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Investigation of some Thermal and Elemental Properties in Clay Brick in Khartoum State

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Abstract

Two clay brick samples an old one and a new one were collected in Khartoum, Sudan. The samples were analyzed by x-ray fluorescence to study the constituent element. The specific heat capacity, water absorption, moisture content and thermal mass were measured, then the two samples were coated with a layer of cement and measurements were repeated. The obtained results for the specific heat capacity ranged between 710.6$JKg^{-1}K^{-1}$ and 930$JKg^{-1}K^{-1}$ for the water absorption they ranged between 6.05% and 9.9%, for the volumetric heat capacity they ranged between 0.94 $\times 10^6$ $Jm^{-3}K^{-1}$ and 2.74 $\times 10^6$ $Jm^{-3}K^{-1}$ while for the moisture content at 400^0C they ranged between 0.19% and 0.03%.

المستخلص

أخذت عينتان من الطوب أحداهما قديمة الصنع والأخرى حديثة الصنع في مدينة الخرطوم في السودان .حللت العينتان لدراسة المكونات بواسطة الاشعة السينية المتفلورة .حسبت الحرارة النوعية ،الامتصاصية للماء ، محتوى الرطوبة و الكتلة الحرارية في العينتين ثم طليت العينتان بطبقة من الاسمنت وكررت الحسابات. تراوحت النتائج المتحصل عليها للحرارة النوعية بين 710.6$JKg^{-1}K^{-1}$ و 930$JKg^{-1}K^{-1}$ و لامتصاصية الماء تراوحت بين 6.05% و 9.9% و للحرارة النوعية الحجمية تراوحت بين 0.94 $\times 10^6$ $Jm^{-3}K^{-1}$ و 2.74 $\times 10^6$ $Jm^{-3}K^{-1}$ بينما لمحتوى الرطوبة عند 400^0C تراوحت بين 0.19% و 0.03%.

Keywords: volumetric heat capacity, constituent elements, thermal mass, moisture content, cement, clay brick.

Introduction

Climate in Sudan is rather hot and to keep buildings cool, artificial cooling methods are needed. These artificial methods like air conditioners are rather expensive and consume a lot of electricity. To help to solve this problem the researchers suggest that if some appropriate kind of clay brick is used in building it may lower the temperature inside the building and lower consumption of electricity. To achieve this, some properties of clay bricks are studied to improve the choice of clay brick to be used in construction so as to keep the temperature lower inside buildings beside keeping the same quality of bricks.

High thermal mass materials are those that are able to store a high amount of heat and give high thermal inertia to the building components. There properties, when included in a building, give thermal stability and smooth the thermal fluctuations between outside and inside conditions (Kalogirou et al., 2002). This allows the indoor environment inside a house to be more comfortable with less energy consumption. The use of higher heat capacity structures helps in the reduction of the energy consumption in air-conditioned buildings. Hence thermal inertia has been used as a climate moderator. Most commonly used materials in buildings with high thermal inertia are stone, adobe, rammed earth, brick, water, and concrete.

The benefits of the effect of thermal inertia depends on several parameters such as climate conditions, thermal properties, ventilation, thermal insulation, occupancy and internal heat gains. To achieve the best result, it is important to understand the relation of these parameters in the performance of thermal mass.

Clay bricks are used in a wide range of buildings from housing to factories, and in the construction of tunnels, waterways, bridges etc. Their properties vary according to the purpose for which they are intended, but clays have provided the basic material of construction for centuries. Bricks have been used since the early civilization. Brick is a kind of crystalline ceramic and is among the most common construction materials found all over the world. Bricks can be made with sophisticated factory methods, simple lab methods or a range of mechanized technologies in between (Shakir et al,**,** 2013). The lab production methods are most suitable for rural areas where the demand for bricks is limited. Bricks that are produced by hand have relatively lower quality, especially compressive strength, and will tend to have irregular dimensions. However, they are economical and require little capital investment or transportation cost. Bricks made in this manner have been used in building which have lasted for centuries. Their longevity has depended on the quality of the ingredients, the skill of the artisan and the climate in which they were used.

