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Corresponding Author: Lars Wadsö,

Corresponding Author's Institution:

First Author: Lars Wadsö

Order of Authors: Lars Wadsö; Jonathan Karlsson; Kristian Tammo

Abstract: Concrete is the most common building material with a high thermal mass, and it is of interest to study how thermal mass of buildings influences such factors as their peak power consumption and their thermal comfort. We have studied whether it is possible to improve the thermal properties of concrete for buildings with high thermal mass by using aggregates with high heat capacity and/or materials with high thermal conductivity. It was found that both volumetric heat capacity and thermal conductivity could be simple means be increased by at least 50% compared to standards concrete.

Suggested Reviewers: Dale Bentz

NIST

dale.bentz@nist.gov

Has used the HotDisk technique we use

Sungchul Yang

Department of Architectural Engineering, Hongik University, South Korea

scyang@hongik.ac.kr

Has published on thermal properties of concrete

A G Entrop

Univ Twente, NL

a.g.entrop@utwente.nl

Has published on phase change materials in concrete (a related topic to that of our paper)

Dear Editor of Cement and Concrete Research

10 April 2012

We hereby submit the manuscript "Thermal properties of concrete with various aggregates".
This is a novel work not considered for publication anywhere else.

Best Regards

Lars Wadsö
Building Materials
Lund University
Box 118
221 00 Lund

Thermal properties of concrete with various aggregates

L. Wadsö^{a,c}, J. Karlsson^a and K. Tammo^b

^a Building Materials, Lund University, Box 118, 221 00 Lund, Sweden

^b The Swedish Cement and Concrete Research Institute (CBI), Box 118 Lund, Sweden

^c Corresponding author

ABSTRACT

Concrete is the most common building material with a high thermal mass, and it is of interest to study how thermal mass of buildings influences such factors as their peak power consumption and their thermal comfort. We have studied whether it is possible to improve the thermal properties of concrete for buildings with high thermal mass by using aggregates with high heat capacity and/or materials with high thermal conductivity. It was found that both volumetric heat capacity and thermal conductivity could be simple means be increased by at least 50% compared to standards concrete.

INTRODUCTION

The thermal properties of building materials are of importance for the designer of energy efficient buildings. This includes light insulating materials that can be used to reduce the heat losses through the building envelope, but also materials with high thermal inertia that can store heat and delay the conduction of heat through structural elements. The most common example of the latter type of material is concrete that is widely used in the building sector to make for example slabs on the ground, walls (both precast, cast on site and in the form of concrete building blocks), floors (both precast and cast on site), and roof tiles. In all these applications the thermal properties of the concrete will influence the performance of the building. For example will the efficiency of cast-in flooring systems depend on the thermal properties of concrete, concrete roof tiles will to some extent buffer day-time solar radiation and night-time heat losses, and all concrete structures inside the insulation of the building envelope will decrease indoor temperature variations.

Thermally heavy structures inside the building envelope may be of significant relevance in a future more energy efficient society as they can lower peak power needs by moving energy use in time [1]. Another scenario where significant savings can be made with thermally heavy buildings in cold climates is if the energy price will follow the cost of energy production and thus increase significantly during cold spells. A thermally heavy building can then save heating costs by not needing heat during cold-spells [2]; a similar situation exists for cooling needs in warm climates [3]. However, a prerequisite for this is that the indoor temperature is allowed to change significantly as no savings are possible with a constant indoor temperature.

There are two principles of using thermally heavy materials: passive and active. In passive structures heat will pass into and out of for example walls by the natural thermal processes that take place in any building: natural convection, radiation and conduction. In the case of active heat storage, forced convection of a liquid or a gas is used to move heat (or cold) from one place to another. An example of where this is used is in offices where heat from solar radiation, people and machines can give too high daytime temperatures. Cool outdoor air can then be used to cool, e.g., a hollow-core concrete slab during the night; and this stored “coldness” can then be used for daytime cooling of the office ventilation air. Note that such systems do not require heating or cooling devices, but instead use free heat/cold by shifting heating and cooling needs in time.

When discussing passive or active heat storage the thermal properties of concrete are of importance as concrete is the most common structural material that can store significant amounts of heat (other such materials are natural stone materials and bricks), as quantified by the following three parameters: the thermal conductivity λ ($\text{W m}^{-1} \text{K}^{-1}$), the volumetric heat capacity c ($\text{J m}^{-3} \text{K}^{-1}$), and the thermal diffusivity a ($\text{m}^2 \text{s}^{-1}$). These three parameters are related by the following equation:

$$a = \frac{\lambda}{c} \tag{1}$$

Note that the specific heat capacity multiplied by the density can be used instead of the volumetric heat capacity. Throughout this paper we use the volumetric heat capacity and denote this by c , and we will discuss thermal properties mainly in the terms of volumetric heat capacity and thermal conductivity.

Of the two parameters heat capacity and thermal conductivity, it is the heat capacity that is most important for high thermal inertia components in buildings. If the volumetric heat capacity of a concrete member is increased by 50%, 50% more heat can be stored in this construction part. At least for temperature variations on the time scale of the order of a day, nearly the whole thickness of standard concrete walls will follow the room temperature variations so an increased thermal conductivity is normally not an asset in this case. This can be illustrated by the following figures. Standard concrete has an approximate thermal diffusivity of $10^{-6} \text{ m}^2 \text{ s}^{-1}$. If a concrete wall with a homogeneous temperature distribution is exposed to the same temperature change on both its surfaces, the time it takes for 90% of the heat to flow in or out of the wall to achieve a new stationary condition is 40 min, 2.5 h and 10 h for walls with thicknesses 10 cm, 20 cm and 40 cm (in the absence of surface mass transfer resistances like boundary layers or wall papers). However, the situation may be different when quick heat storage is important; for example to take care of intensive free solar heat during a few hours.

