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COST-EFFECTIVE THERMAL-INSULATING BUILDING MATERIALS

CENENI IN UČINKOVITI TOPLOTNO IZOLATIVNI GRADBENI MATERIALI

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We report on the development of a formula for an adequate mix of aggregates to produce concrete blocks, which, while preserving high mechanical resistance, show good thermal insulation and reduced production costs. Three aggregates with different proportions were compared, consisting of pumice, wood shavings and basalt; the amounts of each material were 1800, 1970 and 2150 kg. A three-factor experimental design was applied to statistically determine the best factors for the response variables, namely, a high compression resistance and low thermal conductivity. The best mix obtained is composed of 250 kg of cement, 1970 kg of pumice and three amounts of sand with minor differences.

Keywords: thermal conductivity, thermal resistance, concrete block, aggregates

Avtorji poročajo o razvoju formule primerne za proizvodnjo betonskih blokov iz mešanice agregatov. Izdelani betonski bloki so poceni in imajo dobre mehanske ter termične izolativne lastnosti. Med seboj so primerjali tri vrste agregatov (lehnjak, lesne ostružke in bazalt), v različnih deležih, vsakega po (1800, 1970 in 2150) kg. Izvedli so trofaktorski eksperimentalni dizajn, da bi lahko statistično ovrednotili najboljše faktorje za izbrani optimalni vrednosti obeh spremenljivk; ti sta: najvišja tlačna trdnost in najnižja toplotna prevodnost. Na osnovi analize so ugotovili, da je najboljša mešanica sestavljena iz 250 kg cementa in 1970 kg lehnjaka. Pri tem pa so minimalne razlike v izbranih deležih peska (bazalta).

Ključne besede: toplotna prevodnost, termična upornost, betonski blok, izolacijski materiali

1 INTRODUCTION

It is well known that the average temperature on the planet surface is rising. Indeed, between 1901 and 2012, the global average surface temperature increased by about 0.89 °C,[1] and it is projected to rise by an additional 1.4 °C to 5.8 °C over the 21st century; this increase mainly depends on the emission trends of the greenhouse gases.[2–4] These changes in the temperature are occurring worldwide and they also affect regional weather because the heat in the atmosphere drives the climate system.[5] In the desert and high desert regions of the northern hemisphere, winters are cold and summers are hot. In such climates, the extreme temperatures, fluctuating in a range of –10–40 °C, increase the demand for thermal comfort, which brings, in turn, an increase in the energy consumption for heating, ventilation and air-conditioning systems. Therefore, there is a growing concern about the energy consumption in buildings needed for air conditioning and the likely adverse impacts on the environment.[6,7] In 2018, the U.S. Energy Information Administration reported a production of 106,877.162 PJ, and a consumption of 7,279.88 PJ only by the building sector in this country.[8] While in Mexico, in 2017, the consumption of the residential, commercial and public sectors was 74.89 GJ per capita, i.e., 5,498.89 PJ, of which 944.09 PJ was the consumption only in the residential sector.[9]

Nowadays, the International Energy Agency[10] is focusing on the efficient use of energy. In fact, buildings currently use up to 40 % of the primary energy consumption in most countries.[11–13] Also, 79 % of the world energy consumption comes from fossil fuel, which is a finite and non-renewable source.[14] Therefore, in recent years, both energy and environment have become high-priority areas for the developed and developing countries. The United Nations Industrial Development Organization promotes energy efficiency, with the aim of mitigating climate change and making industry environmentally sustainable.[15] Nevertheless, the economic/in-

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dustrial development and population boom in the last few centuries resulted in a huge increase in the energy demand with an annual incremental trend of about 2.3 %.[16] An alternative to reduce the energy consumption is the use of building envelopes. However, the use of building envelopes increases the thickness of the walls and requires a higher cost.

Hence, another possible alternative to reduce this high energy demand is the use of thermal building materials.[17] Generally speaking, the main properties of a thermal material is a low thermal conductivity and high thermal resistance. The thermal conductivity (λ) is one characteristic of concrete that can be changed when combined with other materials. It is defined as the quantity of the heat transmitted through a thickness unit in the direction normal to the surface of the unit area due to the unit temperature gradient under steady state conditions.[18] The thermal resistance of building materials is an important property while defining the total energy consumption of heating and cooling systems and achieving the optimal thermal comfort for the occupants.[19,20] Meanwhile, the thermal resistance is proportional to the thickness of a layer of the construction and inversely proportional to its conductivity:[21]

$$R=\frac{e}{\lambda} \tag{1}$$

where e is the thickness of the layer (m) and λ is the thermal conductivity (W m^{-1} K^{-1}).

