compression strength	−0.8158	−0.9263	−0.8595	0.4059	0.7673	0.6127	−0.8024	1.0000
	Boiling water absorption	Capillary water absorption	Cold water absorption	Linear Shrinkage	Bulk density	Weight loss	Open porosity	Compression strength

Table 4 shows the results obtained from the factorial analysis of the studied variables and reflects how the first two factors explain up to 99.081% of the total variability.

Table 4. Factor analysis.

Factor Number	EIGENVALOR	Percentage of Variance	Percentage Accumulated
1	6.91589	90.329	90.329
2	0.670119	8.752	99.081
3	0.0537087	0.701	99.783
4	0.0112696	0.147	99.930
5	0.00535657	0.070	100.000
6	0.0	0.000	100.000
7	0.0	0.000	100.000
8	0.0	0.000	100.000

Based on what was said, these first two factors were chosen for the present study. Its factorial matrix is shown in Table 5.

Table 5. Variable loadings of the first two factors from a Principal Component Analysis.

Variable	Factor 1	Factor 2
Boiling water absorption	1.00174	0.0484075
Capillary water absorption	0.955474	−0.223192
Cold water absorption	0.988144	−0.0505878
Linear Shrinkage	−0.788506	−0.451345
Bulk density	−0.9110662	0.0148954
Weight loss	−0.93085	−0.290827
Open porosity	1.00063	0.077084
Compression strength	−0.839198	0.56653

The values shown in Table 5 can be improved by rotating the axis through the Varimax rotation method, as shown in Table 6.

Table 6. Variable loadings on first two factors after Varimax rotation.

Variable	Factor 1	Factor 2
Boiling water absorption	0.766922	0.646266
Capillary water absorption	0.548185	0.81378
Cold water absorption	0.689588	0.709546
Linear Shrinkage	−0.884903	−0.0205916
Bulk density	−0.657107	−0.630664
Weight loss	−0.879958	−0.420399
Open porosity	0.785626	0.6245
Compression strength	−0.229337	−0.986206

These rotated values are plotted on a graph in Figure 4.

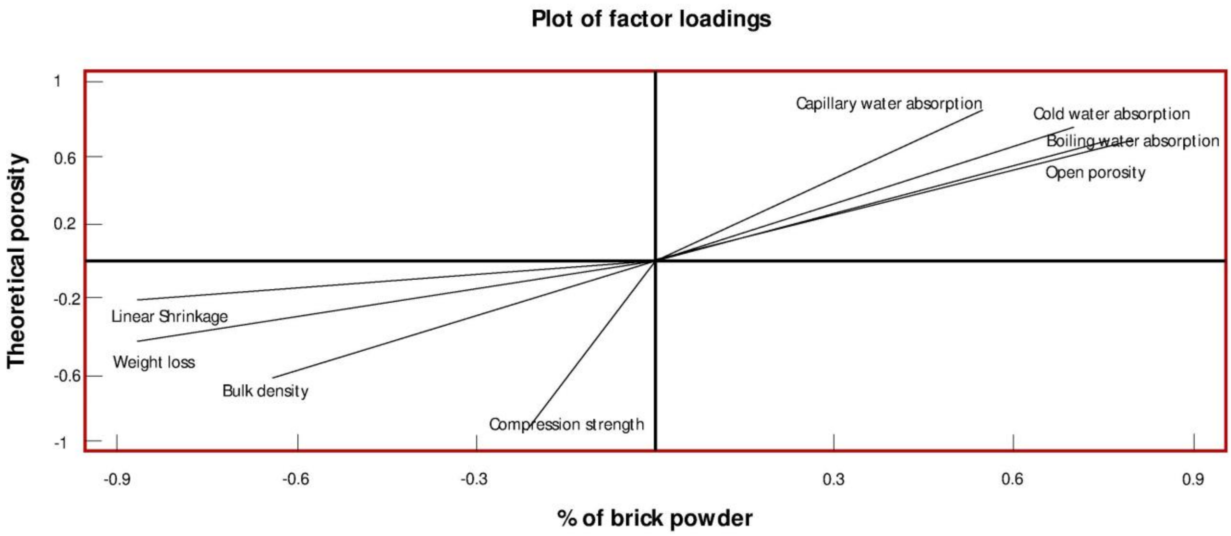

Figure 4. Correlation plot between factor 1, % of brick powder, and factor 2, theoretical porosity.