Concrete is a composite material and its thermal properties are a function of the thermal properties, volume fractions and morphology of its constituents (phases): cement paste, air (pores), fine aggregate (sand), and large aggregates (rock material). The thermal properties of a cement paste – including fine (gel and capillary) pores – depends on the water/cement-ratio, the degree of hydration and the moisture content. In well hydrated and air-dried concrete the thermal properties are mainly functions of the water/cement-ratio (w/c) as higher such ratios give a more porous structure. Typical thermal conductance values for OPC (ordinary Portland cement) pastes in the literature are between $0.5 \text{ W m}^{-1} \text{ K}^{-1}$ for $w/c=0.5$ [4] to 1.0 for $w/c=0.3-0.4$ [5]. Volumetric heat capacities are strongly dependent on the water content as both chemically bound, physically bound and free water have high heat capacity. Liquid water has a specific heat capacity of about $4.2 \text{ J g}^{-1} \text{ K}^{-1}$ and bound water in cement hydrates has a specific heat capacity of about $2.2 \text{ J g}^{-1} \text{ K}^{-1}$ [5] (similar to that of ice). The specific heat capacity of a seal cured $w/c=0.4$ OPC cement paste with a degree of hydration of 0.8 is approx. $1.4 \text{ J g}^{-1} \text{ K}^{-1}$ [5]. With a density of air dried $w/c=0.5$ cement paste of about 1480 kg m^{-3} [6] this gives a volumetric heat capacity of approx. $2.1 \text{ MJ m}^{-3} \text{ K}^{-1}$. However, note that this value is very dependent on the moisture content.

The larger pores – usually 2-4% of a concrete - have such a low thermal conductivity and heat capacity compared to the other phases (if they are filled with air) that the values of both these properties can in practice be assumed to be zero. If the pores are partially or fully filled with

water – something that will happen in for example outdoor applications or in concrete in contact with the ground – both thermal conductivity and heat capacity will be increased.

Sand and larger aggregates are normally natural minerals with different thermal properties. However, from a practical point of view, most minerals and rocks used as aggregates have similar thermal properties except that quartz and quartz based rocks have a significantly higher thermal conductivity than feldspars, limestone and most rocks used as aggregates (cf. Fig. 1D in [7]). It is thus of importance to know how much quartz the aggregate contains to be able to make calculations of thermal properties of sand, aggregate and concrete.

For special applications other types of concrete aggregates with quite different thermal properties can be used. For example can insulating expanded clay particles be used as aggregate to make a more insulating concrete. A special group of material for heat storage are phase change materials (PCMs) that will consume heat by melting in a rather narrow temperature range; this can be seen as that the material has an extremely high heat capacity in a limited temperature interval. Such materials are commonly made from paraffin and have been investigated also for use in concrete [8-9].

Thermal properties of composite materials are of significant interest in many fields. Some examples are thermal properties of rock materials [7, 10] and polymers [11]. There have also been presented several studies of thermal properties of concrete. For example did Marshall [12] give an overview of the work done up to 1972. Valore [4] discussed thermal conductivity of mortars and concrete to be used for the calculations of U -values of walls, including the influence of moisture content and type of aggregate. His methods and values have later been used in a design guide report issued by the American Concrete Institute [13]. Khan [14] measured thermal conductivity on concretes with different aggregates and found that the thermal conductivity was about 35% higher when the large aggregate was quartz-based, than when it was based on basalt, limestone and siltstone. He also found that the moisture content of the concrete had a significant influence on the thermal conductivity of concrete; for a quartzite concrete the thermal conductivity increased from 2.7 to 4 W m⁻¹ K⁻¹ when the moisture content increased from zero to 7.5%. Kim et al. [15] studied the thermal conductivity of concrete as a function of aggregate fraction, water/cement-ratio, temperature and humidity. Bentz et al. [16] measured the thermal properties of fly ash concretes. Thermal conductivity was strongly influenced by whether the aggregate contained quartz. Several fire-related

studies have also been made on high temperature properties of concrete (see for example reference [17]).

The aim of the present study was to investigate how the thermal properties of concrete inside the building envelope could be changed in the direction of higher thermal conductivity and/or higher heat capacity by the use of different aggregates. Eleven different concretes were cast and their thermal properties were investigated with a TPS (Transient Plane Source) technique. We also compare our results with approximate calculations using the mixing model (volumetric heat capacity) and the Hashin-Shtrikman model (thermal conductivity).

METHODS

We used transient plane source (TPS) measurements to measure volumetric heat capacity and thermal conductivity of concretes and aggregates. For the TPS-measurements [18] we used a HotDisk 1500 (HotDisk AB, Göteborg, Sweden) in the single side mode using an extruded polystyrene ($\lambda=0.032 \text{ W m}^{-1} \text{ K}^{-1}$; $c=0.5 \text{ MJ m}^{-3} \text{ K}^{-1}$) on the other side. As concretes are inhomogeneous materials we used the largest available sensor (HotDisk number 5599) with a diameter of almost 57 mm for the concrete measurements. This is about 3.6 times the diameter of the largest aggregate of the investigated concrete composite structures. For measurements on magnetite – where we only had 30 mm diameter samples – we used a sensor with a 12.8 mm diameter (HotDisk number 5501).

