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Characteristics and properties of lightweight concrete manufactured with cenospheres

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Abstract

The cenospheres produced in a coal-burning power plant have been characterized and the manufacture of lightweight concrete using this residue has been studied. Different concrete specimens were manufactured using powder-packing theory in order to obtain concrete with the lowest possible density. Several tests related to different properties like density, porosity, thermal conductivity, freezing and acoustic behavior were subsequently carried out and different equations that relate certain properties to others are formulated. The dependence between density and resistance to flexion or compression, the relationships between thermal conductivity and density and also between conductivity and resistance were carried out. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Packing; Cenospheres; Light concrete; Comprensive strength; Thermal conductivity

1. Introduction

In the processes of electrical energy generation in coal-burning power plants that consume pulverized solid fuels, cenospheres are produced as one of the solid residues that, as a result of their characteristics and properties, could be used as aggregate in the manufacture of lightweight concrete.

Cenospheres have a similar composition and form to fly ashes, though greater in size. The properties of cenospheres depend on the selection of coals and on grinding operations, combustion and withdrawal in the process of electrical energy generation.

The aim of this work was to study the possibility of using cenospheres as aggregate to manufacture lightweight concrete. Mechanical resistance, thermal conductivity and acoustic absorption were studied. The main advantage presented by cenospheres in comparison with other competitive filling compounds is their light weight since they are hollow.

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2. Experimental

2.1. Characteristics of cenospheres

Cenospheres from the Narcea (Asturias, Spain) coal-burning power plant, which burns anthracites, were employed.

Regularity in their properties is an indispensable requirement in all raw materials, since variability impairs the manufacturing processes in which they are used. Therefore, the taking of a fortnightly sample during 3 months was established.

The following characterization of the cenospheres was carried out: chemical analysis by atomic absorption spectroscopy with a PYE UNICAM SP9 apparatus, analysis of X-ray diffraction ($k\alpha = 1.54$Å) using a Phillips apparatus. A helium autopycnometer, Micromeritics model 1320, was used to calculate density and the granulometric analysis was done using sieves.

The chemical analysis (Table 1) demonstrates that the chemical composition is maintained practically constant over all the time studied.

Cenospheres are largely made up of a vitreous phase and a small proportion of quartz (Fig. 1). The existence of the vitreous phase is detected by the presence of the so-called "diffuse band," which is located in the interval $2\theta = 20-26°$.

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Table 1
Chemistry composition of the cenospheres withdrawals fortnightly during 3 months

Sample	Al_2O_3 (wt.%)	SiO_2 (wt.%)	Fe_2O_3 (wt.%)	CaO (wt.%)	MgO (wt.%)	Na_2O (wt.%)	K_2O (wt.%)	TiO_2 (wt.%)
1ªQ	26	56	7.0	4.7	1.9	0.53	3.2	1.2
2ªQ	24	56	6.9	4.1	2.1	0.50	3.5	1.1
3ªQ	24	55	6.8	4.3	2.2	0.49	3.4	1.1
4ªQ	24	55	7.1	4.4	2.2	0.48	3.4	1.1
5ªQ	24	57	6.8	4.3	2.2	0.37	3.3	1.2
6ªQ	25	56	6.9	4.2	2.2	0.35	3.4	1.2

The density of ground cenospheres (Table 2) is higher than the density of the unground cenospheres, which indicates that the cenospheres are principally hollow (Fig. 2). Two classes of cenospheres exist, some close (close porosity) and another open (open porosity). The closed porosity will not interact with penetrating fluid but open porosity will be accessible to it. Close cenospheres is formed by a solid phase that constitute their wall and an interior gas that has remained inside. The density of cenospheres or true density is obtained by dividing the mass by volume not accessible to fluid. When the cenospheres were grinding, the interior volume of cenospheres would already be accessible and the true density of the solid that constitutes the wall of the cenospheres is obtained.

The mean density of cenospheres is 995 kg/m^3, which is within the density interval of expanded clay, which is located between 600 and 1600 kg/m^3 [1].

The apparent density is obtained by dividing the cenospheres mass by volume that they occupy, accessible or not, increasing the existent porosity between them. Therefore, the volume increases and the density diminishes. It was determined by measuring the volume that occupies a well-known mass of cenospheres with a packing by vibration.

The fractional density is the density expressed as a fraction of the theoretical density for the material. It is equal to the unit less the porosity, this being the fraction of volume not occupied by the solid particles.

