THERMALLY IMPROVED LIGHTWEIGHT MORTARS

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ABSTRACT

In most parts of Europe and particularly the United Kingdom, thermally efficient lightweight concrete blocks whose density can be as low as 475 kg/m^3 are being jointed using traditional cement/lime/sand mortars whose density is about 1,750 kg/m^3. Such disparity in density and, hence, thermal conductivity results in a disproportionate amount of heat being conducted through the mortar joint. This results in a quantifiable reduction in the thermal performance of the external envelope. Other problems associated with the differential heat loss are formation of cold bridges, surface standing, and, in extreme cases, condensation.

In this investigation, several mortars were developed using lightweight aggregates as a replacement for the sand fraction used in traditional mortars. Resulting densities were in the region of 1,100 kg/m^3 to 1,400 kg/m^3. The thermal conductivity of all the lightweight mortars was measured in a plain hot-plate apparatus to standards in BS 874 (BSI 1988) and compared with the thermal conductivity of a traditional cement/sand/lime mortar measured in the same apparatus.

Measured values of thermal conductivity, when corrected to an equilibrium air-dry moisture content of 3% by volume, showed that by using certain replacement aggregates, reductions in thermal conductivity of 30% could easily be achieved.

Measured thermal conductivity data were then used to calculate the U-factor of typical external envelopes using the "proportional area" method given in CIBSE Guide A3 (CIBSE 1980). Results indicated that by using lightweight mortars instead of traditional types, reductions in U-factors of between 6% and 10% could be achieved.

INTRODUCTION

Mortar joints can account for between 5% and 20% of a wall's area. UK building regulations state that the maximum permissible thermal transmittance or U-factor for a wall in new buildings is 0.45 W/m^2·K or 0.6 W/m^2·K if the trade-off provision with double glazing is used. When calculating this figure, several assumptions are made about the method of heat flow through the wall. The most important of these is that heat flows at right angles to the face of the wall. This assumption may be valid if all the components in the wall are of similar density. However, it is common practice to have mortar joints on the internal leaf of the cavity that are four times denser than the blockwork they are bonding. In such cases, the role of the mortar joint acting as a cold bridge is significant. Gradual reduction in wall transmission values have focused the industry's attention on the problem of energy efficiency and this has resulted in a new generation of blockwork being specifically designed to achieve the statutory requirement. Unfortunately, mortar has received little attention; consequently, thermally efficient blocks are still being jointed using dense mortar.

Not only are mortar producers concerned about the role that mortar plays in the heat lost through a wall, but insulation manufacturers have expressed a similar concern and commissioned a report that highlights the effects of the mortar joint. Based on the results of measurements carried out at three independent thermal conductivity test houses, the report highlighted a significant shortfall in the thermal performance of walls built with ultra-lightweight blocks jointed with dense mortar. Walls designed and calculated to have U-factors of approximately 0.6 W/m^2·K were measured with a U-factor of 0.9 W/m^2·K. The report concluded that the heat flux through the mortar joint was partially responsible for the difference in thermal transmission but more significantly suggested, from the test results, that the current method of theoretically predicting thermal transmission values underestimates the actual heat loss.

At present there is no allowance made in the regulations for the effect of the mortar joint. The CIBSE Guide (CIBSE 1980) recommends that where there is a significant density difference between materials, the effect of the mortar joint should be taken into consideration. This recommendation is virtually always ignored when the U-factor is determined and thus anomalies have resulted in the way in which the total U-factor is deter-

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mined. In Europe, the effect of the mortar joint is taken into account in relevant national standards, and specific allowances are made when using mortars with low thermal conductivity. To overcome this problem, from the beginning of July 1995, the UK regulations include specific reference to the problem of heat losses via cold bridges such as mortar joints. It is anticipated that the proportional area method, recommended in the CIBSE Guide, will be used when determining the total U-factor of external walls made from lightweight blockwork and jointed using traditional mortar.

There currently is little information available on the thermal conductivity of mortars and, as a result, when the joint is included in the U-factor calculation, a standard value of 0.84 W/m·K is assumed in most cases. In practice, there are five distinct mortar grades classified in BS 4551 (BSI 1980). A designation (i) mortar is the strongest and a designation (v) is the weakest. The standard thermal conductivity value generally used in calculations is based on a designation (iii) mortar, which is by far the type most commonly used.