The HotDisk measurement time for the concrete measurements was about 160 s and the thermal power was about 0.5 W. For each material, at least three measurements were made in each of three areas on a sample. Most concretes were measured at about 24 °C, while the PCM (phase change materials) containing concretes were measured at 5 and 50 °C as the HotDisk method does not work if the studied materials melt in the temperature range of a measurement. Measurements were thus conducted both below and above the phase change temperatures of the PCMs. Note that the phase change of the PCMs were not studied.

MATERIALS

We used eleven different concretes: one reference, seven with aggregate with high heat capacity and/or high thermal conductivity, and three concretes with phase change materials (PCM). The recipes are given in Table 1 together with details on the used materials. Note that none of the PCM products used here are normally used in concrete.

PLACE TABLE 1 HERE

The concretes were mixed in a free fall mixer, cast in 150 mm steel cube forms, demoulded after about 1 day, and hydrated for 28 days in water. The cubes were water cut in two halves after 28 days and thereafter stored in room climate for about one year. Their relative humidity (measured on four random samples) was 30-40%, which is in the range that indoor concrete will have in cold climates or exterior protected concrete in warm climates. Before the measurements the used surfaces were made plane with a diamond planer (dry).

The materials used were as follows (cf. Table 1).

Reference concrete (REF)

This is a standard concrete with a water/cement-ratio of 0.5 and a cement content of 381 kg m⁻³. The fine aggregate was 0-8 mm sand of mixed composition (quartz and other minerals); the large aggregate was quartzite.

Magnetite concrete (MAG)

This concrete is similar to REF, but with less fine aggregate and with magnetite (iron ore) as large aggregate. Magnetite has a high density and a high volumetric heat capacity.

Graphite concrete (GRA)

This concrete has a significantly higher cement content (533 kg m⁻³) and higher water/cement-ratio (0.59) than REF, and also contains expandable graphite that has a high thermal conductivity. Expandable graphite is produced from natural graphite by introducing sulfur or nitrogen atoms between the carbon layers. When it is exposed to high temperature expandable graphite will expand up to a hundred times and it can therefore be used, e.g., as a high temperature fire protection. The expandable graphite used here was not expanded, and is here assumed to have similar properties as natural graphite.

Graphite and magnetite concrete (GAM)

This concrete is a combination of MAG and GRA with water/cement-ratio 0.60.

Steel fiber concrete (STI)

This is similar to REF, but also contains 100 kg m⁻³ of steel fibers.

Steel fiber concrete with high concentration of fibers (ST2)

Similar to ST1, but with 197 kg m^{-3} of steel fibers.

Concrete with brass shavings (BRA)

Similar to REF, but with an addition of 5%(vol) of brass shavings that have a high thermal conductivity.

Concrete with copper wires (COP)

Similar to REF, but with an addition of 2.5%(vol) of copper wires that have a very high thermal conductivity.

Concrete with PCM pellets (PEL)

This micro-concrete had a water/cement-ratio of 0.5 and did not contain any large aggregate, but an addition of a macro-encapsulated phased change material (PCM) product with the size of rice grains.

Concrete with micro PCM (MIC)

This micro-concrete had a high water/cement-ratio and did not contain any large aggregate, but an addition of micro-encapsulated PCM particles with a diameter of less than 0.5 mm.

Concrete with PCM dispersion (DIS)

This concrete had an addition of a PCM dispersion product.

Cement paste (PAS)

A water/cement-ratio 0.5 cement paste was also included to get values of the heat capacity and thermal conductivity of the cement paste.

Of the above materials, only REF, MAG, ST1, ST2, BRA and COP had normal cube strengths. The macro-encapsulated PCMs in the PEL concrete expanded out of the specimens when they were heated, and the DIS sample had to be handled with care as it would easily break (none of the PCM products are produced for use in concrete).

RESULTS

The results of the TPS-measurements on concretes are given in Figs. 1 and 2 and in Table 2. The standard deviations of the measured thermal conductivities and volumetric heat capacities were between 2 and 11% of the measured values, i.e., the spread in the data is reasonable considering that the materials contain phases with very different properties. No particular type of material showed higher deviations than the other. The results of the TPS-measurements on quartzite and magnetite are given in Table 3.

PLACE FIG. 1 HERE

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DISCUSSION

The measured thermal properties are qualitatively reasonable. When quartzite is replaced by magnetite as aggregate the thermal conductivity does not change much, but the heat capacity increases with about 50%. This is consistent with that magnetite has a significantly higher volumetric heat capacity than quartzite, but a similar thermal conductivity (Table 3). Magnetite is regularly used as concrete aggregate in heavy foundations and as radiations shields, but it has not been used as high thermal mass in buildings.

When a relatively small amount of graphite is used, the thermal conductivity increases significantly as graphite is a good heat conductor. It should be noted that the expandable graphite used in this study was not expanded, and was assumed to have the same thermal properties as natural graphite as no thermal data could be found on (unexpanded) expandable graphite.

The concretes with copper, brass and steel fibers all showed an increased thermal conductivity compared to the reference concrete, while the thermal conductivity of the concretes with PCMs decreased significantly. Also note that the relatively dry cement paste has the lowest thermal conductivity of the measured materials.