The granulometric analysis (Table 3) demonstrates that most of the cenospheres, more than 50%, range between 1.50 and 2.00 mm. And that cenospheres greater than 4 mm or smaller than 0.2 mm practically do not exist.

The form of the cenospheres is virtually spherical (Fig. 2). Therefore, they are highly appropriate for carrying out studies of packing.

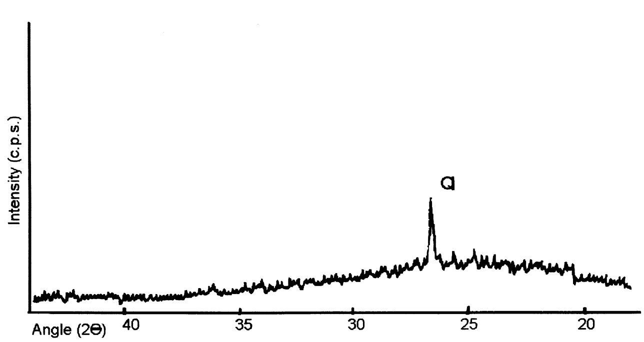

Fig. 1. Diffractograph of cenospheres.

2.2. Powder-packing theory

Different packings of cenospheres were studied, gross and with different granulometric fractions, in order to obtain concrete with the lowest possible density.

An attempt was made to reduce porosity by increasing the fractional density; thus decreasing the quantity of paste, and hence cement, that would be necessary for the manufacture of the concrete, though always within the limits that should be observed in the subsequent uses to be given to it. This increase in the fractional density not only produces a decrease in the quantity of cement needed, but furthermore, a number of interesting variations are produced with respect to thermal and acoustic properties [2,3].

Once the particles greater than 5 mm were eliminated, the density of packing of the gross cenospheres was studied, as well as that of different mixtures, combining particles of two different sizes since it produces higher packing densities than that with a single particle size. The smallest particles must to be chosen in such a way that they may occupy the holes left by the large particles, without forcing the latter particles to be separated.

To study the improvements in the density of packing, cenospheres were classified in six granulometric fractions and six different bimodal mixtures were examined.

One of the problems with cenospheres is that they do not present large variations in size (Table 3), and hence the difficulty of improving the fractional density, that is to say, the relation of the bulk density over the true density.

The six bimodal mixtures that were studied were: three with the large fraction of with a mean diameter (D_m) of 4.50 mm and the fine fractions of $D_m = 1.75$, 1.25 and 0.6 mm; two with the large fraction, $D_m = 3.60$ mm, and the fine, $D_m = 1.25$ and 0.60 mm; and one with $D_m = 2.60$ mm with one of 0.60 mm.

Table 2
Densities of the cenospheres (kg/m^3)

Samples	Density of cenospheres (true density)	Density of grinding cenospheres
1ªQ	997	2616
2ªQ	1003	2595
3ªQ	993	2590
4ªQ	995	2609
5ªQ	991	2590
6ªQ	991	2598

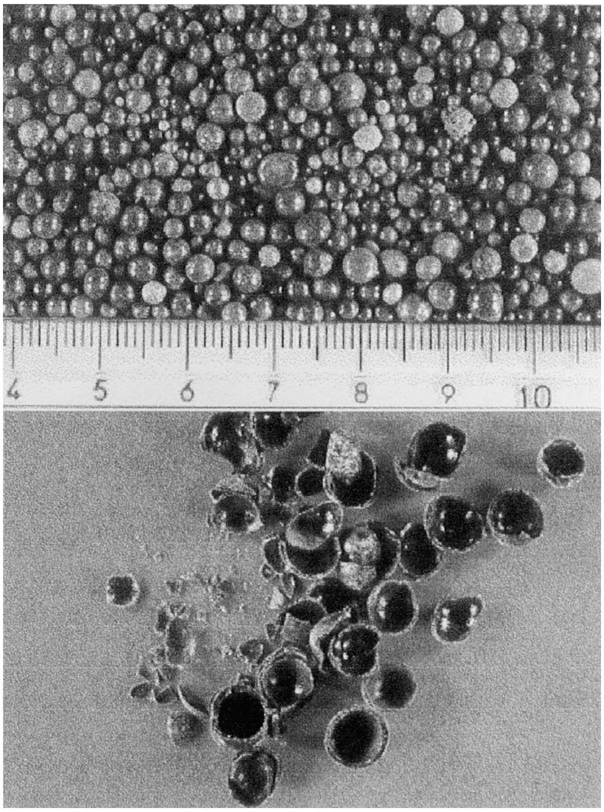

Fig. 2. Photographs: Different size of cenospheres and some broken cenospheres.