Burnt clay bricks have good resistance to moisture, insects and erosion and create a good room environment. They are medium in cost and have medium to high compressive strength.

Good brick material is composed of Alumina: It is the chief constituent of every kind of clay. A good brick should contain 20% to 30% of alumina. This constituent imparts plasticity to the clay so that it can be molded. Silica: It exists in clay either as free or combined, as free sand. It is mechanically mixed with clay. In combined form, it exists in chemical composition with alumina. A good brick material should contain about 50% to 60% of silica. Lime: small quantity of lime not exceeding 5 percent is desirable in good brick material (Sankar et al., 2019). It should be present in a very finely powdered state because even small particles of the size of pin-head cause flaking of the bricks. The lime prevents shrinkage of raw bricks. The sand alone is infusible. Oxide of iron: a small quantity of oxide of iron to the extent of about 5 to 6 percent is desirable in good brick material. It helps as lime to fuse sand. It also imparts red color to the bricks. The excess of oxide of iron makes the bricks dark blue or blackish. Magnesia: a small quantity of magnesia in brick material imparts yellow tint to the bricks and decreases shrinkage. However, excess of magnesia leads to the decay of bricks.

This article is composed of three parts. In the first part the identification of samples was performed in order to study the main constituent elements of them. The second part of this work presents an experimental study conducted to investigate the specific heat capacity, thermal mass, absorption of water, and moisture content in clay bricks. Finally, the results are shown and discussed.

Theoretical Background

Specific heat capacity

Specific heat capacity c refers to a material's capacity to store heat for every kilogram of mass. It is measured in J/kgK. According to the law of conservation of energy the unknown specific heat is computed from the following equation (**Noakes et al.**, 1967)

$$Mc(T_2 - T) = (c_w m_w + c_{cal} m_{ca} \quad (T T_1) \qquad (1)$$

where M is the mass of the brick, c is the specific heat of the brick, T_2 is the temperature of the brick, T is the equilibrium temperature, T_1 is the initial temperature of the water and calorimeter, $m_{cal} c_{cal} = C_{cal}$ is the water equivalent of the calorimeter and stirrer, and m_w is the mass of the cold water.

Thermal mass and volumetric heat capacity

Thermal mass describes a material's capacity to absorb, store and release heat. It is a property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations. Thermal mass will absorb thermal energy when the surroundings are higher in temperature than the mass, and give thermal energy back when the surroundings are cooler, without reaching thermal equilibrium (Hickson, 2013).

The mechanism of heat transfer begins during the day, when the external wall temperature increases as a result of the heat balance between the gain caused by incident solar radiation and the losses by the convection and radiation. As the time passes, some of the heat is absorbed by the wall and the temperature increases according to the material's thermal properties and the boundary conditions. The heat moves, then, through the wall, towards the inside surface. During the night, a reverse process takes place, as the temperature outside decreases and there is no solar radiation. Hence, the wall temperature decreases, depending again on the thermal properties of the materials and the boundary conditions. Heat dissipates from the higher temperature locations to lower temperature places, in order to reach a balance. Thus, higher the thermal inertia of the building, slower the mechanism of heat transfer through its structures will be.

The thermal inertia, or reluctance of the wall to change its temperature when exposed to changing environmental temperatures, also has a significant impact on the thermal quality of the wall, the thermal comfort of the interior space and energy consumption due to space heating.

Scientifically, thermal mass is equivalent to thermal capacitance or heat capacity, the ability of a body to store thermal energy. It is typically referred to by the symbol C_{th} and its SI unit is J/°C or J/K. A material of 'high' thermal mass has a high specific heat capacity. Thermal mass may also be used for bodies of water, machines or machine parts, living things, or any other structure or body in engineering or biology. The equation relating thermal energy to thermal mass is:

$$Q = C_{th}\,\Delta T \qquad (2)$$

where Q is the thermal energy transferred, C_{th} is the thermal mass of the body, and ΔT is the change in temperature. For a body of uniform composition, C_{th} can be approximated by

$$C_{th} = mc_p \qquad (3)$$

where m is the mass of the body and c_p is the isobaric specific heat capacity of the material averaged over temperature range in question.