The combined impact of the climate variables, such as the temperature, solar irradiation, wind and humidity on the energy balance of a building depends on the characteristics of the building, such as its design, orientation, mode of operation, maintenance, and construction materials. Concrete is the most widely used material in the world with an annual consumption of around five billion tons,[22] and the most used material in the construction industry is a concrete block, although its highest quality leads to higher housing prices, even more so when the heating and cooling costs are taken into account. Therefore, it is very important to develop better thermal qualities of concrete blocks, searching for adequate materials and the best mix for the improvement of the thermal insulation and acceptable strength.

Cement is the binding phase in concrete and it usually constitutes about 15–25 % of the concrete weight,[22] while the aggregates can constitute between 70 % and 80 %. One of the means to increase the efficiency of energy consumption in the case of building materials and, specifically, blocks of concrete, is based on the reduction of the cement percentage[23] as well as adding other materials, which may result in improved properties, such as the thermal resistance and compressive resistance.[24] The common aggregates for the reinforced concrete are plastics, clays, volcanic slag like basalt and pumice stone, rubber, cork and wood. Furthermore, one of the effects of swelling clay additions to concretes is an increase in the compressive yield stresses.[25]

Basalt is the most frequent rock in the earth crust. It has a vesicular texture, with traces of the bubbles produced by water vapor during the cooling of lava. Basalt is an inert, naturally occurring volcanic rock, with advantages in terms of cost[26] and because it can be aggregated without other additives. In addition, it is well known that less energy is needed for the production because of its production simplicity. Also, adding basalt to concrete increases the critical compressive strain and, consequently, the deformation capacity of geopolymer concrete can notably be improved.[27] Regarding wood shavings, they are easily acquirable, low-priced and renewable. When wood is added to concrete, a stable, compact, resistant and durable structure is obtained; at the same time, the alveolar structure causes a good thermal behavior and lowers the weight.[28] It exhibits an unlimited durability, without a chemical or biological degradation, and this is why it is considered one of the best ecological materials. Pumice stone is a natural material of volcanic origin; it is light and resistant; due to its properties, it helps to reduce the weight of concrete.[29]

This paper reports about a search for a formulation of a cost-effective mixture of materials, including three aggregates, for the production of concrete blocks with a high compressive resistance and low thermal conductivity. This is very important because the sustainable world's economic growth greatly depends on the use of new products in the construction industry.

2 MATERIALS AND METHODS

The manufacturing technology for concrete blocks is based on the Mexican Official Norms NMX-C-404-ONNCCE-2005 and NMX-C-441-ONNCCE-2005,[30,31] which have equivalents in other countries, specifically in the US and Europe. By definition, a concrete block is a prefabricated concrete piece, prism-shaped and with one or more vertical openings; it is used in masonry systems or simple structures, which opens the possibility of having strengthening pieces in both directions of its plane.[30] According to the Mexican Official Norm NMX-C-038,[32] for manufacturing concrete blocks, the thickness of each block must be at least 15 mm^2 and the dimensions of the blocks are (20 × 20 × 40) cm, based on the standard NMX-C-441-ONNCCE-2005.[32] Also, the compressive resistance was based on the standard NMX-C-036,[33] and the standard values are 40 kg f cm^{-2} for the standard line and 60 kg f cm^{-2} for the structural line.

In general, the properties of concrete are mainly determined by the quality of aggregates as they are the major constituents of concrete, typically occupying between 60 % and 80 % of the concrete volume.[34,35] The materials used in this study include ordinary Portland cement complying with the ASTM Type I standards, at an average percentage of 8.8 %, sand at an average percentage of 22 %, and the studied aggregates including pumice, basalt and wood shavings at an average percentage of 69 %.[36]

The block production process consists of vibration/compression of the mix, together with a conveyor feed of the materials into a mold, vibration and compression to displace air and enhance cohesion. After that, the blocks are placed in a cure chamber with controlled water vapor to obtain ready-to-use high-quality blocks within 24 h. The process involves molding in a Besser machine block, model Dynapac. The measured variables were: the thermal conductivity (R factor), compressive resistance and total thermal resistance (R_T). The thermal conductivity was obtained through the Netzsch equipment, model 2300 Lambda, which measures the heat flow in W m^{-1} K^{-1}. The compressive resistance was measured based on the ASTM C 31, C 39, C 617, C 1077 and C 1231 norms,[36] which are applied when testing the compressive resistance of concrete. Finally, the total thermal resistance is the sum of the partial thermal resistances and was obtained with Equation (2), which is based on Equation (1).