The amount of void space left by the large particles are [Eq. (1)]

$$1 - f_g \tag{1}$$

where f_g is fractional density. The weight of large particles is calculated as:

$$W_g = f_g \rho_g \tag{2}$$

where ρ_g is the density.

Small particles fill the void space with the fractional packing density f_g. The weight fraction of small particle is giving as follows

$$W_s = \rho_s (1 - f_g) f_s \tag{3}$$

where ρ_s is the density of small particles.

Dividing Eqs. (2) and (3), the saturation composition of large particles was obtained [Eq. (4)]:

$$X_g = \frac{W_g}{(W_g + W_s)} = \frac{\rho_g f_g}{[\rho_g f_g + \rho_s (1 - f_g) f_s]}. \tag{4}$$

In the case where the two particles making up the bimodal mixtures are of the same composition, the density of the small and large particles will be the same, $\rho_s = \rho_g$

In order to obtain a mixture with the maximum packing density, X_g, which is the fraction in weight of the larger cenospheres, should be calculated [Eq. (5)]:

$$X_g = \frac{f_g}{f_g + f_s - f_g f_s} \tag{5}$$

where X_g is the fraction in weight of the large particles, f_g is the fractional density of the large particles and f_s is the fractional density of the fine particles.

The decrease in theoretical volume according to Mangelsdorf and Washington [2] [Eq. (6)]:

$$\Delta V = A (V_g + V_s) X_g X_s \tag{6}$$

where (Eq. (7))

$$A = 0.039 \left[4 \frac{V_g - V_s}{V_g + V_s} \right]^2 \tag{7}$$

and V_g is the specific volume of the large particles, X_g is the fraction in weight of the large particles, V_s is the specific volume of the small particles and X_s is the fraction in weight of the small particles.

An experimental packing was carried out to prove that the theoretical values presented above are valid. The percentage of the large fraction was varied, calculating at the same time the volume, the fractional density and the dense volume. Experimental results adjusted well to the theoretical ones, as can be seen in Table 4.

Table 3
Granulometric analysis and densities of gross cenospheres and different granulometric fraction

Interval (mm)	Weight percent	Apparent density (kg/m^3)	True density (kg/m^3)	Fractional density (kg/m^3)
Gross		461	995	464
4.00–5.00	0.70	451	950	474
3.15–4.00	11.9	452	968	467
2.00–3.15	18.7	470	938	501
1.50–2.00	55.0	489	939	521
1.00–1.50	9.7	462	1020	453
0.20–1.00	4.0	480	1143	420
< 0.20	≈ 0			

Table 4
Percentage of larger cenospheres fraction and decrease of volume in the experimental packing of different bimodal mixture

Composition of the mixture	Percent of larger fraction	ΔV theoretical	ΔV measured
$D_{4.50}-D_{1.75}$	67.99	6.68	7.7
$D_{4.50}-D_{1.25}$	65.61	10.38	11.4
$D_{4.50}-D_{0.60}$	67.17	16.35	13.1
$D_{3.60}-D_{1.25}$	65.57	7.98	8.3
$D_{3.60}-D_{0.60}$	67.14	14.85	13.2
$D_{2.60}-D_{0.60}$	66.26	12.18	14.3

Table 5
Densities of the different mixtures

Mixture composition	Apparent density (kg/m^3)	True density (kg/m^3)	Fractional density (kg/m^3)
$D_{4.50}$–$D_{1.75}$	500.0	994	503.0
$D_{4.50}$–$D_{1.25}$	505.6	1012	499.6
$D_{4.50}$–$D_{0.60}$	542.2	1059	512.0
$D_{3.60}$–$D_{1.25}$	505.1	1002	504.1
$D_{3.60}$–$D_{0.60}$	543.5	1048	518.6
$D_{2.60}$–$D_{0.60}$	537.6	1070	502.4

Fractional density increases on increasing the difference between the diameters of granulometric fractions that make up the bimodal mixture (Table 5). Thus, the fractional density is 464 kg/m^3 for gross cenospheres and 518.6 kg/m^3 in the best of the studied cases, which means an increase by 12%. Furthermore, an increase in the fractional density was observed in all the cases.