Thermal mass is mainly described by the evaluation of brick's volumetric heat capacity VHC whose unit is J m^{-3} K^{-1}, defined as the product of specific heat capacity c and mass density of brick ρ given in kg m^{-3}. Hence (Giada et al., 2019)

$$VHC = c\rho \qquad (4)$$

VHC represents the ability of a material to store heat while undergoing a given temperature change. It also refers to the amount of heat required to elevate the temperature of a unit volume of the material. The Volumetric Heat Capacity term is used to characterize a material while Heat Capacity is used in the description of building components (Solange, 2004). The VHC defines the 'per unit volume' measure while the specific heat is a 'per unit mass' measurement. The amount of useful thermal storage is calculated by multiplying the VHC by the total accessible volume of the material.

Water absorption

Water absorption test on bricks is conducted to determine durability property of bricks such as degree of burning, quality and behavior of bricks in weathering. It is normally employed to determine the compactness of the bricks as pores of the bricks absorb water (Jamaludin et al., 2019). If the brick absorbs more water than the recommended, it gives adverse effects on the strength of brick as well as the durability of the structure. Bricks of low water absorption have good resistance to external weather conditions. So, water absorption is a significant and useful property of bricks. Water absorption W % by mass, after immersion in water is given by the formula,

$$W\% = \frac{M_2 - M_1}{M_1} \times 100\% \qquad (5)$$

Moisture content

Moisture content in the clay brick is defined as the ratio of the water contained in the material to the original mass of the sample (Raimondo et al., 2007). Moisture contents above 18% can increase the growth of fungus in earthen materials, especially when stabilized with natural fibers (Ashour et al., 2015). Moisture content is influenced by the geographical location, the particular material exposed, the direction of exposure, and the season of the year (Ritchie, 1968). For an overview of the different methods which can be used to evaluate moisture content, see (Hola, 2017).

The moisture content of each test sample was calculated by the following formula:

$$\text{Moisture content\%} = [(M_{wet}-M_{dry})/M_{wet}]100\% \quad (6)$$

where M_{wet} is the weight of sample before drying and M_{dry} is the weight of the sample after drying.

Methodology

Two clay brick samples were collected from two buildings an old building more than 30 years old and a new one in Khartoum, Sudan to study some of their physical properties. A small broken piece of each brick samples was thoroughly hand grounded in a mortar to make a fine powder for XRF analysis (Lourenço et al., 2010). The chemical composition can provide information needed for an estimation of the quality of the clay.

Chemical composition

Chemical composition tests using X-ray fluorescence (XRF) spectrometry were carried out to study the composition of each sample. Each sample was irradiated with X-Rays. The radiation that is generated by the different brick's elements is characterized by a specific wavelength and intensity, which is related with its concentration, allowing, therefore, their identification in the X-Ray spectrum. The calculation of the elemental concentration of samples was performed using Canberra 35+ device. A semiconductor detector in the form of crystal materials: lithium, silicon, cadmium was implemented. The used energy was 30mlkorean and the software used was an excel program, Figure1.

Figure1: Canberra 35+ device used to calculate elemental concentration within samples

Thermal Properties of Bricks

Experimental studies were carried out to investigate the specific heat capacity, the thermal mass, the absorption of water and the moisture content of the two samples before and after coating with a thin layer of cement, Figure2.

Figure2: New and old samples before and after coating with cement

Specific heat capacity, thermal mass and volumetric heat capacity

Specific heat capacity was determined by method of mixtures which consists of dropping a known mass of the brick at a known high temperature into a known mass of water at a known low temperature. The equilibrium temperature is then measured. The heat absorbed by the water, calorimeter, and stirrer is equal to the heat lost by the brick. The unknown specific heat was computed from equation (1), the calculated specific heat was used to compute the thermal mass from equation (3) and volumetric heat capacity from equation (4).