In Figure 4, the eight physical properties previously determined by measurement of the different families of geopolymer specimens made from brick dust and biomass bottom ash are grouped around two essential factors to be determined. In this graph, the different straight lines represent the "weight" of each of the properties around the factor under study. Therefore, and based on the factorial analysis carried out, as well as on the knowledge of the different properties obtained from the evaluation of geopolymers, two essential and conditioning factors in the formation of geopolymers can be clearly defined with the detailed methodology and materials. Consequently, these factors will be considered essential to be able to define different combinations of brick dust and biomass bottom ash for the formation of geopolymers with specific properties.

The first factor, defined in Figure 4 on the horizontal axis, is the percentage of brick dust. This factor is decisive for correctly manufacturing geopolymers, as it is the source of aluminosilicates. At the same time, it must be taken into account that the increase in the percentage of brick dust or "chamotte" implies a decrease in the biomass bottom ash used, which is the basis of the alkaline activator for the formation of the geopolymer. This fact is corroborated in Table 1, shown above, where it can be seen how the increase in biomass bottom ash is produced by a reduction in the percentage of brick dust.

On the other hand, factor 2, derived from the factorial analysis, corresponds to the theoretical porosity of the material (vertical axis). This property, different from the open porosity and evaluated by the tests, represents the quality of the formed geopolymeric structure. That is, a higher theoretical porosity will condition a much more open geopolymer structure in which its density will be lower and, consequently, the resistance of the geopolymer will also decrease. However, a reduced theoretical porosity implies the creation of a much more compact material with a high apparent density and, therefore, greater resistance.

Once the two essential factors that condition the formation of geopolymers with brick dust and biomass bottom ash have been determined by factorial analysis, it can be affirmed from Figure 4 that a higher theoretical porosity and a higher percentage of brick dust determine a greater absorption of water by capillarity, absorption of cold water, absorption of boiling water and open porosity. This is demonstrated by the fact that geopolymers with a higher percentage of “chamotte” or brick dust do not form a solid geopolymer structure.

On the other hand, a lower percentage of brick dust combined with a lower theoretical porosity, which means a much more closed geopolymeric structure, determines a greater linear shrinkage, weight loss, apparent density and resistance to simple compression. This is to be expected if one takes into account that geopolymers with a lower percentage of brick dust and, consequently, a higher percentage of biomass bottom ash, have a higher linear shrinkage so that the material will have a higher bulk density. This higher bulk density translates into higher mechanical strength, as the theoretical and open porosity is lower. At the same time, it is obvious that the weight loss of the geopolymer increases as the percentage of brick dust decreases, as the biomass bottom ash has different chemical compounds that do not help in the geopolymerisation process, nor react with the aluminosilicate source. Consequently, these compounds are eliminated in the manufacturing process by continuous water recirculation and, in turn, are discarded in higher quantities as the percentage of biomass bottom ashes increases.

4. Conclusions

The methodology followed in the present study on the possible formation of geopolymers with brick dust and biomass bottom ashes allows us to obtain a series of essential partial conclusions for the confirmation of the final hypothesis. This final hypothesis is based on the feasibility of forming geopolymers with the aforementioned residues. Consequently, the partial conclusions derived from the investigation are the following:

- As the percentage of biomass bottom ashes increased, the conformation of various families of samples with varying proportions of brick dust and biomass bottom ashes showed the development of a geopolymer with a lower open porosity, lower absorption of cold water and suction, as well as a higher apparent density;
- The higher percentage of biomass bottom ashes and, consequently, the lower percentage of brick dust or “chamotte” makes creating a geopolymer with greater mechanical resistance possible. However, there is a limit on biomass bottom ashes incorporation from which the resistance decreases;
- The factorial analysis of the results demonstrated the quality of the measured data, with high percentages of correlation between them;
- The factorial analysis of the data obtained by measuring the different physical properties evaluated in the different families of geopolymers reflected a positive correlation between the absorption of water by capillarity, the absorption of cold water, the absorption of boiling water and the open porosity, as well as a positive and negative correlation with the previous properties, of mechanical strength, bulk density, weight loss and linear shrinkage;
- The factorial analysis of the physical properties of geopolymers determined statistically that there are two main factors that determine the formation of geopolymers: the percentage of brick dust and the theoretical porosity. An increase in both factors would cause greater absorption of water by capillarity, absorption of cold water, absorption of boiling water and open porosity. On the contrary, a decrease in both factors will determine a higher mechanical strength, bulk density, weight loss and linear shrinkage.

