Int J Thermophys (2010) 31:844–851
DOI 10.1007/s10765-010-0750-8

Thermal Conductivity of Building Materials Employed in the Preservation of Traditional Structures

Maria Stefanidou · Marc Assael · Konstantinos Antoniadis · Gregory Matziaroglou

Received: 28 May 2009 / Accepted: 12 September 2009 / Published online: 20 May 2010
© Springer Science+Business Media, LLC 2010

Abstract Historic structures are a part of our cultural heritage and nowadays, in the polluted environment, the need of their preservation is more intense than ever. One of the anticipated problems includes new materials that have to be compatible with those existing in older structures. In the case of mortars, traditional binders such as lime, natural pozzolanas, brick dust, and white cement have been combined successfully. In the present article a series of mixtures combining lime, two types of natural pozzolanas, brick dust, and different types of cement have been produced in order to measure their thermal conductivity for the first time. The parameters tested are: the binder type, the proportion of the binders, and the water/binder ratio. For the measurement of the thermal conductivity of the samples, a commercial instrument was used. To test its operability and extend its range, a transient hot-wire instrument was employed.

Keywords Lime · Pozzolana · Thermal conductivity · Traditional binders

1 Introduction

Throughout history, man has used the materials available in the environment in order to build his shelter. From herbs and clays to stone and brick, up to steel and concrete structures, man could find solutions in order to solve problems related to his homes. The importance of materials in human civilization can be pointed out from the fact that the first historic periods are characterized as Stone Age, Copper Age, and Iron Age.

M. Stefanidou
Laboratory of Building Materials, Civil Engineering Department, Aristotle University, 54124 Thessaloniki, Greece
e-mail: stefan@civil.auth.gr

M. Assael (✉) · K. Antoniadis · G. Matziaroglou
Laboratory of Termophysical Properties & Environmental Processes, Chemical Engineering Department, Aristotle University, 54124 Thessaloniki, Greece
e-mail: assael@auth.gr

In the countries around the Mediterranean basin, brick masonry was used since 2000 B.C. as bricks and mortars were possible to make and could cover the needs deriving from the climatic conditions. Studies have shown that old masons were using their intuition in order to build structures economically, energy efficient, and harmonically adapted to the environment. The principles of economy and ecology seem to be embodied in the philosophy of ancient masons [1]. In order to succeed, they were using appropriate materials and right techniques. Thick walls, structures oriented according to the sun route, and heating the place where the families were spending most of their time, were some of the techniques employed in order to heat their residences. On the other hand, the selection and combination of the materials were based on criteria such as easy to find and work with, aesthetically harmonized, and functional in terms of strength efficiency and durability [2].

Mortars are one of the oldest and most diachronic building materials [3]. First it was based on clay while later lime, gypsum, pozzolana, brick dust, and recently cement were used as binding materials. The most important property of these binders was their cementing capacity, which is developed after mixing them with water at normal environmental conditions. Lime is used mainly due to its ability to add plasticity and workability to the mixture. In pure lime mortars, setting and hardening is a slow procedure because it depends mainly on the reaction of calcium hydroxide with atmospheric carbon dioxide as shown in

$$\mathrm{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O} \tag{1}$$

Mortars made from lime can be used to allow a certain amount of moisture to pass through them mainly due to their high open porosity (the porosity of the old lime mortars measured according to "Reunion Internationale des Laboratoires et Experts des Materiaux" (RILEM) CPC 11.3 ranges from 22 % to 35 %).

Natural pozzolanas have been used since the 5th century B.C. in Greek monuments in order to produce hydraulic character mortars. Their main property is the ability to harden in a wet environment and produce a compact structure. Natural pozzolanas were mixed with lime in order to increase the rate of setting and hardening due to the reaction of the silico-aluminate compounds with calcium hydroxide producing hydrated calico-silicate and calico-aluminate products according to

$$\mathrm{Ca(OH)_2} + \text{amorphus aluminate-silicate} \xrightarrow{+\mathrm{H_2O}} \mathrm{C{-}S{-}H + C{-}A{-}H} \tag{2}$$

The porosity of the old lime-pozzolana mortars ranges from 19 % to 25 % measured by the above-mentioned method.

Brick dust is also considered a traditional component of mortars since its usage in lime mortars dates from the Minoan period through the ancient Greek and Roman civilizations. Despite the pozzolanic properties of brick dust calcinated at low temperature (700 °C to 850 °C), its usage was adding a colorful result to the produced mortar. In structures of the 6th to 7th centuries A.D. "kourasania", mortars of exceptional beauty and durability were used in Byzantine architecture [4].