2.3. Design and preparation of concrete using powder-packing theory

Several specimens were manufactured using the gross cenospheres in some cases, only one granulometric fraction in others and finally a mix of cenospheres with two different sizes.

The Portland cement used was type II-C/35/MR, the relationship (water/cement) $W/C = 3/10$ always being maintained.

Some specimens were manufactured with all the holes filled with paste and others leaving a part of the pores unfilled.

Having chosen a volume of cenospheres, the necessary quantity of paste (cement + water) was calculated, both for concrete with the holes left by the particles in the packing process completely filled with paste, as well as leaving a part of this without filling.

To ascertain the amount of cenospheres, water and cement needed for the manufacture of each specimen, the apparent density of the cement, $\rho_C = 1286$ kg/m^3, was measured. The decrease in volume of the paste with respect to the volume that the water and the cement would occupy separately (30.6%) was calculated.

Once the specimen to be manufactured, with its corresponding percentage of holes without filling, has been chosen, the amount of each component was obtained by means of a simple calculation.

Let us call V as the volume of concrete to be manufactured (m^3), H as the percentage of holes not filled with paste, R as the true density of the fraction or chosen bimodal mixture (kg/m^3), A as the apparent density of the fraction or chosen bimodal mixture (kg/m^3), T as the percentage of large fraction that gives the maximum density of packing, for the chosen bimodal mixture, C as the amount of cement, W as the amount of water and F as the amount of cenospheres.

The volume of holes to be filled by the cement paste will be [Eq. (8)]:

$$V_{hr} = V(1 - 0.01H)\left[1 - \frac{A}{R}\right] \quad (8)$$

but as there is a decrease in the theoretical volume of water and cement separately, the volume prior to the mixture will be [Eq. (9)]:

$$V_{prior} = V_w + V_c = \frac{1}{1 - 0.306} V(1 - 0.01H)\left[1 - \frac{A}{R}\right]. \quad (9)$$

As the weight relations employed in all specimens is $W/C = 0.3$, the volume relationship will be [Eq. (10)]:

$$\frac{V_w}{V_c} = \frac{\frac{W}{\rho_w}}{\frac{C}{\rho_c}} = \frac{W}{C}\frac{\rho_c}{\rho_w} = 0.3 \times 1286. \quad (10)$$

Resolving the equations system, a solution expressed in volume was obtained [Eqs. (11)–(14)]:

$$V_c = \frac{1}{1.3858}\frac{1}{1 - 0.306} V(1 - 0.01H)\left[1 - \frac{A}{R}\right], \quad (11)$$

$$V_c = 1.0398V(1 - 0.01H)\left[1 - \frac{A}{R}\right], \quad (12)$$

$$V_w = \frac{0.3858}{1.3858} 1 - 0.306V(1 - 0.01H)\left[1 - \frac{A}{R}\right], \quad (13)$$

$$V_w = 0.4011V(1 - 0.01H)\left[1 - \frac{A}{R}\right]. \quad (14)$$

To ascertain the amount of cement and water, we multiply by their respective densities [Eqs. (15) and (16)].

$$C = 1.3372V(1 - 0.01H)\left[1 - \frac{A}{R}\right], \quad (15)$$

$$W = 0.4011V(1 - 0.01H)\left[1 - \frac{A}{R}\right]. \quad (16)$$

Table 6
Cement, water and cenospheres quantities in concrete manufactured with gross cenospheres

Holes without filling (%)	Cement (kg)	Water (m^3)	Cenospheres (m^3)
0	717.2	0.2151	0.4636
10	645.5	0.1936	0.4636
20	573.8	0.1721	0.4636
25	537.9	0.1614	0.4636
30	502.1	0.1506	0.4636
40	430.3	0.1291	0.4636
50	358.6	0.1076	0.4636

Table 7
Densities and porosities of different specimens manufactured with gross cenospheres, with different granulometric fractions and with bimodal mixtures