Consequently, and based on the partial hypotheses detailed above, it can be stated that the geopolymers creation with brick dust and biomass bottom ashes is possible, as shown by the tests. On the other hand, it should be noted that the shaped geopolymers have different properties depending on two essential factors determined by factor analysis, these being the percentage of brick dust and the theoretical porosity. For this reason, it can be affirmed that it is possible to create a sustainable geopolymeric material with 100% waste and with diverse properties for multiple uses, conditioning its creation by statistical methods.

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References

1. Riaz, H.; Iqbal Ahmad Khan, K.; Ullah, F.; Bilal Tahir, M.; Alqurashi, M.; Alsulami, B.T. Key factors for implementation of total quality management in construction Sector: A system dynamics approach. *Ain Shams Eng. J.* **2023**, *14*, 101903. [CrossRef]
2. Zhang, L.; Liu, B.; Du, J.; Liu, C.; Li, H.; Wang, S. Internationalization trends of carbon emission linkages: A case study on the construction sector. *J. Clean. Prod.* **2020**, *270*, 122433. [CrossRef]
3. Sani, R.; Nzihou, A. Production of clay ceramics using agricultural wastes: Study of properties, energy savings and environmental indicators. *Appl. Clay Sci.* **2017**, *146*, 106–114. [CrossRef]
4. Barros, M.C.; Bello, P.; Roca, E.; Casares, J.J. Integrated pollution prevention and control for heavy ceramic industry in Galicia (NW Spain). *J. Hazard. Mater.* **2007**, *141*, 680–692. [CrossRef]
5. Shi, Z. Green manufacturing of silicate materials using desert sand as a raw-material resource. *Constr. Build. Mater.* **2022**, *338*, 127539. [CrossRef]
6. Furszyfer Del Rio, D.D.; Sovacool, B.K.; Foley, A.M.; Griffiths, S.; Bazilian, M.; Kim, J.; Rooney, D. Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112081. [CrossRef]
7. Norouzi, M.; Chàfer, M.; Cabeza, L.F.; Jiménez, L.; Boer, D. Circular economy in the building and construction sector: A scientific evolution analysis. *J. Build. Eng.* **2021**, *44*, 102704. [CrossRef]
8. Monteiro, S.N.; Vieira, C.M.F. On the production of fired clay bricks from waste materials: A critical update. *Constr. Build. Mater.* **2014**, *68*, 599–610. [CrossRef]
9. Martínez, C.; Cotes, T.; Corpas, F.A. Recovering wastes from the paper industry: Development of ceramic materials. *Fuel Process. Technol.* **2012**, *103*, 117–124. [CrossRef]
10. Bertozzi, C. How is the construction sector perceiving and integrating the circular economy paradigm? Insights from the Brussels experience. *City Cult. Soc.* **2022**, *29*, 100446. [CrossRef]
11. González, I.; Barba-Brioso, C.; Campos, P.; Romero, A.; Galán, E. Reduction of CO2 diffuse emissions from the traditional ceramic industry by the addition of Si-Al raw material. *J. Environ. Manag.* **2016**, *180*, 190–196. [CrossRef]
12. Fuertes, V.; Reinosa, J.J.; Fernández, J.F.; Enríquez, E. Engineered feldspar-based ceramics: A review of their potential in ceramic industry. *J. Eur. Ceram. Soc.* **2022**, *42*, 307–326. [CrossRef]
13. Kovářík, T.; Hájek, J.; Pola, M.; Rieger, D.; Svoboda, M.; Beneš, J.; Šutta, P.; Deshmukh, K.; Jandová, V. Cellular ceramic foam derived from potassium-based geopolymer composite: Thermal, mechanical and structural properties. *Mater. Des.* **2021**, *198*, 109355. [CrossRef]
14. Davidovits, J. Geopolymers and geopolymeric materials. *J. Therm. Anal.* **1989**, *35*, 429–441. [CrossRef]
15. Raza, M.H.; Zhong, R.Y. A sustainable roadmap for additive manufacturing using geopolymers in construction industry. *Resour. Conserv. Recycl.* **2022**, *186*, 106592. [CrossRef]
16. San Nicolas, R.V.R.; Walkley, B.; van Deventer, J.S.J. Fly ash-based geopolymer chemistry and behavior. In *Coal Combustion Products (ccp's)*; Woodhead Publishing: Cambridge, UK, 2017; pp. 185–214.
17. Farhan, K.Z.; Johari, M.A.M.; Demirboğa, R. Assessment of important parameters involved in the synthesis of geopolymer composites: A review. *Constr. Build. Mater.* **2020**, *264*, 120276. [CrossRef]
18. Kaplan, G.; Öz, A.; Bayrak, B.; Görkem Alcan, H.; Çelebi, O.; Cüneyt Aydın, A. Effect of quartz powder on mid-strength fly ash geopolymers at short curing time and low curing temperature. *Constr. Build. Mater.* **2022**, *329*, 127153. [CrossRef]