It is not known how accurate the TPS-technique is for in-homogeneous materials like concrete. Even if the TPS-sensor used was several times larger than the largest aggregate particles, it could still be sensitive to local in-homogeneities, especially in the materials with extreme differences in thermal conductivity. Such problems would probably be more severe

the larger the aggregate is and the larger the difference is between the mortar phase and the aggregate. For example could the COP specimens have more problems than the BRA and PEL specimens, as the used copper wires have about 700 times the thermal conductivities of the mortar phase. However, the precision of the COP results were similar to the other results, which indicates that this is not a problem with the HotDisk method.

We have made calculations of the heat capacity and thermal conductivity of the concretes used in this study. These calculations were based on the recipes given in Table 1 and the thermal phase properties given in Table 3, which were collected from various sources or measured. A problem with these calculations is that rocks (in contrast to minerals) do not have fixed compositions and their properties will thus not be constant. For example can quartzite – a metamorphic rock formed from quartz sand – have different porosities and impurities, and can therefore have variable properties. Most minerals do also have different thermal conductivities in different directions and the thermal conductivity of a rock will therefore depend on whether the mineral grains from which it is made are randomly oriented or not. Because of this we measured the thermal properties of the used quartzite and on magnetite from the same source as that used as aggregates. For all models used, the masses given in Table 1 were converted to volume fractions with the densities given in Table 3.

The volumetric heat capacity of a composite material containing different phases can be calculated by mixing theory:

$$c = \sum v_i c_i \quad (2)$$

Here, c is the (volumetric) heat capacity of the composite (the concrete) and v_i and c_i are the volume fractions and (volumetric) heat capacities of the different phases. The thermal conductivity is a more complex property as it also involves how the particles are arranged: which shapes they have, which phase that is continuous, and whether the material is isotropic. A common composite model for conduction is the Hashin-Shtrikman (HS) model [19]. Written for a discontinuous (d) phase within a continuous (c) phase the HS model for thermal conductivity is:

$$\lambda = \lambda_c + \frac{v_d}{\frac{1}{\lambda_d - \lambda_c} + \frac{v_c}{3\lambda_c}} \quad (3)$$

The HS-model is based on a structure in which spherical particles of different sizes – each with the correct volume fractions of the discontinuous phase (a core) and the continuous phase (a shell) - completely fill out the volume. Note that the HS-model is often used to calculate extreme bounds by making two calculations with switched matrix and particles properties; here we know which of the two phases that is the matrix, and therefore only make one calculation. Although the materials studied here do not conform perfectly to the HS-model it is used here as it is a reasonable approach (significantly better than the extreme serial and parallel models often used).

For concrete, which is made from cement paste, sand and larger aggregates, the calculation of the thermal conductivity is made in two steps: first with the sand (d) in the cement paste (c) to give the thermal conductivity of the mortar; and secondly with the large aggregate (d) in the mortar (c). For materials GRA, BRA, PEL, MIC and DIS a third HS-calculation was made to incorporate the graphite, the brass or the phase change material. The influence of air pores was not taken into account. For materials with fibers the HS-model is not appropriate and no calculations were made for materials ST1, ST2 and COP. Material data was taken from the literature (Table 3) or – in the case of cement paste, quartzite and magnetite – measured with the hot disk method.

To use the heat capacity and thermal conductivity models above one need the volume fractions v of the phases. These are calculated from the mix compositions μ ($\text{kg m}_{\text{concrete}}^{-3}$) and the densities ρ ($\text{kg m}_{\text{phase}}^{-3}$):

$$v = \frac{\mu}{\rho} \quad (4)$$

When we add the volume fractions calculated by this equation for all phases we will not get exactly 1.00, mainly because the densities are not known well enough. Typically our results were within 5% of 1.00. For the composite model calculations we adjust all volume fractions so that their sum equals 1.00.

The thermal properties of the cement paste were taken from the measurements on the cement paste sample. However, the volume fraction of the cement paste could not be calculated directly with Eq. 4, as the mix composition of cement paste cannot be directly taken from the concrete recipe, both because part of the used water leaves the cement paste by drying, and because the remaining water is both chemically and physically bound, and these two “types”

of water have different properties. We have solved this by using the cement mix composition value and adjusting it to get the correct mass fraction by:

$$\mu_{cp} = f \cdot \mu_c \quad (5)$$

Here, indices cp and c denotes cement paste and cement, respectively. The factor f is the mass of cement paste in a concrete specimen per mass of cement in the recipe. Its value is greater than unity as the mass of the cement paste also includes water. The chemically bound (hydrate) water can be calculated from Powers and Brownyard [20] as 0.25α , where α is the degree of hydration. We have here assumed that $\alpha=0.8$, and then get 0.20 grams of chemically bound water per gram of cement. For the physically bound water we have used the results in reference [21] (Fig. 4.10) that gives about 0.12 grams of physically bound water per gram cement at a degree of hydration of 0.8 (valid at w/c -values of 0.5-0.7). When these values are combined we get an f -value of $1.32 \frac{\text{g}_{\text{cement paste}}}{\text{g}_{\text{cement}}}$.

The results from measurements and calculations are given in Table 2. It is seen that the calculations show a fair agreement with the measured data in most cases; and that the results are good enough for engineering calculations of thermal storage in construction details for these cases. Two materials for which the HS-model did not calculate the correct thermal conductivity value is GRA and GAM. This mismatch between measurement and calculation is most probably because the anisotropic graphite particles are arranged as flakes, with the highest thermal conductivity in the plane of the flakes, and this case cannot be handled by the HS-model (the HS-calculation will not give such high thermal conductivity as was measured even if the thermal conductivity of the 18 vol% graphite was set to infinity).