Specimen	ρ_r (kg/m^3)	ρ_a (kg/m^3)	ρ_g (kg/m^3)	ρ_a (%)	ρ_c (%)	ρ_t (%)
BOP	2444	1478	1304	11.82	34.84	46.66
B10P	2444	1490	1292	13.28	33.87	47.14
B20P	2444	1502	1290	14.09	33.11	47.20
B25P	2444	1543	1277	17.19	30.54	47.73
B30P	2444	1531	1268	17.53	30.57	48.10
B40P	2444	1556	1264	18.79	29.48	48.27
B50P	2444	1561	1246	24.56	24.45	49.01
$D_{4.50}$	2444	1556	1351	13.17	31.54	44.71
$D_{3.60}$	2444	1570	1355	13.67	30.89	44.56
$D_{2.60}$	2444	1562	1347	13.75	31.14	44.89
$D_{1.75}$	2444	1583	1372	13.35	30.52	43.87
$D_{1.25}$	2444	1507	1289	14.44	32.81	47.25
$D_{0.60}$	2444	1490	1294	13.14	33.92	47.06
4.5–1.75	2444	1538	1340	12.85	32.31	45.16
4.5–1.25	2444	1474	1292	12.34	34.78	47.12
4.5–0.60	2444	1433	1270	11.35	36.69	48.03
3.6–1.25	2444	1499	1307	12.86	33.68	46.54
3.6–0.60	2444	1431	1257	12.18	36.40	48.59

The total volume occupied by the cenospheres is [Eq. (17)]:

$$F = V\frac{A}{R}, \tag{17}$$

and the volume of the greater fractions, G, and smaller ones, S, in bimodal mixtures, are [Eqs. (18) and (19)]:

$$G = 0.01VT\frac{A}{R}, \tag{18}$$

$$S = F - G = V\frac{A}{R} - 0.01TV\frac{A}{R} = V\frac{A}{R}(1 - 0.01T). \tag{19}$$

Multiplying by the corresponding true density, the amount of cenospheres was obtained. Table 6 lists the quantities of cement, water and cenospheres needed to manufacture 1 m^3 of concrete using gross cenospheres. For the gross cenospheres, $A = 461.3$ kg/m^3 and $R = 995$ kg/m^3.

Specimens were prepared by mechanical pugging and compacting in different moulds depending on the test to which they were to be submitted, in a mechanical vibration compactor. For the mechanical resistance test, specimens of $40 \times 40 \times 160$ mm were used, while to calculate the thermal conductivity, the specimens were of $40 \times 90 \times 160$ mm.

The specimens have to be cured in a moist atmosphere for 24 h at $20 \pm °C$ and $\geq 95\%$ relative humidity. Subsequently, some specimens remained in the moisture chamber and others were submerged immediately in water until testing. In the case of the mechanical resistance test, they were withdrawn from the water at the required age, were broken into two pieces by means of the flexion trial and

Table 8
Mechanical resistances of specimens

Specimen	Density (kg/m^3)	σ_f (MPa) 3 days	σ_f (MPa) 7 days	σ_f (MPa) 28 days	σ_c (MPa) 3 days	σ_c (MPa) 7 days	σ_c (MPa) 28 days
Gross	1415	4.02	4.58	5.05	25.88	28.88	30.09
B10P	1387	3.80	4.15	4.34	24.44	26.00	27.00
B20P	1368	3.35	3.88	4.20	18.56	23.94	25.63
B25P	1325	3.20	3.69	4.13	16.69	19.50	21.66
B30P	1308	2.73	2.90	3.91	9.50	11.56	14.78
B40P	1228	2.05	2.57	2.86	7.88	9.25	11.06
B50P	1090	1.21	1.60	2.09	2.00	4.25	5.04
$D_{4.50}$	1510	4.59	5.22	5.86	26.38	27.50	33.03
$D_{3.60}$	1502	4.44	4.77	5.43	24.31	2.38	32.75
$D_{2.60}$	1479	3.98	4.74	5.39	26.06	27.00	30.25
$D_{1.75}$	1474	3.87	4.71	5.27	23.56	25.69	28.84
$D_{1.25}$	1428	3.79	4.25	4.84	24.00	25.06	28.31
4.50–1.75	1439	3.71	4.40	4.80	22.44	24.81	28.08
4.50–1.25	1419	3.68	3.92	4.14	22.88	23.06	26.87
3.60–1.25	1429	3.86	4.00	4.78	20.44	24.06	27.22

each half was subsequently submitted to the compressive strength test according to the UNE 80-101 norm [4].

Specimens for thermal conductivity test were not submerged in water, remaining in the moist atmosphere, in some instances, for up to 28 days.

3. Experimental results

Global, true and apparent densities were measured, as well as the open, closed and total porosity of the different specimens by means of dousing methods.

Table 7 presents the values of the densities and porosities for the specimens manufactured with gross cenospheres, with different degrees of filling of the holes (B0P–B50P), for the specimens manufactured with different granulometric fractions ($D_m = 4.50-0.60$) and for the bimodal mixtures in their optimum composition. In the last two cases, the cement paste occupied the entirety of the holes left by the cenospheres.