3.2.2 Water absorption

Water absorption of bricks was investigated by obtaining the weight of dry specimen M_1 then dried specimens were immersed completely in clean water at room temperature for 24 hours. Traces of water on specimens were removed with damp cloth and the specimen were weighed again to obtain the weight M_2. Measurements were repeated after covering the samples with a thin layer of cement. Equation (5) was used for calculations.

Moisture content

To evaluate moisture or water content, masses of the samples (with the actual moisture content) were measured at room temperature giving M_{wet}. This was achieved using a sensitive balance allowing a reading to an accuracy of 0.1% of the samples dry mass. Samples were then immediately placed in an oven at 100^oC to heat them. The used oven ranges from 100^oC to 800^oC ± 2 ºC. Sensitive balance and oven are shown in Figure3.The samples were heated for an hour then they were weighed again to give M_{dry}. This procedure was repeated four times until the constant mass at temperature of 400^oC was reached. Constant mass is considered to be reached when the mass does not differ more than 0.1%. The samples shall be clean without additional surface moisture, and free from mortar. The samples were covered with a thin layer of cement and measurements were repeated. Equation (6) was used for calculations.

Figure3: Sensitive balance and oven used in measurements

Results

Results of chemical composition of the old sample is presented in Table1, and that of the new sample is shown in Table 2. Counts versus channel number for the old sample are given in Figure4. Counts versus channel number for the new sample are given in Figure5.

Results of the average specific heat capacity and average thermal mass for the four specimens are shown in Table3. Comparison of the specific heat capacity of samples is represented in Figure6.The results of the density of the four samples are shown in Table4. Results of water absorption for the four specimens are shown in Table5 and comparisons of the results are represented in Figure7. Results of percentage of moisture content for the four specimens are shown in Table6. Percentage of moisture content versus temperature for the four specimens is represented in Figure8. Comparison of the volumetric heat capacity for the four samples is shown in Figure9.

Discussion

Results of XRF analysis indicate that elements which were found in both samples are calcium, titanium, iron, lead, rubidium, strontium, zirconium and niobium with calcium, titanium and iron most abundant. The two samples differ greatly only in the amount of iron and lead and the difference in other constituents is quite negligible.

It was found that there is no significant difference in the value of the specific heat capacity between the old and new specimens and both results are lower than measurements reported in the literature on compressed stabilized earth bricks ranging from 939 to 1170 $J.kg^{-1}K^{-1}$ (Touré et al., 2017), but slightly higher than those measured on unfired earth bricks (El Fgaier et al., 2016) ranging from 545 to 712 $J.kg^{-1}K^{-1}$, or on adobe (Abanto et al., 2017) where it ranged from 560 to 614 $J.kg^{-1}K^{-1}$,also the results are in agreement with (Kamal, 2016). The specific heat capacity increased in both samples after coating with cement that is heat will be accumulated more within cement coated clay samples which have higher heat capacity than in bare samples (Ioan et al., 2018). The increment of specific heat capacity in cement coated samples is quite natural as for brick alone the specific heat capacity is about 800 $Jkg^{-1}k^{-1}$ and for concrete alone it is about 1000 $Jkg^{-1}k^{-1}$in agreement with (Touré, 2017).

Concerning the absorption of water the obtained results seem accepted as the average water absorption should be between 15% and 25% for different classes of clay bricks(McBurney et al., 1938), (Fadele et al., 2018),(Grabarz et al., 2012) which means that the quality of bricks was not reduced after the samples were coated with cement.

The results showed that the water absorption increased after coating with cement in the old sample from 8.94% to 9.9% and it increased in the new sample after coating from 6.05% to 9.4%. The four samples are first class bricks, as the water absorption should not be more than 18 % (Karaman et al., 2006).