Figure 4 shows comparisons between the measurements and the calculations. The calculations under-estimates the measured heat capacities; whereas the thermal conductance calculations give results close to those measured except for the materials with graphite (discussed above). It is somewhat surprising that the thermal conductance calculations with the HS-model are better than the mixing model heat capacities. However, the volumetric heat capacities are well-correlated with the densities of the samples (Fig. 4C).

The present study concentrated on investigating to what extent the thermal properties of concrete can be changed in a favorable direction for thermal storage applications. From a physical point of view the results are encouraging as both volumetric heat capacity and thermal conductivity could be increased by 50% (relative to a concrete with quartzite

aggregate with a comparatively high thermal conductivity). A quite different question is whether the use of concrete with enhanced thermal properties is interesting from an economical point of view. Special aggregates like magnetite are much more expensive than standard rock aggregate. Magnetite concrete is also significantly more difficult to produce, transport and cast as it is so heavy. The high density can also give design problems as much higher loads need to be carried by the building structures. Special materials that increase the thermal conductivity – like graphite and copper – are also probably too expensive to be used regularly in concrete in the construction industry. Standard concrete does have a high volumetric heat capacity compared to most other construction materials and is therefore useful by itself in buildings to give high thermal mass. Therefore these materials with improved thermal properties may only be of interest in special applications.

CONCLUSIONS

It is possible to increase the volumetric heat capacity and the thermal conductivity of concrete by at least 50%. The present results also show that it is possible to predict the thermal conductivity using the Hashin-Strikman composite model, and that the volumetric heat capacity is well correlated with the density for dry concrete.

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Figure 1. Measured thermal conductivities of the concretes (cf. Table 1). Each measurement is given as a point. For each set of at least three measurements made in a certain position on a specimen an ellipsis is drawn. The radius in the y-direction of this ellipsis is the standard deviation and the center of the ellipsis is the mean of each such data-set (the radius in the x-direction is the same for all ellipses). For the materials containing phase change materials measurements were made at 5 and 50 °C, as indicated in the figure. The overall mean values are given in Table 3.

Figure 2. Measured heat capacities of the concretes (cf. Fig. 1).

For the authors own use: Measured values from Fig.3 from evalBNnov.m in c:\measure\measure4\cement\termiska.

Figure 3. An overview of the measured volumetric heat capacities and thermal conductivities of the different concretes. The lines connect points in which the thermal diffusivities are the same ($0.5 \cdot 10^{-6}$, $1 \cdot 10^{-6}$, $2 \cdot 10^{-6}$, and $3 \cdot 10^{-6} \text{ m}^2 \text{ s}^{-1}$ from top to bottom).

Figure 4. Comparisons between measured and calculated vales. All properties of the materials with PCM are averages of the two measurements made at different temperatures. For thermal conductivity no values are given for the PCM-materials.

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Figure 1. From Fig. 1 from evalBNnov.m in c:\measure\measure4\cement\termiska.

Figure 2. From Fig. 3 from evalBNnov.m in c:\measure\measure4\cement\termiska.

Figure 3. From Fig. 4 from evalBNnov.m in c:\measure\measure4\cement\termiska.

Figure 4. From Fig. 1 in plotres.m in c:\measure\measure4\cement\termiska

Table 1. Concrete recipes

	REF	MAG	GRA	GAM	ST1	ST2	BRA	COP	PEL	MIC	DIS	PAS
	Mass / kg m ⁻³											
Cement ^A	381	342	533	530	379	374	365	374	425	489	290	-
Water	190	170	315	318	189	187	182	187	218	342	58	-
Sand 0-8 mm	887	281	492	-	876	865	844	865	1062	791 ^I	674	-
Quartzite 8-12 mm	443	-	246	-	434	429	418	429	-	-	337	-
Quartzite 12-16 mm	443	-	246	-	434	429	418	429	-	-	337	-
Other	-	1517 ^B	298 ^D	956 ^B	100 ^E	197 ^E	422 ^F	223 ^G	213 ^H	176 ^J	322 ^K	-
Other	-	1599 ^C	-	974 ^C	-	-	-	-	-	-	-	-
Other	-	-	-	296 ^D	-	-	-	-	-	-	-	-
w/c	0.50	0.50	0.59	0.60	0.50	0.50	0.50	0.50	0.51	0.70	0.70	

A. A Portland-limestone cement (CEM II/A-LL 42.5R, "Byggcement", Cementa AB, Sweden)

B. Magnetite aggregate (MagnaDense 8S, 0-8 mm, Minelco AB, Luluå, Sweden). Contains 98-99% magnetite.

C. Magnetite aggregate (MagnaDense 20S, 0-20 mm, Minelco AB, Luleå, Sweden). Contains 98-99% magnetite.

D. Expandable graphite (ES250B5, Grafit Kropmühl AG, Hauzenberg, Germany).

E. Steel fibers; 50 mm long, with hooked ends (Dramix, Bekaert, Zwevegem, Belgium).

F. Drill shavings (1-2mm) of brass.

G. Copper wires (diameter 2 mm) cut into 30 mm pieces; randomly arranged in sample.

H. Macroencapsulated paraffin based phase change material (Rubitherm PK, Rubitherm Technologies GmbH, Berlin, Germany). Rice-shaped grains with a length of about 5 mm. Melting temperature of 42 °C.

I. Only the 0.5-8 mm fraction.

J. Microencapsulated paraffin based phase change material (Micronal PCM, BASF) with a diameter of less than 0.5 mm. Melting temperature of 23 °C.

K. Dispersion of paraffin based phase change compound (Micronal DS5007X, BASF) with 55% dry matter. Melting temperature of 26 °C.