Tests of mechanical resistances — flexion and compression — and volumetric density were carried out on specimens with 3, 7 and 28 days of curing (Table 8).

An exhaustive study was made of the thermal conductivity of the specimens after different days of curing. Subsequently, the same specimens were placed in an oven at 100°C during 72 h and their conductivity was measured again (Tables 9 and 10). Thermal conductivity was measured using a Shotherm Qtm-F1 apparatus.

Thermal conductivity was related to other variables, such as density, and mechanical resistance to flexion and to compression.

The freeze–thaw test was also carried out in accordance with the UNE 67-028-84 norm [4].

Table 9
Conductivity of different specimens

Specimen	K conductivity (W/m K)	K_c conductivity at 100°C (W/m K)
Gross	0.6016	0.4568
B10P	0.5786	0.4362
B20P	0.5630	0.4319
B25P	0.5470	0.4294
B30P	0.5464	0.4196
B40P	0.5216	0.4077
B50P	0.4628	0.3613
$D_{4.50}$	0.6925	0.5033
$D_{3.60}$	0.6644	0.4889
$D_{2.60}$	0.6593	0.4850
$D_{1.75}$	0.6433	0.4859
$D_{1.25}$	0.6113	0.4496
$D_{0.60}$	0.5860	0.4433
4.50–1.75	0.6289	0.4523
4.50–1.25	0.6147	0.4509
4.50–0.60	0.5584	0.4272
3.60–1.25	0.6128	0.4446
3.60–0.60	0.5871	0.4396

Table 10
Thermal conductivity of specimen from different ages of cured (5 and 28 days)

Specimen	K_5 (W/m K)	K_{28} (W/m K)	K_{5c} (W/m K)	K_{28c} (W/m K)
Gross	0.6003	0.6016	0.4539	0.4568
B10P	0.5739	0.5786	0.4358	0.4362
B20P	0.5625	0.5630	0.4298	0.4319
B25P	0.5432	0.5470	0.4286	0.4294
B30P	0.5442	0.5464	0.4187	0.4196
B40P	0.5211	0.5216	0.4052	0.4077
B50P	0.4599	0.4628	0.3611	0.3613

Finally, a study was made of the behavior of lightweight concrete manufactured with cenospheres in soundproofing.

4. Discussion of results

It was observed that a strong dependency exists between the density and the resistance to flexion (Fig. 3), giving rise to certain curves with the following expressions [Eqs. (20)–(22)]:

$$\sigma_{f3} = 2 \times 10^{-12} \rho^{3.90} \quad R = 0.978, \tag{20}$$

$$\sigma_{f7} = 5 \times 10^{-11} \rho^{3.47} \quad R = 0.979, \tag{21}$$

$$\sigma_{f28} = 1 \times 10^{9} \rho^{3.05} \quad R = 0.981, \tag{22}$$

where ρ is the volumetric density of the specimen expressed in kg/m^3.

The relationship between the density and the resistance to compression is similar, the equations in this case being [Eqs. (23)–(25)]:

$$\sigma_{c3} = 1 \times 10^{-23} \rho^{7.68} \quad R = 0.952, \tag{23}$$

$$\sigma_{c7} = 5 \times 10^{-18} \rho^{5.92} \quad R = 0.950, \tag{24}$$

$$\sigma_{c28} = 2 \times 10^{-17} \rho^{5.77} \quad R = 0.971. \tag{25}$$

It can be observed (Fig. 4) that the strength increases with cured time and the lowest resistance values are obtained in those specimens that have the lowest density.

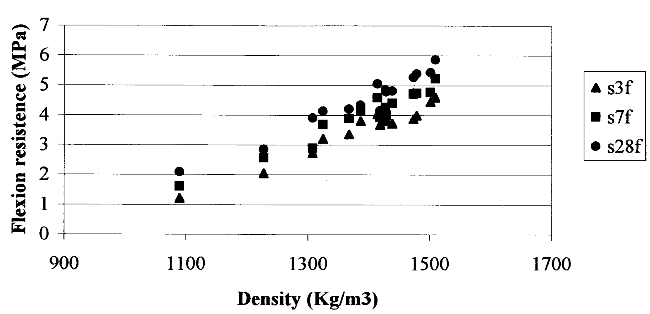

Fig. 3. Relationships between flexion resistance and density.

