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INVESTIGATION OF THERMAL PROPERTIES OF SHIELDING CONCRETE

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ABSTRACT

The paper presents the results of investigation of the specific heat and the thermal conductivity of shielding concrete and the specific heat of selected crushed aggregates used to produce them. The results of the specific heat were obtained by two methods: a stationary method, using a calorimeter, and a non-stationary method. The obtained results were compared to the results available in the literature. In addition, in the case of measuring the specific heat, the results obtained with the two methods were compared and attempt has been made to explain the differences between them.

Keywords
shielding concrete, heavy aggregates, specific heat, thermal conductivity

INTRODUCTION

In the most common applications of structural concrete the influence of the mix design on its thermal properties is usually neglected or considered only during concrete hardening as in the case of heat induced deformation of massive elements. However, the thermal properties of hardened concrete are of primary importance for the performance of concrete shielding structures surrounding nuclear reactors used in nuclear power plants [1, 2]. The integrity of concrete containment plays a significant role in the whole nuclear safety system - the containment forms a biological barrier during normal operation and represents the final passive barrier against a release of radionuclides into the environment in a case of accidents.

The thermal exposure conditions on shielding concrete are defined by ASME 2007 [3]; the concrete temperature shall not exceed:

- during normal operating or post accident conditions over any prolonged periods,
  - (a) 65°C over large areas; or
  - (b) 95°C over local areas in the proximity of penetrations for hot piping; or
- during accident conditions or over any short periods on interior containment surfaces only
  - (a) 175°C over large areas; or
  - (b) 345°C over local area affected by impingements from steam or water jets.

The reactor vessels are usually designed to operate with concrete temperatures up to about 70°C, but higher accidental temperatures and some thermal cycling (due to a fuel cycle) are expected during the service life. So for a proper engineering design of shielding structures the thermal properties of hardened concrete are needed, in particular the thermal conductivity, the heat capacity and the coefficient of thermal expansion. Another aspect is a possible detrimental effect of long term elevated temperature on concrete strength [4] and permeability that is not considered in this paper.

Earlier studies summarized by S. Tatro [5] showed that different aggregates had different thermal properties and therefore their mineral composition and content had a major effect on thermal properties of concrete. For radiation-shielding concrete (RSC) applied in nuclear power structures most often high-density aggregates are used to attenuate gamma rays and light atomic weight aggregates are used to absorb neutrons [6]. The thermal conductivity of concrete, including RSC, falls within the range from 1.9 to 4.1 W/(m·K). The degree of saturation plays a major role because of a large (up to fourfold) difference in the thermal conductivity of hardened cement paste in a complete saturation state versus an oven-dry state [5]. The heat capacity of hardened concrete is usually within the range from 840 to 1170 J/(kg·K). Because of a high heat capacity of water, about 4200 J/(kg·K), the heat capacity of concrete increases with increasing moisture content, but decreases with the increase in concrete density. A recent review of such empirical relationships is presented in [7]. The mentioned thermal properties of aggregates are found to be dependent on their mineral composition, in particular the content of silica. Since an increased variability in the mineral composition of high-density aggregates is found [8] such a variability of the thermal properties can be expected.

The investigation of the thermal conductivity and the heat capacity of radiation shielding concrete was performed in regard to the currently planned nuclear power program in Poland. The range of investigated materials included also concrete from the first but unfinished nuclear power plant in Poland (in Żarnowiec), abandoned in 1989 [9], soon after a tragic disaster in Chernobyl nuclear power plant.

MATERIALS AND METHODS

Materials

Selected mineral aggregates adequate for RSC, were tested as well as three series of concrete specimens. The first series consisted of core specimens drilled in different parts of structural elements of the unfinished Polish nuclear power plant in Żarnowiec [9]. They are marked in the paper with symbols CNPP - x, where x is one of the letters: A, B , C , E, F and identifies the place of sampling. The concrete mix design is not available.