These inorganic binders were used in order to connect stone pieces, earth blocks, or bricks in humble and monumental structures which provide longevity, durability, and exceptional beauty combining functional and ecological standards.

In the case of old monumental structures, the preservation of the historic and aesthetic value of the structure is of high importance. The Venice Chart (1964) defines the guidelines under which the approach of intervention should proceed. Following these principles, the new repair materials should be compatible with those existing in the old structure. In the case of repair mortars, "traditional" binders such as modern produced lime, natural pozzolanas, brick dust, and a small percent of cement have proved to be sufficient for preservation purposes [5]. The need of a cement addition in a small amount (10 % to 15 % by mass of the binders) to mortar mixtures covers the modern demand of an intense work rate without altering significantly the properties of the repair mortars.

The purpose of this article is to examine if the new repair mortars which are compatible with the old authentic ones in terms of mechanical, physical, and structural properties, can also cover the demand of thermal insulation, a property which has never been tested up to now for these materials.

The above-mentioned binders have a beneficial ecological profile as they:

- consume low energy during their production
- do not pollute the environment during their usage
- do not include toxic elements.

In order to examine their thermal behavior, the thermal conductivity of different mixtures was determined as explained below.

2 Experimental

2.1 Instrumental

The thermal conductivity of the samples was measured using the commercial instrument Quickline 10 (Anter Corporation, USA). The Quickline-10 uses the ASTM E1530 guarded heat flow meter method in order to measure the thermal conductivity of solid samples. The test sample is held under a compressive load between two polished metal surfaces. The upper surface is temperature controlled. The lower surface is part of a calibrated heat flux transducer, which is attached to a liquid-cooled heat sink. An axial temperature gradient is established through the stack as heat flows from the upper surface through the test sample to the heat sink. After reaching thermal equilibrium, the temperature difference across the sample is measured along with the output from the heat flux transducer. These values and the sample thickness are then used to calculate the thermal conductivity. The temperature drop through the sample is determined from temperature sensors in the metal surfaces on either side of the sample. The device has an estimated uncertainty of 3 % to 8 % depending on the thermal resistance of the sample and the measuring conditions.

It should be mentioned that while checking the operation of the instrument it was noticed that the temperature and the flow of the cooling water affected the accuracy and the repeatability of the measurements. Thus, in order to ameliorate the measuring

Fig. 1 Photograph of the thermal-conductivity instrument

conditions, some additional equipment was acquired and connected to the Quickline-10. First of all, the cooling water was provided from a 60 l bath. The temperature of the bath was monitored and controlled with the use of a thermoregulator (TE-8D Tempette, Techne, UK) and an immersion cooler (EK 51-1, HAAKE, Germany). The water temperature was always controlled at 20 °C. Moreover, the water flow was controlled with the use of a pump (Model 100 Nautilus, SHURflo, UK). The pump flow was connected to a power supply (TT EL302D, Thurlby Thandar Instruments Ltd, UK) capable of supplying up to 30 V/2 A. The current was kept stable and thus was the water flow. Another piece of equipment connected to the Quickline-10 was an air compressor of 2 HP which was utilized to supply the required air for the proper operation of some small pneumatic actuators inside the instrument. The supplied air was dried and filtered to 10 μm. The use of all the above equipment (see Fig. 1) resulted in stable experimental conditions and thus in an improvement of the repeatability and the accuracy of the instrument. It is thus believed that the uncertainty of the instrument is better than 6 %.

2.2 Quickline-10 Calibration

The Quickline-10 instrument must be calibrated before measuring materials of unknown thermal conductivity. The calibration procedure consists of testing at least three samples of materials of known thermal conductivity. In the present work four

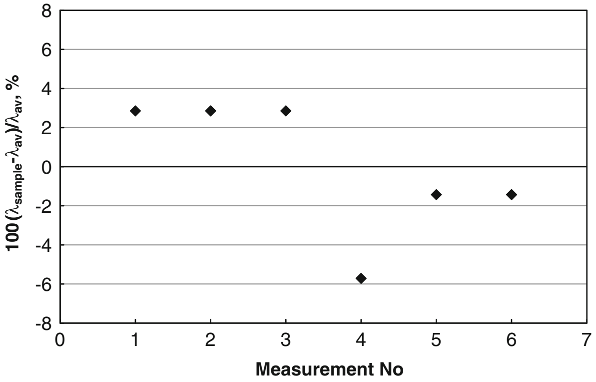

Fig. 2 Repeatability of the thermal-conductivity measurements (sample 1 at 293.15 K)

samples were used, two samples of Pyrex 7740 with a diameter of 50.8 mm and widths of 6.35 mm and 12.7 mm and two samples of stainless steel 304 with the same dimensions.