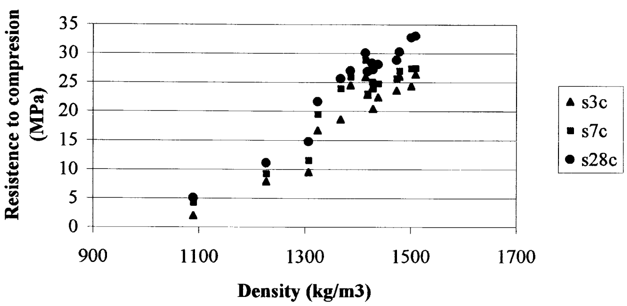

Fig. 4. Relationships between strength and density.

On analyzing the thermal conductivity of the different manufactured specimens (Table 9), it can be observed that the lowest values are obtained in those specimens that have part of the holes unfilled with paste, being lower when the proportion of these holes that remain unfilled is greater. The conductivity of specimens with all the holes filled is 0.6016 W/m K and that of specimens with half of the holes filled is only 0.4628 W/m K.

The specimens manufactured with a single granulometric fraction present a higher conductivity than those manufactured with gross cenospheres, except for the minor fraction of 0.60 mm. Furthermore, the said conductivity decreases with the decrease in the size of the cenospheres.

When working with bimodal mixtures, only a relative decrease in thermal conductivity is produced, with the bimodal mixture 4.50–0.60 mm, which in addition to being that with the greatest difference in sizes, is also composed of the scarcest fractions. It is hence of interest to eliminate the small fraction larger than 4.0 mm, which presents a high percentage of irregularities, and to manufacture the rest of the specimen with gross cenospheres.

The thermal conductivity was also measured in the specimens submitted to heating at 100°C during 72 h, a decrease in thermal conductivity higher than 20% being observed (Table 9).

The dependency between the thermal conductivity and the volumetric density was also analyzed; the best regression being obtained with an expression of the exponential type (Fig. 5) [Eqs. (26) and (27)]:

$$K = 0.165 \times 1.0009^{\rho} \quad R = 0.980 \tag{26}$$

$$K_c = 0.163 \times 1.0007^{\rho} \quad R = 0.971 \tag{27}$$

with the thermal conductivity being expressed in W/m K, and the density in kg/m^3.

The relationship between thermal conductivity and volumetric density was studied for specimens manufactured solely with gross cenospheres with different amounts of paste (Fig. 6).

The expressions obtained were [Eqs. (28)–(31)]:

$$K(28) = 0.205 \times 1.0007^{\rho} \quad R = 0.991, \tag{28}$$

$$K_c(28) = 0.179 \times 1.0007^{\rho} \quad R = 0.982, \tag{29}$$

$$K(5) = 0.203 \times 1.0008^{\rho} \quad R = 0.988, \tag{30}$$

$$K_c(5) = 0.180 \times 1.0006^{\rho} \quad R = 0.985. \tag{31}$$

The volumetric density of the concrete was related to thermal conductivity as well as mechanical resistances, a strong dependency being observed. It is hence logical to think that thermal conductivity might also be related to mechanical resistances.

A clear functional dependency exists in all the cases and thermal conductivity increases with an increase in the resistances. The relationships found were:

- resistance to compression (28 days):

$$K = 0.3785\sigma_{c28}^{0.1288} \quad R = 0.9716, \tag{32}$$

$$K_c = 0.2996\sigma_{c28}^{0.1035} \quad R = 0.9650, \tag{33}$$

- resistance to flexion (28 days):

$$K = 0.3812\sigma_{f28}^{0.2742} \quad R = 0.9758, \tag{34}$$

$$K_c = 0.3097\sigma_{f28}^{0.2534} \quad R = 0.9822. \tag{35}$$

A study was carried out of the thermal conductivity in relation to the curing time of the specimens manufactured with gross cenospheres (Table 10). Very similar values can be observed for 5 and 28 days. Thus, the conductivity may

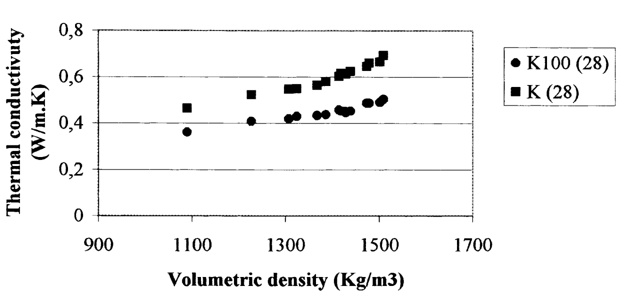

Fig. 5. Relation of thermal conductivity with volumetric density.