The second and third series, denoted by the symbols CP or CS, consisted of concrete specimens made with use of special crushed aggregate: magnetite, serpentine, barite and natural sand, and their mixtures. The reference concrete was made with crushed amphibolite aggregate. Concrete mix design is given in Table 1 and 2.

Methods

The thermal conductivity λ and specific heat C_p of concrete were determined using heat transfer analyser ISOMET 2104 from Applied Precision [10, 11, 12]. Measurements were made by means of a non-stationary method, in which thermal properties are assessed by analysing the rate of temperature changes of the specimen heated with a resistive head. The measuring head API 210413 of the following measurement range was used: from 2 to 6 W/(m·K) for the thermal conductivity and from 1.5 to $4.0 \cdot 10^6$ J/(m^3·K) for the volumetric heat capacity. The specific heat was obtained by dividing the measured volumetric heat capacity by the bulk density of the material. The specific heat of examined aggregates was determined using a developed calorimeter (Figure 1). This method was also used for comparative measurements on concrete specimens. The measurement consisted of heating the test material to a temperature of 80ºC and placing it in a calorimeter with known thermal parameters, filled with water of temperature in the range of 20-25ºC. After stabilization of the temperature the specific heat was calculated taking into account the mass of water and of the mass of the specimen.

Table 1: Concrete mix design of the CP series [kg/m^3]

Material	Concrete series		
	CP-1	CP-2	CP-3
cement CEM I 42.5R	375	-	-
cement CEM II/B-S 32.5R	-	375	375
water	169	169	169
natural sand 0-2 mm	-	-	638
magnetite 0-8 mm	1135	1135	319
magnetite 0-20 mm	2149	2149	1812
water-reducing admixture (WR)	3.53	3.64	3.23
concrete mixture density	3804	3815	3397

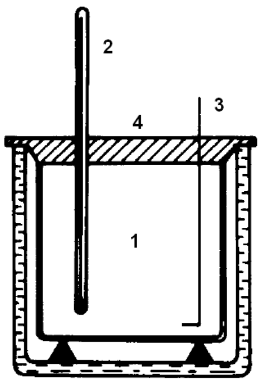

Figure 1. Scheme of the calorimeter test equipment: 1 - water vessel, 2 - thermocouple, 3 - mixer, 4 - lid, 5 - adiabatic jacket

Table 2: Concrete mix design of the CS series [kg/m^3]

Components	Concrete series						
	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7
cement CEM I 42.5R	350						
water	168						
natural sand 0-2 mm	-	-	-	593	-	519	-
amphibolite 2-8 mm	-	-	-	628	-	-	-
amphibolite 8-16 mm	-	-	-	750	-	-	-
magnetite 0-5 mm	-	1544	-	-	1510	805	-
magnetite 0-16 mm	-	-	1275	-	1846	1611	-
serpentinite 0-2 mm	673	-	654	-	-	-	454
serpentinite 2-8 mm	727	491	473	-	-	-	454
serpentinite 8-16 mm	418	491	-	-	-	-	-
barite 0-16 mm	-	-	-	-	-	-	1398
water-reducing admixture (WR)	6.02	8.51	10.4	1.40	5.95	4.34	10.0
high range water-reducing admixture (HRWR)	17.2	4.66	9.59	-	-	-	9.94
concrete mixture density	2292	3073	2859	2476	3886	3412	2776

Specimens

The non-stationary thermal testing was performed on flat specimens of the thickness of 25 or 30 mm. In case of CNPP series they were slices cut off from the cores with a diameter of about 95 mm and the measurements were performed in the middle of a disc. In the case of concretes of CP and CS series test specimens were cut from 150 mm cubes after 60 to 90 days from demoulding. Until then, the cubes were kept in water. After cutting the test pieces, they were re-immersed in the water. Tests on these specimens were performed by applying the measuring head at five points: near the center of the sample and its four corners, as shown in Figure 2.