19. Gao, X.; Yao, X.; Xie, R.; Li, X.; Cheng, J.; Yang, T. Performance of fly ash-based geopolymer mortars with waste cathode ray tubes glass fine aggregate: A comparative study with cement mortars. *Constr. Build. Mater.* **2022**, *344*, 128243. [CrossRef]
20. Tahwia, A.M.; Abd Ellatief, M.; Heneigel, A.M.; Abd Elrahman, M. Characteristics of eco-friendly ultra-high-performance geopolymer concrete incorporating waste materials. *Ceram. Int.* **2022**, *48*, 19662–19674. [CrossRef]
21. Choeycharoen, P.; Sornlar, W.; Wannagon, A. A sustainable bottom ash-based alkali-activated materials and geopolymers synthesized by using activator solutions from industrial wastes. *J. Build. Eng.* **2022**, *54*, 104659. [CrossRef]
22. Yavuz, E.; Kul Gul, N.I.; Kockal, N.U. Characterization of class C and F fly ashes based geopolymers incorporating silica fume. *Ceram. Int.* **2022**, *48*, 32213–32225. [CrossRef]
23. Premkumar, R.; Chokkalingam, R.B.; Rajesh, S. Performance of fly ash based geopolymer concrete with partial replacement of fine aggregate by steel mill slag. *Mater. Today Proc.* **2022**, *59*, 496–500. [CrossRef]
24. Allaoui, D.; Nadi, M.; Hattani, F.; Majdoubi, H.; Haddaji, Y.; Mansouri, S.; Oumam, M.; Hannache, H.; Manoun, B. Eco-friendly geopolymer concrete based on metakaolin and ceramics sanitaryware wastes. *Ceram. Int.* **2022**, *48*, 34793–34802. [CrossRef]
25. Tahwia, A.M.; Heniegal, A.M.; Abdellatief, M.; Tayeh, B.A.; Elrahman, M.A. Properties of ultra-high performance geopolymer concrete incorporating recycled waste glass. *Case Stud. Constr. Mater.* **2022**, *17*, e01393. [CrossRef]
26. Riofrio, A.; Cornejo, M.; Baykara, H. Environmental performance of bamboo fibers and sugarcane bagasse reinforced metakaolin-based geopolymers. *Case Stud. Constr. Mater.* **2022**, *17*, e01150. [CrossRef]
27. Suresh Kumar, A.; Muthukannan, M.; Arunkumar, K.; Sriram, M.; Vigneshwar, R.; Gulshan Sikkandar, A. Development of eco-friendly geopolymer concrete by utilizing hazardous industrial waste materials. *Mater. Today Proc.* **2022**, *66*, 2215–2225. [CrossRef]
28. Oshani, F.; Allahverdi, A.; Kargari, A.; Norouzbeigi, R.; Mahmoodi, N.M. Effect of preparation parameters on properties of metakaolin-based geopolymer activated by silica fume- sodium hydroxide alkaline blend. *J. Build. Eng.* **2022**, *60*, 104984. [CrossRef]
29. González-García, D.M.; Téllez-Jurado, L.; Jiménez-Álvarez, F.J.; Zarazua-Villalobos, L.; Balmori-Ramírez, H. Evolution of a natural pozzolan-based geopolymer alkalized in the presence of sodium or potassium silicate/hydroxide solution. *Constr. Build. Mater.* **2022**, *321*, 126305. [CrossRef]
30. Scanferla, P.; Gharzouni, A.; Texier-Mandoki, N.; Bourbon, X.; Rossignol, S. Effects of potassium-silicate, sands and carbonates concentrations on metakaolin-based geopolymers for high-temperature applications. *Open Ceram.* **2022**, *10*, 100257. [CrossRef]
31. Amran, M.; Huang, S.S.; Debbarma, S.; Rashid, R.S.M. Fire resistance of geopolymer concrete: A critical review. *Constr. Build. Mater.* **2022**, *324*, 126722. [CrossRef]