However, the majority of the measured samples were beyond the calibration range and thus additional calibration was required. In order to extend the operability of the Quickline-10, a transient hot-wire (THW) instrument was used. The present research group has used successfully the transient hot-wire technique (THW) for measuring the thermal conductivity of solids [6,7]. The transient hot-wire instrument has an uncertainty of 1 %, and it was used in order to validate the Quickline-10 results. Samples of the same material were measured using both instruments, and the results were compared. The resulting thermal conductivity values of the Quickline-10 measurements were within the mutual uncertainty of the instruments. Thus, it was concluded that the calibration line used in the Quickline-10 instrument could be extended to the region of concern.

The samples measured had a diameter of 50.8 mm and their width varied from 0.4 mm to 0.7 mm. Moreover, in order to have better contact between the sample and the upper and lower plates of the instrument, a thermal compound was applied on both sides of the samples.

The repeatability of the Quickline-10 was tested. Measurements of the same sample were performed using the same ambient conditions, and the results were satisfactory. In Fig. 2 the repeatability of the measurements of the sample with composition 1 (see Table 1) can be seen.

3 Measurements

Six different binders were used in order to produce 15 normal pastes according to EN 196-3:1994:

– The lime used contains 76 % $Ca(OH)_2$ by mass.
– The pozzolanicity indexes of the two different-in-origin pozzolanas (as measured according to ASTM C 311 standard test method) are in the case of pozzolana A, 4.5 MPa, and in the case of pozzolana B, 10.5 MPa.

Table 1 Physical properties of binders

	Diameter of grains (μm)			Specific gravity ($g \cdot ml^{-1}$)	Specific surface area ($m^2 \cdot g^{-1}$)
	(0.1)	(0.5)	(0.9)		
Lime	1.869	9.40	376.4	1.961	1.207
Pozzolana A	3.0	21.7	79	1.863	0.779
Pozzolana B	1.516	4.87	18.66	1.903	1.770
Brick dust	8.08	70.26	250.4	2.279	0.3061
White cement	1.87	15.57	54.65	2.664	1.3707
Portland cement	2.4	14.56	63.17	3.10	0.954

- Brick dust is of low pozzolanicity (1.8 MPa) due to the modern way of production (burning clay at 1200 °C).
- White cement is used in order not to induce color changes and also due to its alkali-free content. For comparison purposes, Portland cement was also tested.

The first six compositions consist of lime and two natural pozzolanas in 1:1 proportion by mass and different water/binder ratios. Changes in the water content cause differences in the workability of the fresh mixtures and the porosity of the hardened ones. In this way the role of the porosity in the thermal conductivity is measured. In all the other mixtures, water was added to produce normal pastes according to EN 196-3:1994. Three compositions (7, 14, and 15) consist of one component, lime, white cement, and Portland cement, respectively. In compositions 8, 9, and 10, parts of the pozzolana were substituted by white cement, while in compositions 11, 12, and 13 the pozzolana was substituted by brick dust.

The physical properties of the binders are shown in Table 1. In particular, the diameter of the grains, measured in μm, and the specific surface area are measured by particle size analysis (Mastersizer 2000, Malvern) and the specific gravity was measured according to ASTM C188-95. It can be seen that for the lime, as an example, 90 % of the sample is composed of grains of diameters less than 376.4 μm, 50 % less than 9.40 μm, and 10 % less than 1.869 μm.

The produced compositions, the open porosity measured at 7 days, and the measured thermal conductivity at a temperature of 20 °C are shown in Table 2. The thermal conductivity was also measured at the seventh day of the production of each specimen, and each time, three samples were measured.

The parameters tested were:

- the influence of the binder type.
  Mixed binder types were prepared as shown in Table 2. The most commonly used binder mixtures for the production of repair mortars for intervention works in monuments and historic buildings were produced in order to test their thermal-conductivity efficiency.
- the influence of water.
  Different water/binder ratios were added to the same binders. Three different water/binder ratios were tested for two different mixtures. It is known that an increase of the water content in mixtures causes an increase of porosity as empty

Table 2 Composition of mixtures and their measured porosity and thermal conductivity