Table 2. Measured densities and measured and calculated values of thermal conductivities and volumetric heat capacities. The materials are defined in the text and in Table 1. The calculation methods are described in the text; the used phase material data is given in Table 2.

	$\rho / \text{kg m}^{-3}$	$\lambda / \text{W m}^{-1} \text{K}^{-1}$		$c_v / \text{MJ m}^{-3} \text{K}^{-3}$	
	Measured	Measured	Calculated	Measured	Calculated
REF	2240	2.24	2.27	1.78	1.41
MAG	3650	2.57	2.00	2.68	2.48
GRA	1890	3.52	(1.85)	1.53	1.26
GAM	2810	3.85	(1.70)	2.46	1.84
ST1	2330	2.57	-	1.93	1.44
ST2	2441	2.95	-	2.02	1.46
BRA	2520	2.71	2.42	1.75	1.50
COP	2438	3.63	-	2.29	1.46
PEL5	1790	1.23	1.17	1.58	1.58
PEL50		1.23		1.70	
MIC5	1570	0.83	0.97	1.67	1.49
MIC50		0.77		1.63	
DIS5	1900	1.47	1.31	1.30	1.56
DIS50		1.63		1.64	
PAS	1510	0.58	-	1.03	-

For the authors own use: Measured values from evalBNnov.m; calculated values from calcthermal.m (both in c:\measure\measure4\cement\termiska). Densities from Densiteter_exjobbsbetonger_2april.2012.odt

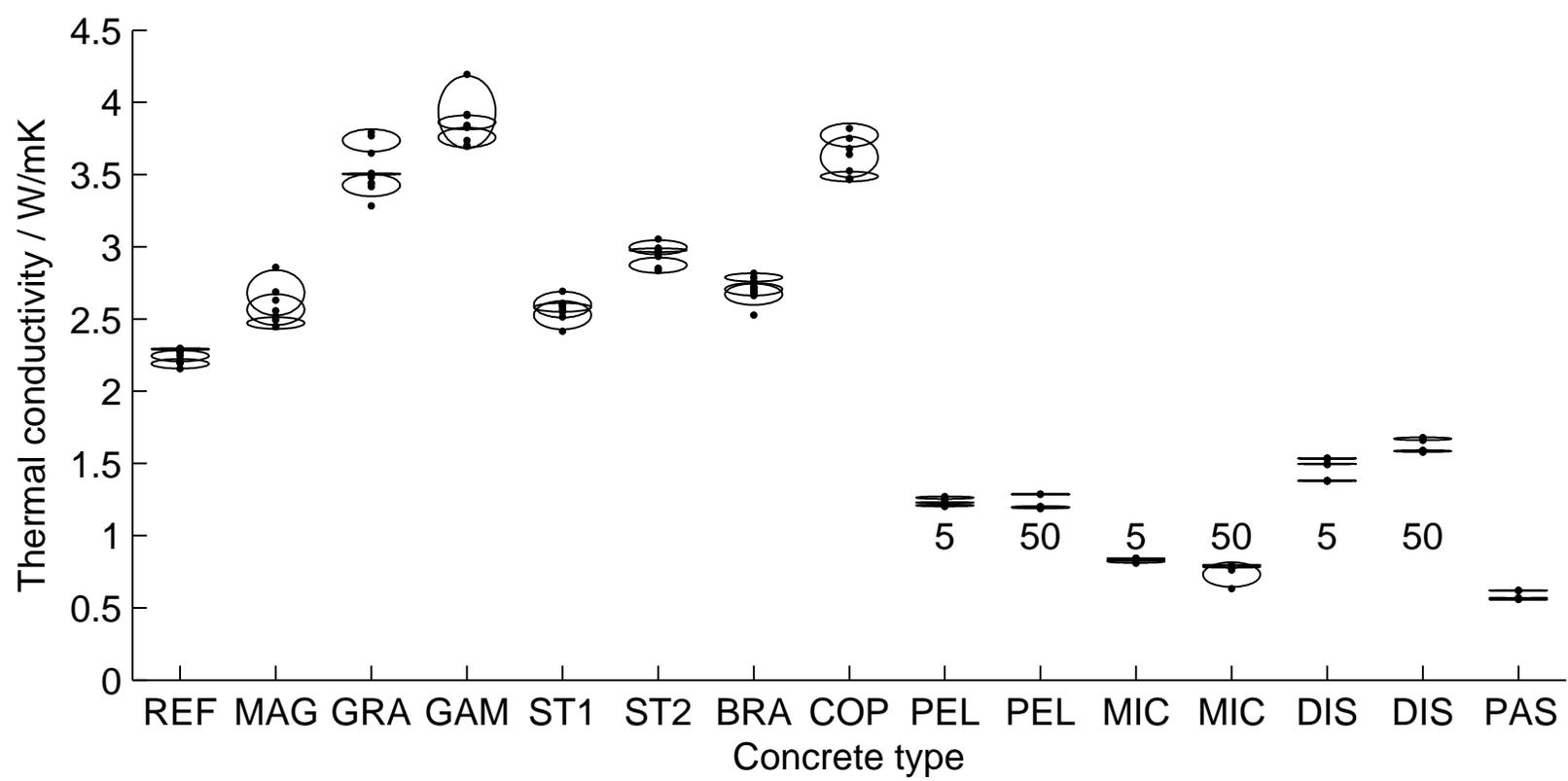
Table 3. Approximate thermal properties of phases in the studied concretes (at about 25 °C and 1 atm). Where more than one value is given, the values used in the calculations are underlined.