$$R_T = r_{si} + R_1 + R_2 + R_3 + r_{se} = \\ = \frac{1}{h_i} + \frac{L}{\lambda_1} + \frac{L}{\lambda_2} + \frac{L}{\lambda_n} + \frac{1}{h_e} \quad (2)$$

Here, L is the thickness of the material layer of the component (m); λ is the thermal conductivity of the material obtained with measurements (W m^{-1} K^{-1}); h_i is the conductance in the inner surface (W m^{-1} K^{-1}), the value used in this study was 8.1 W $m^{-1}K^{-1}$ based on the standard NOM-008-ENER-2001;[37] h_e is the conductance is the external surface (W m^{-1} K^{-1}) and its standard value is 13 W m^{-1} K^{-1}; n is the number of terms of the evolving portion. **Figure 1** presents a schematic representation of the partial compressive resistance.

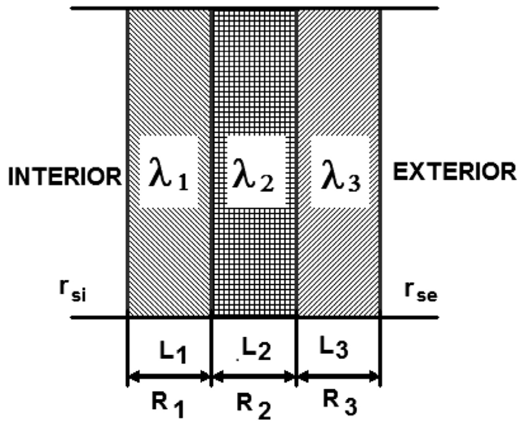

Figure 1: Schematic representation of the partial compressive resistance

2.1 Experimental set-up

The experimental work was performed based on a mixed factorial design of experiments. Three factors were selected: cement content, sand content, and the content of aggregates. For the first factor, we assigned two levels, 250 kg and 300 kg of cement. For the second and third factor, we assigned three levels, (550, 630 and 710) kg of sand, and (1800, 1970 and 2150) kg for each aggregate. Thirty-six samples were analysed and the resistance was measured for the blocks made of different mixtures of aggregates, obtaining twelve values for each aggregate: six values for the combination of cement, sand and aggregate, and two values for each combination of aggregate and sand.

2.2 Statistical analysis

A statistical analysis was performed using a Student's t-test and ANOVA. The former is used to compare the results of the mean compressive resistance for each aggregate, considering the levels of the sand and cement contents. Additionally, in order to determine if there is a significant difference in the average compressive resistance between the aggregates, a statistical analysis was applied involving an analysis of variance (ANOVA), using the SPSS statistical software, version 17.[38]

3 RESULTS AND DISCUSSION

This section presents the findings of the study. **Table 1** shows the results obtained with the study and we can see in the second column that the thermal conductivity is lower than the standard value for concrete, with values of 0.265 W m^{-2} K^{-1} for pumice, 0.274 W m^{-2} K^{-1} for basalt and 0.229 W m^{-2} K^{-1} for wood shavings. When compared to the standard value obtained for the concrete without an aggregate, there are differences of (37, 35 and 45) %, respectively, given that according to F. M. Díez Ramírez et al.[21] the coefficient of thermal conductivity of dry concrete fluctuates in a range of 0.09–2.30 W m^{-2} K^{-1}, and depends on the type of aggregate, its composition and air content. In the case of this study, the standard

Table 1: Thermal conductivity, thermal resistance, total thermal resistance and mean compressive resistance for each aggregate

Material	Thermal conductivity (W m^{-2} K^{-1})	Thermal resistance (m^2 K W^{-1})	Total thermal resistance (m^2 K W^{-1})	Mean compressive resistance (kg f cm^{-2})
Pumice	0.265	0.755	1.036	57.50
Basalt	0.274	0.730	1.011	56.00
Wood shavings	0.229	0.875	1.156	46.00
Concrete	0.420	0.390	0.400	40.00