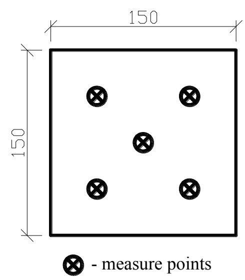

Figure 2: Location of measurement points on the specimen

Specimens of concrete series of CP and CS were tested in a fully saturated state and after drying them to constant weight at a temperature 105°C. This allowed to observe the influence of water content on the measured thermal properties. CNPP series were tested only in air-dry condition. The tests by means of calorimetric method were performed in two ways which differed in the sample preparation procedure. Samples of aggregates and concretes of CP series specimens were crushed in a jaw crusher to a grain size of less than 1 mm. So prepared powders were heated to temperature of about 80°C and then they were placed in water filled calorimeter. In case of CS series specimens were heated and placed in the calorimeter without crushing them beforehand. Flat plate specimens of the mass from 300 to 1000 grams, about 10 mm thick, were used. Due to the selected test procedure it was not possible to examine the effect of moisture content on the specific heat of the material.

TEST RESULTS

Thermal conductivity

In particular series of concretes the measurements of thermal conductivity and specific heat by means of non-stationary method were performed on different number of samples and in different number of measurement points, so the results were averaged from different number of measurements. Properties of concrete of CNPP series were averaged from three measurements. In the case of concretes of CP series the results were averaged from fifteen measurements for each concrete. In the case of concretes of CS series the results for saturated specimens were averaged from twenty measurements. Oven-dried CS specimens were tested only in three points: in the centre and near two of corners, and therefore results were averaged from twelve measurements. The average values of thermal conductivity of CNPP, CP and CS series are presented in Table 3 and 4.

Table 3. Thermal conductivity of concrete specimens of CNPP series

Specimen series	CNPP-A	CNPP-B	CNPP-C	CNPP-E	CNPP-F	CNPP average
λ [W/(m·K)]	2.48	2.19	2.35	2.46	2.28	2.35
COV* [%]	4.43	0.26	6.14	6.44	1.16	6.10

*) coefficient of variation

Table 4: Thermal conductivity of concrete specimens of CP and CS series

Specimen series		CP-1	CP-2	CP-3	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7
λ [W/(m·K)]	saturated	2.95	3.00	2.91	1.89	2.38	2.15	2.39	3.00	3.07	1.83
	oven-dried	2.36	2.40	2.35	1.45	2.10	1.65	1.97	2.51	2.37	1.35
COV* [%]	saturated	3.06	1.03	2.89	4.38	6.04	3.91	3.50	2.55	2.64	4.82
	oven-dried	2.38	0.89	3.32	4.95	4.77	3.83	4.13	6.26	4.11	3.90

*) coefficient of variation

Specific heat

The results of measurements of the specific heat of concrete are presented in Table 5. 6 and 7. In case of CP and CS series the measurements were performed with use of two test methods. The volumetric heat capacity measured by ISOMET apparatus and the bulk density was used to obtain the specific heat. Results of the measurements of the specific heat of aggregates performed by means of calorimetric method are given in Table 8.

Table 5: Values of specific heat - CNPP series

Concrete	average bulk density [kg/m^3]	specific heat ISOMET 2104 average [J/kg·K]	specific heat ISOMET 2104 COV* [%]
CNPP-A	2270	794	8.34
CNPP-B	2209	822	2.94
CNPP-C	2307	760	3.58
CNPP-E	2323	786	5.38
CNPP-F	2153	805	2.66
CNPP average	2252	793	5.03