The highest Volumetric Heat Capacity resulted in the new sample after coating with cement followed by the old sample after coating with cement and both results are higher than those reported in (Laaroussia et al., 2013) whereas the lowest Volumetric Heat Capacity showed in the new sample followed by the old sample, both results are less than results reported in (Laaroussia et al., 2013). Thus, the highest thermal mass will result in the new sample after coating with cement followed by the old sample after coating with cement followed by the old sample, the lowest thermal mass will be in the new sample.

The highest moisture content resulted in the new sample after coating with cement followed by the old sample coated with cement followed by the new sample followed by the old sample which means that moisture content increased with coating with cement for both samples. Most of the loss of moisture occurred when the sample was heated between 100^{o}C and 200^{o}C then it remained almost constant for further heating for all the four samples.

Unlike (Ritchie, 1968) where the moisture content was greater for samples of greater water absorption, moisture content was greater for the new sample whereas water absorption was greater for the old sample.

Conclusion

The specific heat capacity of the brick clay did not differ markedly with age before coating with cement but it increased due to coating with cement which means less temperature change will be noticed within the building. The water absorption increased after coating with cement but was kept within accepted range, both old and new samples are of the first-class clay bricks. The volumetric heat capacity also increased after coating with cement which means that thermal mass also increases. The results of this work showed the importance of thermal mass as a moderator for daytime occupied buildings, such as offices, in warm climates. The increase of thermal capacity in the building stabilizes the internal temperature, keeping conditions cooler than the outside during the daytime hours. Also, the moisture content increased for both samples after coating with cement. Hence one may conclude that coating a sample with cement improves all its thermal properties and that the new sample after coating with cement is the best sample to be used as a thermal mass to lower consumption of electricity. Other physical properties are open for investigation in future work.

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8.Tables:

Table1: chemical composition of the old sample

EL	E{KEV}	INT{c/s}	S	T	CONC {FRAC}	ERROR
Ca	3.690	0.140	6.88E+02	0.0174	4.77E-02	1.30E-02
Ti	4.508	0.143	1.65E+03	0.0246	1.45E-02	3.94E-03
Fe	6.400	4.972	3.92E+03	0.0580	1.06E-01	2.68E-02
Pb	10.540	0.044	1.25E+04	0.1204	1.40E-04	4.38E-05
Rb	13.375	0.076	2.15E+04	0.2008	8.40E-05	2.45E-05
Sr	14.142	0.414	1.96E+04	0.2232	4.52E-04	1.17E-04
Zr	15.746	0.721	2.27E+04	0.2680	5.67E-04	1.46E-04
Nb	16.584	0.107	2.93E+04	0.2893	6.04E-05	1.72E-05

Table2: chemical composition of the new sample

EL	E{KEV}	INT{c/s}	S	T	CONC {FRAC}	ERROR
Ca	3.690	0.123	6.88E+02	0.01766	4.33E-02	1.19E-02
Ti	4.508	0.099	1.65E+03	0.0252	1.01E-02	2.86E-03
Fe	6.400	3.787	3.92E+03	0.0610	7.65E-02	1.94E-02
Pb	10.540	0.025	1.25E+04	0.1405	6.84E-05	2.59E-05
Rb	13.375	0.080	2.15E+04	0.2332	7.64E-05	2.16E-05
Sr	14.142	0.396	1.96E+04	0.2584	3.75E-04	9.72E-05
Zr	15.746	0.521	2.27E+04	0.3080	3.58E-04	9.23E-05
Nb	16.584	0.089	2.93E+04	0.3312	4.40E-05	1.27E-05

Table3: the average specific heat capacity and volumetric heat capacity for the four specimens.