	ρ (kg m ⁻³)	λ (W K ⁻¹ m ⁻¹)	c (MJ m ⁻³ K ⁻¹)
Sand ^A	2624 ^A	4.8 ^A	1.9 ^A
Quartz	2648 [22]	7.7 ^B	1.96 [22]
Feldspar	2500 ^C [22]	2.36 ^C [10]	1.9 ^C [22]
Quartzite	2640 [22]	8.58 [14], <u>5.4</u> ±0.6 (this study)	1.9 [22], <u>1.3</u> ±0.2 (this study)
Cement paste (dry)	1480, 1340 and 1220 for $w/c=0.5, 0.6,$ and 0.7, respectively [6]; $w/c=0.5$ <u>1510</u> (this study) ^D	0.58 (this study) ^E	1.03 (this study) ^E
Magnetite	<u>5100</u> [23]	5.10 [10], 9.7 [23], <u>3.85</u> (this study)	3.74 [23], <u>3.30</u> (this study)
Graphite ^F	1100-1700 [24] ^G	94 ^H	1.2 ^I
Steel	7860 [25]	52 [25]	3.30 [26]
Brass	8470 [25]	120 [25]	3.13 [26]
Copper	8960 [25]	401 [25]	3.45 [25]
Paraffin wax (PCM) ^J	900 [26]	0.26 [27]	1.9 ^K

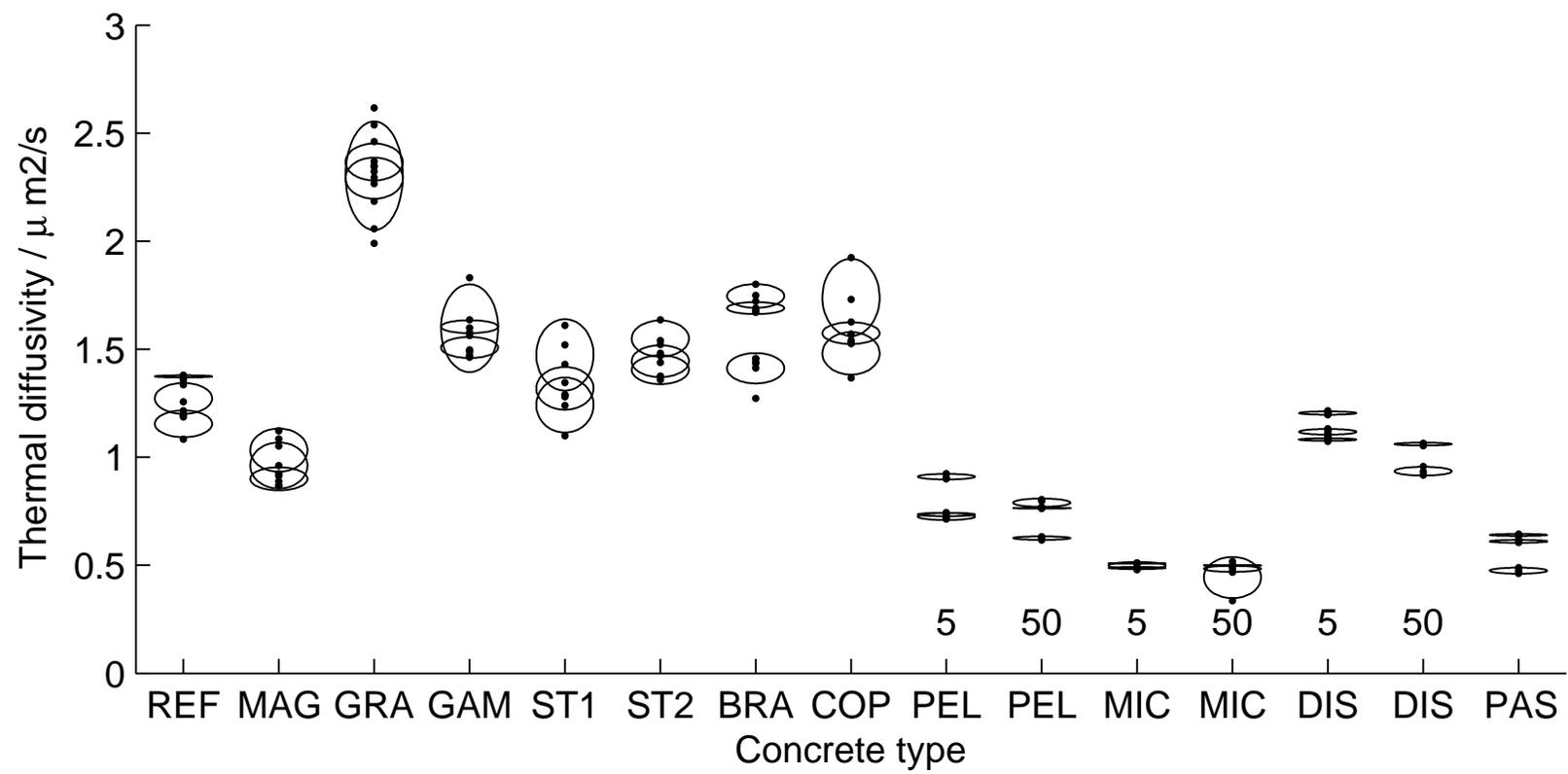
- A. The sand 0-8 was of mixed composition. It was assumed to contain 50 vol% quartz and 50 vol% feldspar. Density, thermal conductivity and heat capacity were all calculated by mixing theory.
- B. Crystalline quartz has significantly different thermal conductivities parallel (=) and perpendicular (\perp) to the crystal axis; a mean value is given by $\frac{1}{3}\lambda_{=} + \frac{2}{3}\lambda_{\perp} = 7.7$ W m⁻¹ K⁻¹ [10].
- C. Approximate mean value for different feldspars.
- D. The same values were used also for GRA and GAM with $w/c=0.6$ and MIC and DIS with $w/c=0.7$.