*) coefficient of variation

Table 6: Values of specific heat - CP series

<table>
<tr><th rowspan="4">Concrete</th><th colspan="6">specific heat</th><th colspan="2" rowspan="3">average bulk density [kg/m^3]</th></tr>
<tr><th colspan="4">ISOMET 2104</th><th colspan="2">calorimeter</th></tr>
<tr><th colspan="2">average [J/kg·K]</th><th colspan="2">COV* [%]</th><th rowspan="2">average [J/kg·K]</th><th rowspan="2">COV* [%]</th></tr>
<tr><th>satu-rated</th><th>oven-dried</th><th>satu-rated</th><th>oven-dried</th><th>satu-rated</th><th>oven-dried</th></tr>
<tr><td>CP-1</td><td>483</td><td>481</td><td>13.89</td><td>4.56</td><td>681</td><td>---**</td><td>4011</td><td>3867</td></tr>
<tr><td>CP-2</td><td>466</td><td>470</td><td>4.02</td><td>2.28</td><td>778</td><td>0.39</td><td>3965</td><td>3843</td></tr>
<tr><td>CP-3</td><td>540</td><td>526</td><td>2.51</td><td>0.81</td><td>834</td><td>0.84</td><td>3447</td><td>3315</td></tr>
</table>

*) coefficient of variation; **) a single measurement

Table 7: Values of specific heat - CS series

Concrete	Specific heat					average bulk density [kg/m³]	
	ISOMET 2104				calori-meter [J/kg·K]		
	average [J/kg·K]		COV* [%]				
	satu-rated	oven-dried	satu-rated	oven-dried		satu-rated	oven-dried
CS-1	843	815	3.68	2.87	1059 ± 27	2325	2168
CS-2	639	589	3.93	4.35	854 ± 5	3148	3046
CS-3	667	657	3.94	3.20	894 ± 3	2900	2744
CS-4	827	739	4.23	2.84	891 ± 7	2520	2420
CS-5	564	528	9.70	3.10	779 ± 18	3765	3657
CS-6	619	548	1.10	2.02	779 ± 20	3369	3268
CS-7	673	643	2.33	2.50	813 ± 4	2890	2729

*) coefficient of variation

Table 8: Values of specific heat of aggregates

Aggregate	Specific heat [J/kg·K]
magnetite	779 ± 1
serpentinite	1071 ± 12
barite	463 ± 23
natural sand	813 ± 47

DISCUSSION

Thermal conductivity

On the basis of the measurements it can be concluded that in the case of CNPP concrete series the values of thermal conductivity obtained for different specimens are very close to each other. The average for all analyzed samples is λ = 2.35 W/(m·K). and the coefficient of variation is equal to 6.10 %. It indicates that. if the thermal conductivity is concerned. all the specimens are made of the material of the same properties.

The thermal conductivity of concrete specimens of the CP series also shows little variation within the range 2.91-3.00 W/(m·K). Considering the minor differences in the mix composition (Table 1) observed slight differences in measured values seem to be justified.

By far the greatest diversity of λ values was observed for CS series, where the minimum average value for the specimens in saturated state was $\lambda_{min.s}$ = 1.83 W/(m·K) (series CS-7). and in oven-dried state $\lambda_{min.d}$ = 1.35 W/(m·K) (series CS-7). The maximum value of the specimen in saturated state was $\lambda_{max.s}$ = 3.07 W/(m·K) (series CS-6) and in the fully dried state $\lambda_{max.d}$ = 2.51 W/(m·K) (series CS-5).

The analysis of concrete mix composition indicated that the smallest value of the coefficient of thermal conductivity was obtained in case of concrete containing barite-serpentine and serpentine aggregate. At the other extreme were the concrete mixes with magnetite aggregate. where the resulting thermal conductivity was the highest. Intermediate. close to each other. values have been obtained for concrete with amphibolite and magnetite-serpentine aggregate.

According to Kaplan [13] thermal conductivity of ordinary concrete is in the range 1.0 to 3.6 W/(m·K). Given in the same work values for a few of heavy concretes are: 0.8 W/(m·K) for serpentine concrete. 1.5-1.6 W/(m·K) for barite concrete and about 1.5 W/(m·K) in the case of magnetite-serpentine concrete. Obtained thermal conductivity values are generally within the cited range [13].