	Z.E =0.0005 kg								
	mC/kg	mw/kg	M/kg	T1/ K	T2/ K	T/ K	c/ J/kgK	cave/ J/kgK	VHC/J m−3 K−1
Old1	0.0962	0.3333	0.2478	301	373	309	724.83	710.6	1.1×106
Old2	0.0962	0.3661	0.2553	303	373	310	696.37		
New1	0.0962	0.3382	0.2557	302	373	311	947.12	726.63	0.94×106
New2	0.0962	0.3575	0.2895	304	373	310	506.14		

Old1cem	0.0949	0.2319	0.0734	306	372	310	834.38	810.685	2.63×106
Old2cem	0.0949	0.1951	0.0974	306	373	312	786.99		
New1cem	0.0949	0.2051	0.0629	306	372	311	1080.8	930.26	2.74×106
New2cem	0.0949	0.2045	0.087	306	372	311	779.72		

Table4: Results of density for the four specimens

	Volume of water/ ml	Volume of water and sample/ ml	Volume of sample/ m^3	Mass/kg	Density/kg /m^3	$Density_{Ave}$/ kg/m^3
New1	60	90	30×10^{-6}	42×10^{-3}	1.4×10^{3}	1.3×10^{3}
New 2	45	70	25×10^{-6}	30×10^{-3}	1.2×10^{3}	
Old1	55	75	20×10^{-6}	32×10^{-3}	1.6×10^{3}	1.5×10^{3}
Old 2	60	80	20×10^{-6}	28×10^{-3}	1.4×10^{3}	
Newcem1	55	100	45×10^{-6}	150×10^{-3}	3.3×10^{3}	2.95×10^{3}
Newcem 2	65	95	30×10^{-6}	80×10^{-3}	2.6×10^{3}	
Oldcem1	50	80	30×10^{-6}	106×10-3	3.5×10^{3}	3.25×10^{3}
Oldcem 2	55	85	30×10^{-6}	90×10^{-3}	31×10^{3}	

Table5: Percentage of water absorption for the four specimens

	M_1/kg	M_2/kg	W%	Ave W%
New_1 with cement	0.132	0.150	13.6	9.4
New_2 with cement	0.076	0.080	5.2	
Old_1 with cement	0.092	0.106	15.2	9.9
Old_2 with cement	0.086	0.090	4.6	
New_1	0.040	0.042	5	6.05
New_2	0.028	0.030	7.1	
Old_1	0.0707	0.0779	10.18	8.94
Old_2	0.026	0.028	7.7	

Table6: Percentage of moisture content for the four specimens

temp	$M_{New\ cem}$/g	M_{New}/g	$M_{Old\ cem}$/g	M_{Old}/g	Percentage of moisture content %			
					New cem	New	Old cem	Old
Room temp.	113.101	65.007	101.303	100.263				
100^0C	112.068	64.915	100.948	100.135	0.91	0.14	0.35	0.13
200^0C	112.001	64.901	100.893	100.111	0.06	0.02	0.05	0.02
300^0C	111.766	64.874	100.692	100.076	0.20	0.04	0.20	0.03
400^0C	111.546	64.855	100.521	100.042	0.19	0.03	0.17	0.03

9.Figures:

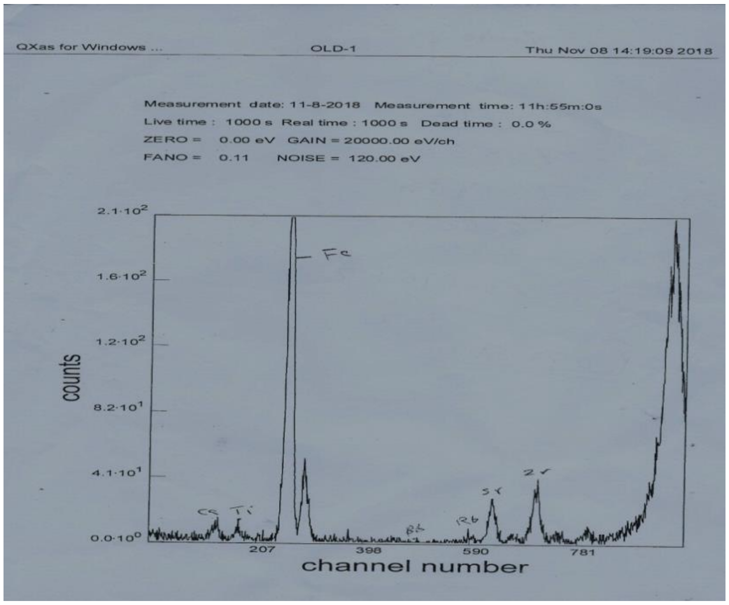

Figure4: Counts versus channel number for the old sample

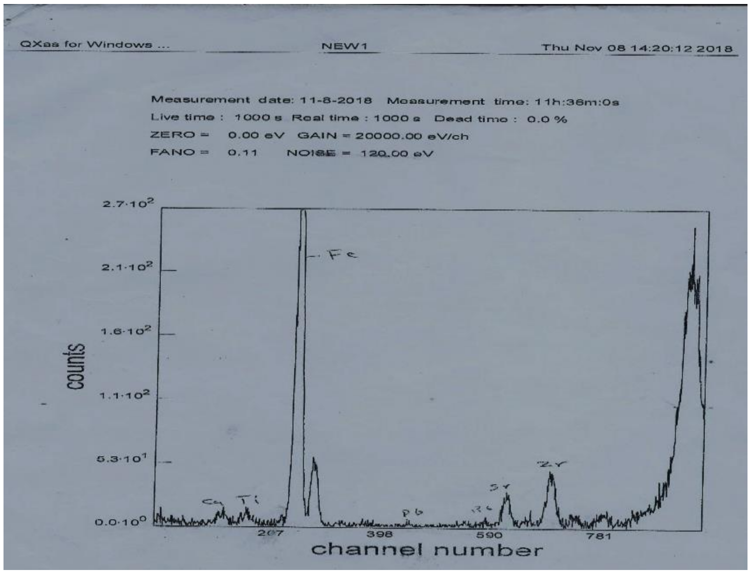

Figure5: Counts versus channel number for the new sample

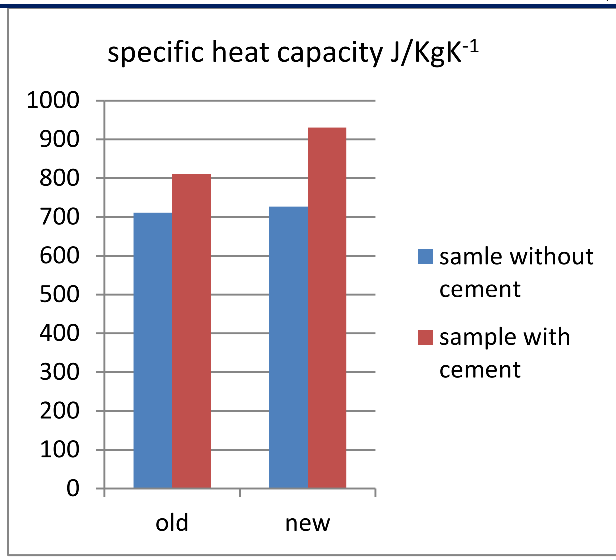

Figure6: Comparison between the specific heat capacities for the four specimens

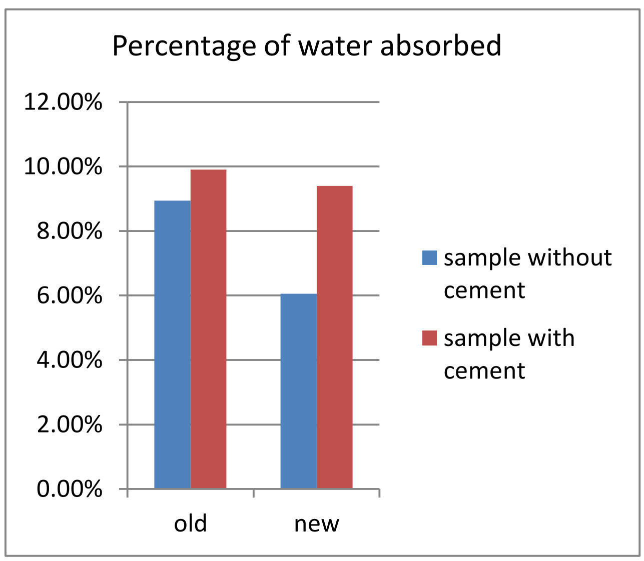

Figure7: Comparison between percentages of water absorbed for the old and new samples before and after coating with cement