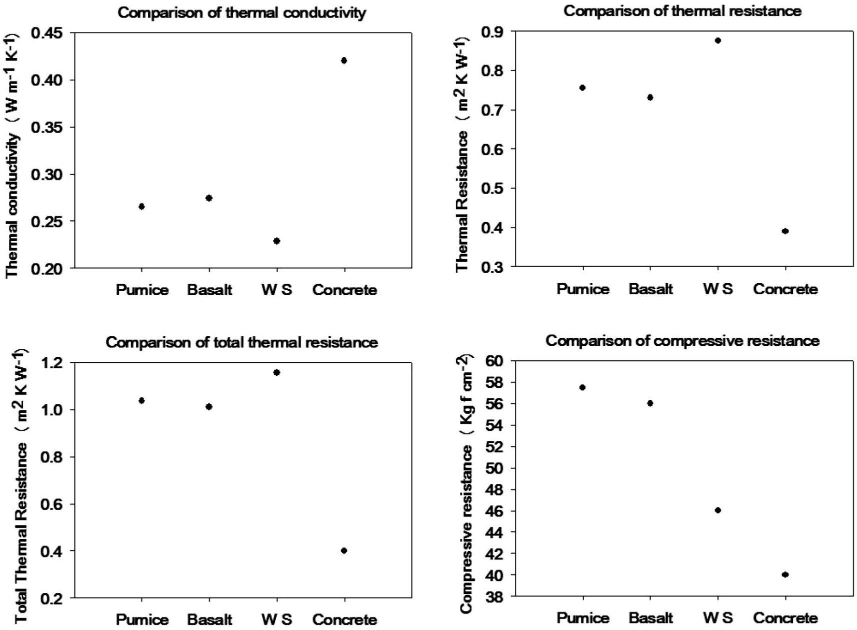

Figure 2: Comparison of the results for pumice, basalt, wood shavings (ws) and concrete, for four measured variables: a) thermal conductivity, b) thermal resistance, c) total thermal resistance, and d) mean compressive resistance

Table 2: Descriptive statistics for block compressive resistance: mean, standard deviation, minimum and maximum values

Cement (kg)	Sand (kg)	Pumice (kg)			Basalt (kg)			Wood shavings (kg)		
		1800	1970	2150	1800	1970	2150	1800	1970	2150
250	550	37	38	25	39	32	22	28	29	19
		33	39	28	35	32	29	25	24	22
	630	46	39	44	42	35	46	33	23	38
		42	44	47	46	47	43	38	31	38
	710	36	50	34	38	53	37	25	47	22
		37	52	33	39	56	36	21	40	20
300	550	57	51	51	55	55	49	52	45	39
		56	56	46	56	53	47	50	47	34
	630	54	58	50	56	57	52	41	45	45
		51	57	49	52	55	46	43	47	46
	710	54	51	42	55	54	39	46	45	31
		57	54	46	59	57	41	51	42	39
Mean		46.67	49.08	41.25	47.67	48.83	40.58	37.75	38.75	32.75
Sd		9.23	7.28	8.94	8.70	9.93	8.65	11.11	9.31	9.75
Min		33	38	25	35	32	22	21	23	**19**
Max		57	58	51	**59**	57	52	52	47	46

value of the concrete was 0.42 W m^{-2} K^{-1}. These results are better than the ones reported by L. Gündüz,[39] who says that by adding pumice to a mix of cement and aggregate, a thermal conductivity of 0.34 W m^{-2} K^{-1} was obtained. In addition, our results are better than the ones from S. A. Marcott et al.[4] who reported a mean thermal conductivity of 1.25 W m^{-2} K^{-1}.

According to the results, in the case of the thermal resistance, the difference is significant and represents an increase of 93.6 % for pumice, 87.1 % for basalt and 124 % for wood shavings, in relation to the concrete standard value. At the same time, the mean compressive resistance measured for the blocks with added materials shows an important increase of (43.75, 40 and 15) % for pumice, basalt and wood shavings, respectively. The mix with pumice exhibits the best properties among the studied mixes. The results described are presented in **Figure 2**, which also gives the differences in the behaviour of the variables measured for the blocks with the concrete mix, sand and aggregates, in relation to the standard values for concrete blocks.