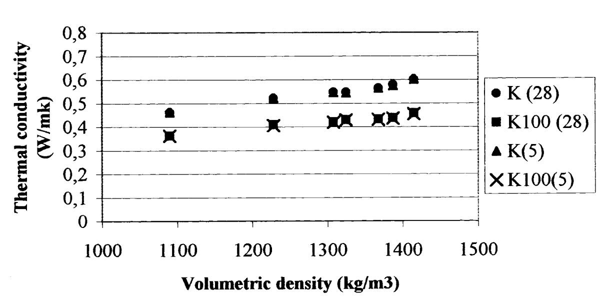

Fig. 6. Influence of amount of paste with the conductivity at different age of curing.

be measured at 5 days and the resistance to compression that concrete, which was cured for 28 days, will have may be estimated using Eqs. (32)–(35).

The soundproofing test made with the 4-cm thick concrete manufactured with cenospheres, at a frequency of 500 Hz, provided a loss of transmission $T_L = 18$ dB, which is a similar value to that obtained with concrete manufactured with expanded clays [5,6]. When compared with other materials, it is observed that a wall of the same thickness manufactured with traditional materials behaved better than the one manufactured with cenospheres. But when compared with a wall of the same weight, the losses in sound transmission are of the same order.

The lightweight concrete manufactured with cenospheres might be used to build noise-proof barriers, since it also fulfils basic static stability requirements and is resistant to weathering and to chemical agents. It also fulfils requirements of adequate acoustic damping, in addition to minimizing costs due to its lower weight and its ease of assembly.

With respect to the freezing test, all the pieces tested surpassed 25 ice–thaw cycles without producing exfoliation, fissures or splitting.

5. Conclusions

According to the granulometric analysis of the cenospheres obtained from the Narcea coal-burning power plant, the cenospheres have an average size of 1.80 mm and more than 50% belong to the granulometric fraction between 1.50 and 2.00 mm, there being practically no cenospheres smaller than 0.20 mm.

The mean density of the gross cenospheres is 995 kg/m^3, which is within the range of densities of expanded clay, situated between 600 and 1600 kg/m^3.

Only the specimen manufactured with gross cenospheres, with 50% of its holes unfilled with paste, does not fulfil the specification that its $\sigma_{c28} \geq 10$ MPa. All other specimens clearly surpass this value, thus obtaining the classification of structural concrete.

The lightweight concrete specimens with cenospheres, with all the holes covered by cement paste, presented values of σ_{c28} that oscillated between 27 and 33 MPa. For lightweight concrete of expanded vermiculite or perlite, σ_{c28} varies between 1 and 5.5 MPa, while for those made of expanded clays this will be between 17 and 40 MPa.

Thermal conductivity in the specimens with all the holes covered by cement paste decreases upon reducing the size of the granulometric fraction of the cenospheres used for manufacturing the specimen. When specimens were heated at 100°C during 72 h, an almost constant improvement in conductivity (of around 25%) was obtained for all pieces.

The greatest improvements in thermal conductivity were obtained when the percentage of holes not filled with cement paste was increased, though this resulted in a reduction in mechanical resistance. One must therefore look for a compromise between the improvement in conductivity and the loss in resistance to compression.

Comparing the results of the test made with specimens manufactured with gross cenospheres and with those manufactured with bimodal mixtures, it was proven that mechanical resistances stay constant or even decrease, while thermal conductivity improves 5% in the best of cases. Therefore, the classification in different granulometric fractions of the cenospheres is not profitable, with only a slight screening being advisable so as to separate the sizes greater than 4.00 mm, which present a high degree of irregularities.

Thermal conductivity remained almost constant after only 5 to 28 days of curing. There is a good correlation between thermal conductivity and mechanical resistances. An idea of the values that σ_{c28} and σ_{f28} will present can be obtained in just 5 days, ascertaining the thermal conductivity values and taking these to be the conductivity at 28 days.

The specimens obtained with this material may be classified as not freezing.

The total porosity of the manufactured specimens was situated between 44.5% and 48.5%. Open porosity of specimens ranged from 12% for those with all the holes filled with cement paste to 25% in those with only half the amount of cement paste.

The acoustic behavior of the lightweight concrete made with cenospheres is similar to that presented by lightweight concrete manufactured with expanded clay.

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