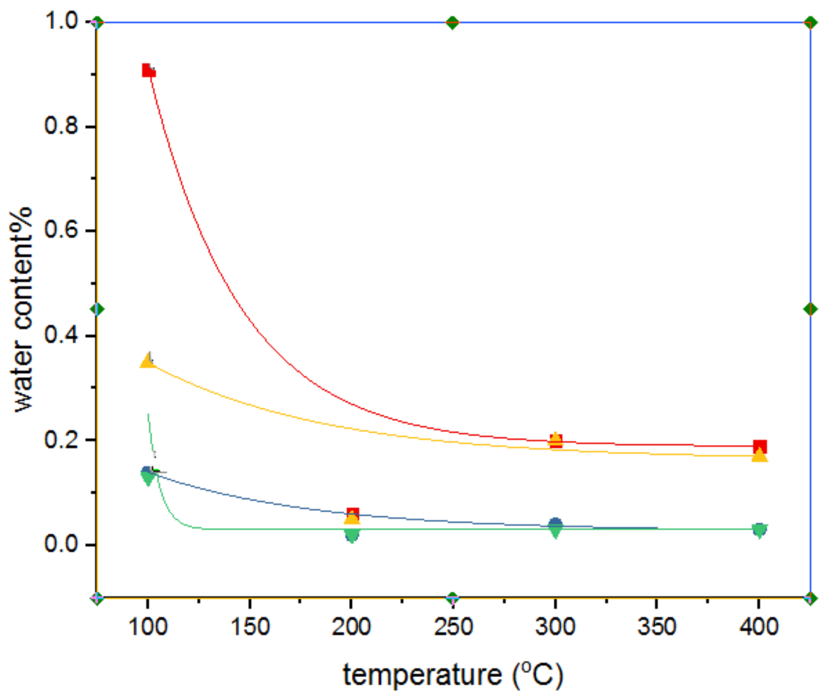

Figure8: Variation of water content with temperature for the four samples: new_{cem} is shown in red, old_{cem} is shown in yellow, old is shown in blue, new is shown in green.

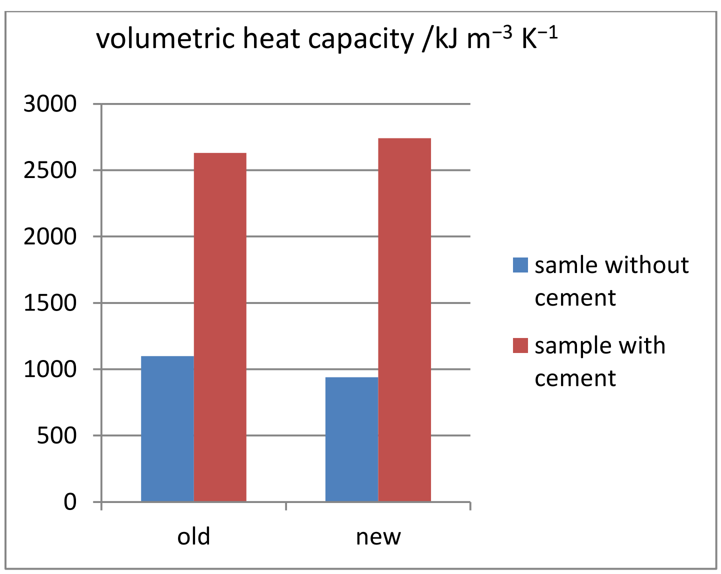

Figure9: Volumetric heat capacity for the four samples