- E. The value from this study was used for $w/c=0.5$ and was scaled with the values from the reference for the other w/c .
- F. Values for natural graphite (which may have different properties from expandable graphite for which the thermal properties have not been found).
- G. Mean value 1400 used.
- H. Natural graphite has an extremely direction dependent thermal conductivity ($\lambda_{\perp} = 140-500 \text{ W m}^{-1} \text{ K}^{-1}$; $\lambda_{\parallel} = 3-10 \text{ W m}^{-1} \text{ K}^{-1}$ [24]). The value given here is $\frac{1}{3}\lambda_{\parallel} + \frac{2}{3}\lambda_{\perp}$ using the lower range values given by [24].
- I. A mean value of the range $0.93 \cdot 10^6 - 1.44 \cdot 10^6$ calculated from data by [24]
- J. The PCM materials used are paraffins, but as the composition of these are not known, the values given here for solid paraffin waxes should be seen as approximate.
- K. From specific heat capacity $2500 \text{ J kg}^{-1} \text{ K}^{-1}$ given by [28].

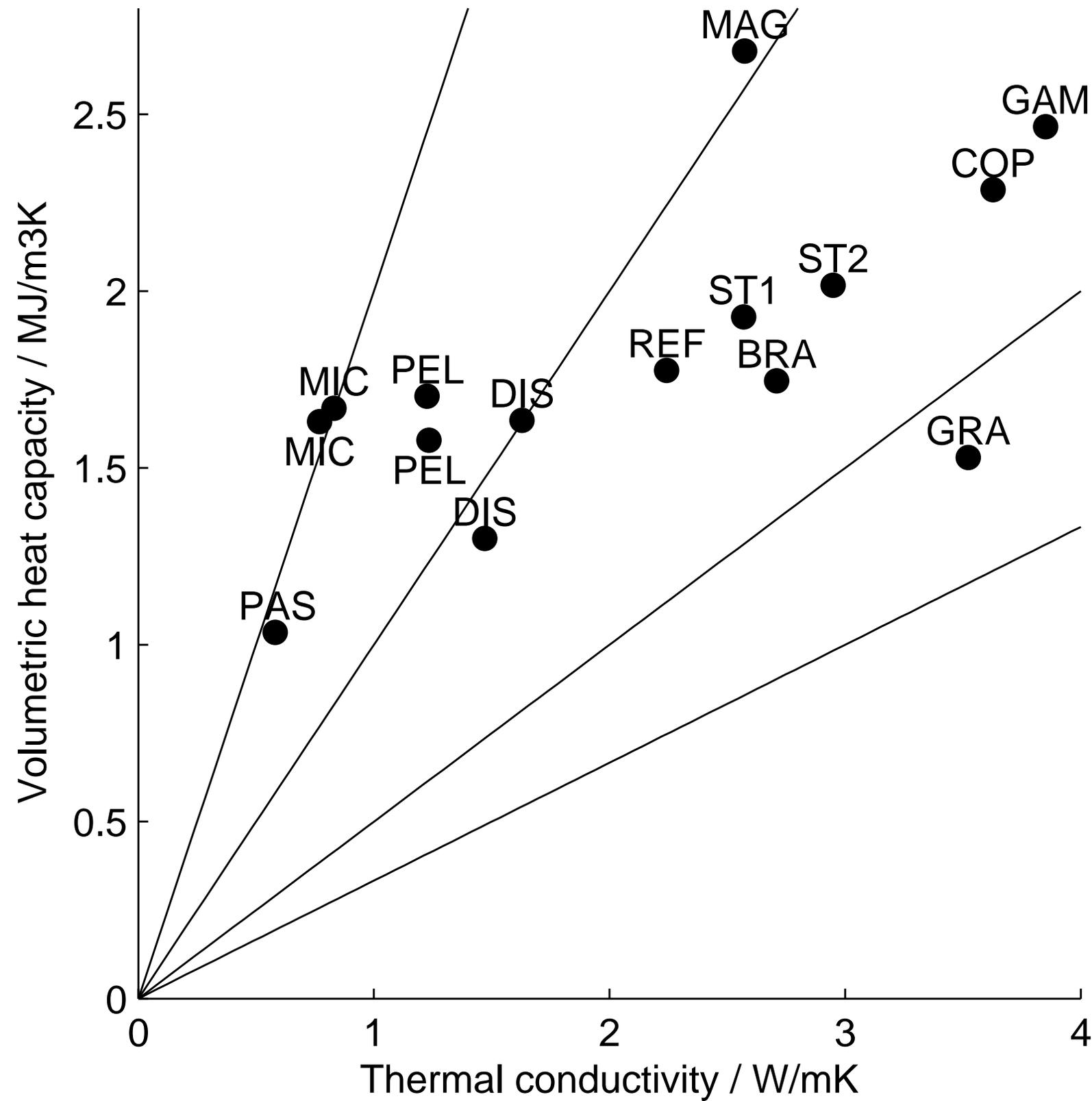
Figure(s)



Figure(s)



Figure(s)



Figure(s)