32. Aziz, A.; Stocker, O.; El Amrani El Hassani, I.E.; Laborier, A.P.; Jacotot, E.; El Khadiri, A.; El Bouari, A. Effect of blast-furnace slag on physicochemical properties of pozzolan-based geopolymers. *Mater. Chem. Phys.* **2021**, *258*, 123880. [CrossRef]
33. Kuranlı, Ö.F.; Uysal, M.; Abbas, M.T.; Cosgun, T.; Niş, A.; Aygörmez, Y.; Canpolat, O.; Al-mashhadani, M.M. Evaluation of slag/fly ash based geopolymer concrete with steel, polypropylene and polyamide fibers. *Constr. Build. Mater.* **2022**, *325*, 126747. [CrossRef]
34. Zhang, X.; Bai, C.; Qiao, Y.; Wang, X.; Jia, D.; Li, H.; Colombo, P. Porous geopolymer composites: A review. *Compos. Part A Appl. Sci. Manuf.* **2021**, *150*, 106629. [CrossRef]
35. Asadi, I.; Baghban, M.H.; Hashemi, M.; Izadyar, N.; Sajadi, B. Phase change materials incorporated into geopolymer concrete for enhancing energy efficiency and sustainability of buildings: A review. *Case Stud. Constr. Mater.* **2022**, *17*, e01162. [CrossRef]
36. Shehata, N.; Mohamed, O.A.; Sayed, E.T.; Abdelkareem, M.A.; Olabi, A.G. Geopolymer concrete as green building materials: Recent applications, sustainable development and circular economy potentials. *Sci. Total Environ.* **2022**, *836*, 155577. [CrossRef]
37. Das, S.; Saha, P.; Prajna Jena, S.; Panda, P. Geopolymer concrete: Sustainable green concrete for reduced greenhouse gas emission—A review. *Mater. Today Proc.* **2022**, *60*, 62–71. [CrossRef]
38. Ren, B.; Zhao, Y.; Bai, H.; Kang, S.; Zhang, T.; Song, S. Eco-friendly geopolymer prepared from solid wastes: A critical review. *Chemosphere* **2021**, *267*, 128900. [CrossRef]
39. Hernández, D.; Astudillo, L.; Gutiérrez, M.; Tenreiro, C.; Retamal, C.; Rojas, C. Biodiesel production from an industrial residue: Alperujo. *Ind. Crop. Prod.* **2014**, *52*, 495–498. [CrossRef]
40. Pasupathy, K.; Ramakrishnan, S.; Sanjayan, J. Formulating eco-friendly geopolymer foam concrete by alkali-activation of ground brick waste. *J. Clean. Prod.* **2021**, *325*, 129180. [CrossRef]
41. Lessard, J.M.; Omran, A.; Tagnit-Hamou, A.; Gagne, R. Feasibility of using biomass fly and bottom ashes in dry-cast concrete production. *Constr. Build. Mater.* **2017**, *132*, 565–577. [CrossRef]
42. Monedero, E.; Hernández, J.J.; Collado, R.; Pazo, A.; Aineto, M.; Acosta, A. Evaluation of ashes from agro-industrial biomass as a component for producing construction materials. *J. Clean. Prod.* **2021**, *318*, 128517. [CrossRef]
43. Cabrera, M.; Rosales, J.; Ayuso, J.; Estaire, J.; Agrela, F. Feasibility of using olive biomass bottom ash in the sub-bases of roads and rural paths. *Constr. Build. Mater.* **2018**, *181*, 266–275. [CrossRef]
44. Cui, J.; Li, J.; Cui, J.; Wang, W.; Wu, Y.; Xu, B.; Chang, Y.; Liu, X.; Li, H.; Yao, D. Removal effects of a biomass bottom ash composite on tailwater phosphate and its application in a rural sewage treatment plant. *Sci. Total Environ.* **2022**, *812*, 152549. [CrossRef] [PubMed]