As mentioned above, the average percentages of the contents of the materials used are 8.8 % for cement, 22 % for sand and 69 % for the aggregates for each formula. **Table 2** shows the calculated compressive resistance. The minimum compressive strength was 19 kg f cm^{-2}, obtained by mixing 250 kg of cement, 550 kg of sand and 2150 kg of wood shavings. The maxi-

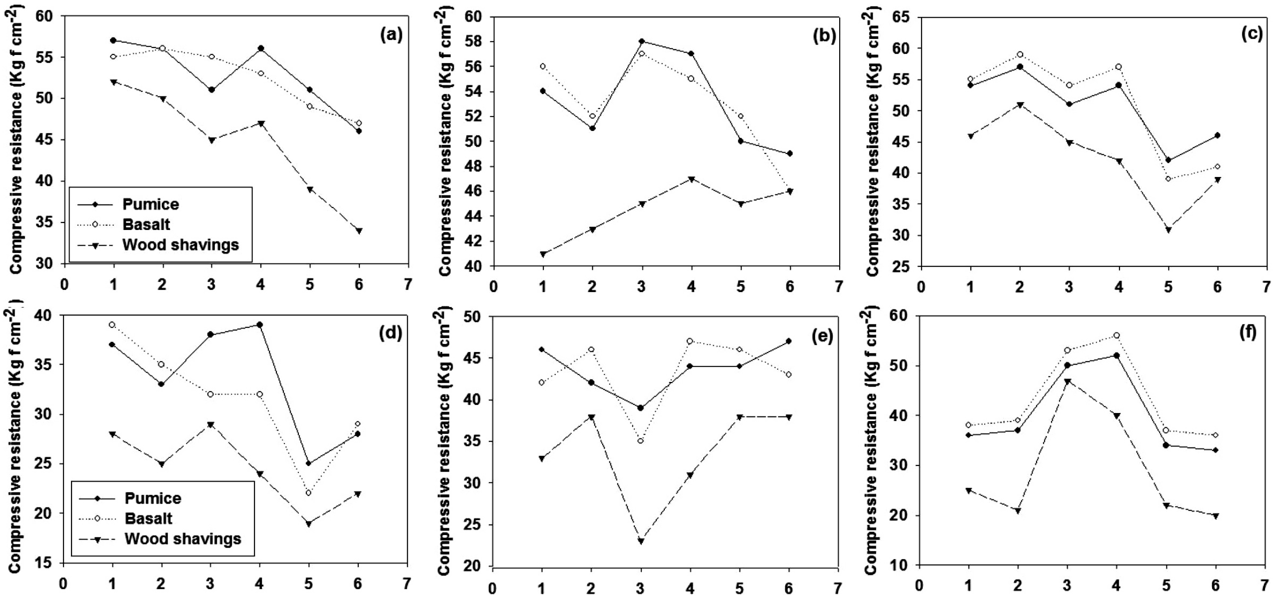

Figure 3: Comparison of the values for the total compressive resistance for three aggregates with three different levels of sand and two different levels of cement: a) 550, b) 630, c) 710 kg of sand for 250 kg of cement; d) 550, e) 630, f) 710 kg of sand for 300 kg of cement

Table 3: ANOVA of the compressive resistance

ANOVA aggregates					
	Sum of squares	df	Mean square	F	Sig.
Between groups	3172.241	8	396.530	4.621	.000
Within groups	8495.833	99	85.816		
Total	11668.074	107			

mum compressive strength was 59 kg f cm^{-2}, obtained by mixing 300 kg cement, 710 kg of sand and 1800 kg of basalt. According to the average and standard deviation values of 49.08 kg f cm^{-2} and 7.28 kg f cm^{-2}, respectively, the best mixture was obtained by adding 1970 kg of pumice. The lower mean value of compressive strength was obtained by adding wood shavings, the value being 32.75. However, with this material, we obtained a lower thermal conductivity and higher thermal resistance. Our results are similar to those reported by D. K. Panesar and B. Shindman[40] who obtained a compressive resistance of 79.5 kg f cm^{-2}, after 28 days of drying, of a mixture of 10 % CSandBlend + 10 % CStoneBlend and 80 % Portland cement. It is noteworthy that our blends contain only 9 % of cement and 22 % of sand. In our study, the aggregate predominates in the mixture with 69 %.

F. Pelisser et al.[23] combined cement and rubber, adding 40 % of this aggregate; the average thermal conductivity was 0.737 and the thermal resistance was 0.306. In the case of the thermal conductivity, our results are, on average, by 65 % lower, and in the case of the thermal resistance, our results are better by more than 100 %. **Figure 3** shows the behaviour of the compressive strength obtained with mixtures of different aggregates. We can see that, in all the cases, the compressive strength of different mixtures containing wood chips is lower than that of the mixtures containing pumice and basalt. Also, the pumice and basalt mixes show similar behaviours at all levels, including the mixes of 250 kg of cement, 630 kg and 710 kg of sand, and the mix of 300 kg of cement with 710 kg of sand.