No	Air lime (parts/mass)	Pozzolana (parts/mass)		Brick dust (parts/mass)	Cement (parts/mass)		W/B[a] ratio (-)	Porosity[b,c] (%)	Thermal conductivity[c] ($W \cdot m^{-1} \cdot K^{-1}$)
		A	B		White	Portland			
1	1.0		1.0				0.526	43.20	0.23
2	1.0		1.0				0.540	43.70	0.22
3	1.0		1.0				0.625	44.10	0.17
4	1.0	1.0					0.370	54.13	0.19
5	1.0	1.0					0.500	54.65	0.16
6	1.0	1.0					0.550	54.90	0.16
7	1.0						0.616	–	0.27
8	1.0		0.8		0.2		0.560	40.41	0.35
9	1.0		0.6		0.4		0.536	39.60	0.36
10	1.0		0.5		0.5		0.550	37.79	0.37
11	1.0		0.8	0.2			0.560	40.21	0.38
12	1.0		0.6	0.4			0.530	39.6	0.27
13	1.0		0.5	0.5			0.497	40.19	0.25
14					1.0		0.352	15.64	0.39
15						1.0	0.330	14.74	0.34

[a] Water/binder ratio
[b] Measured according to RILEM CPC11.2
[c] Measured at the age of 7 days

spaces are created in the structure due to the evaporation of the water excess (Table 2).

4 Discussion

The following very useful observations can be made by examining the results in Table 2.

- In single component mixtures, the thermal conductivity of the mixtures produced using traditional binders such as lime is low in comparison with modern building materials such as cements (compositions 7, 14, and 15). Adding white cement also causes an increase of the thermal conductivity, and this seems to be proportional to the amount of cement added (compositions 8, 9, and 10).
- Increasing the water ratio in the same sample mixtures and thus causing a porosity increase, the thermal conductivity is reduced (compositions 1, 2, 3 and 4, 5, 6). In a way this was expected, as in essence the air content is increased and air has a comparatively very low thermal conductivity.
- The addition of pozzolanic materials reduces the thermal conductivity in comparison with pure lime (composition 7 in comparison with the first six mixtures). Pozzolana A seems to be more effective in terms of a lower conductivity than for B despite the fact that it is coarser and less reactive as the pozzolanicity index is

concerned in comparison with pozzolana B. The role of brick dust when measuring the thermal conductivity seems to be positive when the brick dust is used in high proportions as the thermal conductivity is $0.38\,W \cdot m^{-1} \cdot K^{-1}$ in composition 11 and $0.25\,W \cdot m^{-1} \cdot K^{-1}$ in composition 13. Nevertheless, in compositions containing brick dust, the thermal conductivity is higher in comparison with those containing only lime and pozzolana.

5 Conclusions

Traditional binders were tested in order to examine their thermal conductivity behavior and demonstrate that in addition to being compatible with the old, authentic building materials in monuments and historic structures, they can also add environmental characteristics. In this study the energy profile of lime in comparison with cements is shown as well as the positive role of natural pozzolanas is once again demonstrated.

Porous building materials such as mortars based on lime are shown to have good thermal properties and, furthermore, they can provide the benefit of low cost and energy sufficient construction. Exploring the possibilities of traditional, ecologic materials of low strength, can give modern masons tools for sustainable construction.

References

1. I. Papayianni, Durability lessons from the study of old mortars and concretes, in *P.K. Mehta Symposium on Durability of Concrete* (Nice, France, 1994)
2. I. Papayianni, A diachronic principle in construction: the use of mixed type binders: durability aspects, in *J. G. Cabrera Symposium on Durability of Concrete Materials*, ed. by R.N. Swamy (1998), pp. 115–130
3. J. Schafer, H.K. Hilsdorf, Ancient and new lime mortars—the correlation between their composition, structure and properties RILEM, in *Conservation of Stone and Other Materials*, ed. by M.-J. Thiel (Unesco, Paris, 1993), pp. 605–612
4. I. Papayianni, M. Stefanidou, Study of the structure of hydraulic mortars of ancient technology, in *2nd International Conference on Ancient Greek Technology* (Athens Technical Chamber of Greece, 2006), pp. 151–157
5. I. Papayianni, M. Stefanidou, The influence of mixture design parameters on the long term strength of lime-based mortars, in *Int. Conf. Studies on Historical Heritage SHH07*, ed. by Gorun Arun (Atalya, Turkey, 2007), pp. 347–354
6. M.J. Assael, K.D. Antoniadis, J.T. Wu, Int. J. Thermophys. **29**, 1257 (2008)
7. M.J. Assael, K.D. Antoniadis, K.E. Kakosimos, I.N. Metaxa, Int. J. Thermophys. **29**, 445 (2008)