45. Santisteban, M.; Luís, A.T.; Grande, J.A.; Aroba, J.; Dávila, J.M.; Sarmiento, A.M.; Fortes, J.C.; Cordoba, F.; Rodriguez-Pérez, Á.M. Hydrochemical Characterization of an Acid Mine Effluent from Concepcion Mine Using Classical Statistic and Fuzzy Logic Techniques. *Minerals* **2022**, *12*, 464. [CrossRef]
46. Grande, J.A.; Luís, A.T.; Córdoba, F.; Leiva, M.; Dávila, J.M.; Fortes, J.C.; Santisteban, M.; da Silva, E.F.; Sarmiento, A.M. Odiel River (SW Spain), a Singular Scenario Affected by Acid Mine Drainage (AMD): Graphical and Statistical Models to Assess Diatoms and Water Hydrogeochemistry Interactions. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8454. [CrossRef] [PubMed]
47. Terrones-Saeta, J.M.; Portela, D.C.; Luís, A.T.; Suárez-Macías, J.; Grande, J.A. Ceramics for Building Structures Made from Contaminated Soils: A Fuzzy Logic Intelligence Approach to Circular Mining. *Processes* **2023**, *11*, 1512. [CrossRef]
48. Suárez-Macías, J.; Terrones-Saeta, J.M.; Bernardo-Sánchez, A.; Ortiz-Marqués, A.; Castañón, A.M.; Corpas-Iglesias, F.A. Reutilisation of Water Contaminated by Mining Waste for the Encapsulation of Potentially Toxic Elements. *Materials* **2022**, *15*, 1076. [CrossRef]
49. Terrones-Saeta, J.M.; Suárez-Macías, J.; Bernardo-Sánchez, A.; Álvarez de Prado, L.; Menéndez Fernández, M.; Corpas-Iglesias, F.A. Treatment of Soil Contaminated by Mining Activities to Prevent Contamination by Encapsulation in Ceramic Construction Materials. *Materials* **2021**, *14*, 6740. [CrossRef]
50. Terrones-Saeta, J.M.; Suárez-Macías, J.; Castañón, A.M.; Gómez-Fernández, F.; Corpas-Iglesias, F.A. Retention of Pollutants Elements from Mine Tailings of Lead in Geopolymers for Construction. *Materials* **2021**, *14*, 6184. [CrossRef]
51. Terrones-Saeta, J.M.; Suárez-Macías, J.; Moreno-López, E.R.; Corpas-Iglesias, F.A. Leaching of Zinc for Subsequent Recovery by Hydrometallurgical Techniques from Electric Arc Furnace Dusts and Utilisation of the Leaching Process Residues for Ceramic Materials for Construction Purposes. *Metals* **2021**, *11*, 1603. [CrossRef]
52. Terrones-Saeta, J.M.; Suárez-Macías, J.; Corpas-Iglesias, F.A.; Korobiichuk, V.; Shamrai, V. Development of Ceramic Materials for the Manufacture of Bricks with Stone Cutting Sludge from Granite. *Minerals* **2020**, *10*, 621. [CrossRef]
53. Suárez-Macías, J.; Terrones-Saeta, J.M.; Iglesias-Godino, F.J.; Corpas-Iglesias, F.A. Retention of Contaminants Elements from Tailings from Lead Mine Washing Plants in Ceramics for Bricks. *Minerals* **2020**, *10*, 576. [CrossRef]