4 STATISTICAL ANALYSIS

Table 3 reports the results of ANOVA. It indicates statistically significant differences between the results for the three aggregates. For this purpose, Student's t-test was used. **Table 4** shows significant differences between the three levels of each aggregate. The statistically significant differences were found in the case of the highest level, i.e., 2150 kg of both pumice and basalt, compared to the other two levels, 1800 and 1970 kg, except for the comparison between 1970 and 2150 kg of wood shavings. At the same time, **Table 5** shows Student's t-test for the three levels of the aggregates. In this case, significant differences observed between the mixtures containing wood chips and those containing pumice and basalt, have a .000 P-value for the three levels of the aggregate material studied. On the other hand, the results obtained for the mixtures containing pumice and basalt show no statistically significant differences.

The materials proposed in this study performed better than those reported by O. Ünal et al.[41] who used dio-

Table 4: Student's t-test of the compressive resistance at three levels of each aggregate

		Paired differences					t	df	Sig. (2-tailed)
					95 % confidence interval of the difference				
		Mean	Std. deviation	Std. error mean	Lower	Upper			
Pair 1	P_1800 – P_1970	–2.42	7.05	2.04	–6.90	2.06	–1.18	11	.260
Pair 2	P_1800 – P_2150	5.42	5.11	1.47	2.17	8.66	3.67	11	**.004**
Pair 3	P_1970 – P_2150	7.83	7.25	2.09	3.23	12.44	3.74	11	**.003**
Pair 4	B_1800 – B_1970	–1.17	7.57	2.18	–5.97	3.64	–0.53	11	.604
Pair 5	B_1800 – B_2150	7.08	6.79	1.96	2.77	11.40	3.62	11	**.004**
Pair 6	B_1970 – B_2150	8.25	8.23	2.37	3.02	13.48	3.47	11	**.005**
Pair 7	WS_1800 – WS_1970	–1.00	10.25	2.96	–7.51	5.51	–0.34	11	.742
Pair 8	WS_1800 – WS_2150	5.00	7.65	2.21	0.14	9.86	2.26	11	**.045**
Pair 9	WS_1970 – WS_2150	6.00	11.21	3.24	–1.12	13.12	1.85	11	.091

Table 5: Student t-test for the compressive resistance between three agreggates

		Paired differences					t	df	Sig. (2-tailed)
					95 % confidence interval of the difference				
		Mean	Std. dev	Std. error mean	Lower	Upper			
Pair 1	P_1800 – B_1800	–1.00	2.13	0.62	–2.35	0.35	–1.62	11	.132
Pair 2	P_1800 – WS_1800	8.92	3.65	1.05	6.59	11.24	8.45	11	**.000**
Pair 3	B_1800 – WS_1800	9.92	3.99	1.15	7.38	12.45	8.61	11	**.000**
Pair 4	P_1970 – B_1970	0.25	4.07	1.18	–2.34	2.84	0.21	11	.835
Pair 5	P_1970 – WS_1970	10.33	3.92	1.13	7.85	12.82	9.14	11	**.000**
Pair 6	B_1970 – WS_1970	10.08	4.21	1.22	7.41	12.76	8.30	11	**.000**
Pair 7	P_2150 – B_2150	0.67	2.93	0.85	–1.20	2.53	0.79	11	.448
Pair 8	P_2150 – WS_2150	8.50	3.40	0.98	6.34	10.66	8.67	11	**.000**
Pair 9	B_2150 – WS_2150	7.83	5.02	1.45	4.64	11.03	5.40	11	**.000**

tomite as the aggregate and cement contents of 250 kg and 300 kg, obtaining average compressive strengths of 42 kg f cm^{-2} and 51 kg f cm^{-2}, respectively. In the same study, these authors reported a thermal conductivity of 0.314 W m^{-1} K^{-1}. This is lower by (15, 12 and 27) % than for pumice, basalt and wood shavings, respectively.

5 CONCLUSIONS

This study verifies the adequateness of the material aggregation for the production of high-strength lightweight concrete blocks. Because of various concrete mixes and the use of standard techniques, it was possible to obtain a high-quality lightweight concrete mix, suitable for application in reinforced-concrete structures.

According to the results, the recommended mix determined during this project includes 1970 kg of pumice, with minimum and maximum values of 38 kg f cm^{-2} and 58 kg f cm^{-2}, respectively, a mean value of 49.08 and a standard deviation of 7.28. It is recommended to continue the search for other natural materials and the best formulations to improve concrete blocks and production processes.

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