As expected. in the water saturation condition the concrete specimens exhibited a higher thermal conductivity than in the dry condition. The differences are from 13% in the case of series CS-2 to 36% in the case of series CS-7. wherein the average value is 25%. According to the investigation performed by means of a non-stationary method on mortars with varying degree of water saturation [14] the dependence of the thermal conductivity on water saturation was linear. and the average difference in values between the dry and saturated condition was about 26%.

Specific heat

The results of measurements of specific heat of concrete CNPP series show a similar proximity as the measurement results of the coefficient of thermal conductivity. The average value of all the results which have been determined by means of a non-stationary method. is 793 J/(kg•K). and the coefficient of variation is 5.03%.

In the case of CP series a clear difference in the measurement results can be seen between stationary and non-stationary method. The values obtained using the calorimeter were much higher than those obtained with the ISOMET 2104. the difference being about 37-40%. Test results obtained using both methods show the same trend: concrete specimens CP-3 with less magnetite content and more natural sand than concrete CP-2 showed a higher specific heat.

The discrepancies between the results obtained by means of calorimetric and non-stationary method were also found for CS series. They range from 13% for CS-4 series to nearly 32% in the case of CS-5 series. However both methods result in similar trends related to concrete mix design. In both methods. the maximum value of the specific heat was obtained for CS-1 series which is the serpentine concrete. The specific heat measured by means of the non-stationary method has been 843 J/(kg·K) in the saturated state. 815 J/(kg·K) in the dry state. and 1056 J/(kg·K) when measured with use of calorimeter. The smallest value of specific heat was obtained for CS-5 concrete. for which by the means of non-stationary method values measured in the saturated and the dry state were 564 and 528 J/(kg·K). respectively. The result obtained with use of calorimeter was 779 J/(kg·K) and it was also the lowest value obtained in this series along with the result of CS-6 series.

The results of specific heat measurements of aggregate. made solely by means of stationary method. show high similarity with the values in the literature [15]. This indicates a proper accuracy of the results obtained by this method.

The influence of the saturation on the specific heat of concrete is consistent with expectations [5. 10]. As water has a much higher specific heat capacity than cement matrix and aggregates. the results obtained for saturated concrete are expected to be higher than those for dry concrete. And it is so in the case of almost all tested specimens. The saturation induced difference was up to 11.5%, and the average difference being 5.4%.

The results of measurements of both thermal conductivity and specific heat by means of non-stationary method are being disputable.

This seems to confirm the conclusions of the work of Pogorzelski [16], which highlighted the weaknesses of the non-stationary methods. Probably, in the case of heterogeneous materials with large differences in thermal properties between the components, the results obtained by these methods require a deep consideration.

CONCLUSIONS

The test results allow to draw the following conclusions.

- The coefficient of thermal conductivity of concrete containing aggregates proper for nuclear shielding applications was found to within the generally expected limits from 1.0 to 3.6 W/(m·K). The lowest coefficient of thermal conductivity $\lambda = 1.83$ W/(m·K) was obtained for serpentine CS-1 concrete and the highest $\lambda = 3.07$ W/(m·K) for saturated CS-6 magnetite concrete.
- The results of the specific heat measurements of aggregates adequate for shielding concrete obtained by calorimetric method, which show very good accordance with values in the literature, are: the lowest - 466 J/(kg·K) (saturated specimens). 470 J/(kg·K) (oven-dried specimens) and 778 J/(kg·K) (in calorimeter) were obtained in case of CP-2 series specimens of magnetite concrete; the highest - 843 J/(kg·K) (saturated specimens), 815 J/(kg·K) (oven-dried specimens) and 1059 J/(kg·K) (in calorimeter) in the case of CS-1 series specimens of serpentine concrete.
- Differences in the obtained specific heat values by means of stationary and non-stationary method increase with the increase of specific heat values difference between the aggregate and concrete matrix and range from 21% for amphibolite CS-4 concrete to 66% for magnetite CP-2 concrete.
- As it has been expected saturation of concrete has an impact on the thermal conductivity and specific heat. For saturated concretes conductivity coefficient value increases by 13-36 %. and specific heat value of the 0.4 - 11.5 %.

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