This paper gives the results of tests on the thermal conductivity of a wide range of designation (iii) traditional and lightweight mortars. For this investigation traditional mortar samples were first prepared and similar samples were then developed using selected lightweight aggregates made from waste materials such as pelletized blast furnace slag, crushed coal waste, and pulverized fuel ash. A naturally occurring aggregate—pumice—also was used. These aggregates were used as a full replacement for the sand component in the mortar. Due to the number of mixes involved, the mixing regimen was restricted to designation (iii) mortars only. For each mortar, the following types were investigated:

masonry cement: sand/lightweight aggregate,
cement: sand/lightweight aggregate,
cement: lime: sand/lightweight aggregate,
cement: sand/lightweight aggregate and air entrainer.

In all cases, the thermal conductivity of the mortars was measured in accordance with BS 874 (BSI 1988) using a plain hot-plate apparatus. Thermal conductivity data were then corrected to a standard moisture content of 3% by volume using the correction factors proposed by Jakob (1949). These are the standard factors used in the UK. The corrected thermal conductivity data were then used to determine the U-factor of four typical external walls and to assess the potential benefits of using a lightweight mortar in place of a traditional mortar when bonding lightweight blocks together.

MORTAR CONSTITUENTS AND MIX DESIGNS

Consistency in the production of all the mortar samples was important and careful consideration was given to the choice of the cement, lime, aggregate, and air-entraining agent to be used. Once selected, a sufficient quantity of each material was obtained to last the duration of the test regimen.

The use of lightweight aggregates in mortars is not widespread in the UK and consequently there are no standard recommendations for their use and performance. Initial investigations showed there were many aggregates produced from industrial and waste by-products, as well as several that occurred naturally that may be suitable. However, for a lightweight mortar to be commercially successful it has to be economically viable and have a proven technical record. The use of lightweight aggregates in blockwork is well established and this proved to be a useful starting point for the selection of suitable replacement aggregates for use in mortars. The aggregates selected were all physically different and chosen primarily because of their economic viability. They included:

(i) coal waste, an aggregate made from colliery spoil;
(ii) an aggregate produced by pelletizing fly ash and coal slurry (pfa);
(iii) an aggregate made from expanded blast furnace slag (exp. bfs); and
(iv) pumice, a naturally occurring volcanic rock.

Once selected, the lightweight aggregates were crushed and regraded so that they were of a similar size grading to the sand used in the traditional mix designs. After delivery, the aggregates were predried in an oven prior to use. This practice was subsequently altered and all the aggregates were stored outdoors and used in their natural state, as is normal practice in the construction industry with the use of sand. All the mortar samples produced contained aggregates conditioned in this way.

In the UK, mortars traditionally were batched by volume. Problems arose with this method because the amount of water required to produce a suitably plastic mortar varied considerably with different aggregate types. BS 4551 (BSI 1980) now recommends that all the ingredients used in a mortar should be specified by dry mass only. This approach was followed for batching all the mortar mixes.

To obtain a suitable range of samples, a mixing regimen based upon the standard mortar classifications in BS 4551 (BSI 1980) was chosen for all the mortar mix designs. A total of 22 traditional mortars and 71 lightweight mortars was produced. Due to space limitations, only a selection from the full range of mortars mixed is presented here. Table 1 shows the mortar constituents, designation and, where applicable, the percentage lightweight aggregate replacement. Also shown in the table is the mortar's mix proportions by weight and volume, water content, water: cement ratio, and dropping ball consistency.

It is a requirement of BS 4551 (BSI 1980) that all mortars be produced to a standard consistency. Unlike con-

TABLE 1 Summary of Mix Designs

Mortar constituents, designation, sample number and percentage aggregate replacement	Dry mass of cement and lime expressed as a percentage of cement/lime	Equivalent volumetric proportions	Water content (litres)	Water: cement ratio	Dropping ball consistence (mm)
Traditional mortars					
Cement: sand					
1. (iii)	14.0	1:5.5	2.1	0.75	—
Masonry cem.: sand					
2. (iii)	15.8	1:5	2.5	0.79	11.00
Cement: lime: sand					
3. (iii)	13.6/5.0	1:1:6	2.5	0.92	10.60
Cement: sand plus air-entrainer					
4. (iii)	16.5	1:4.25	2.3	0.71	10.40
Lightweight mortars					
Cement: sand/c.w.					
5 (iii) 100%	14.0	1:5.5	6.5	2.72	10.1
Cement: sand/pfa					
6. (iii) 100%	14.0	1:5.5	7.4	2.64	11.0
Cement: sand/bfs					
7. (iii) 100%	14.0	1:5.5	4.5	1.61	11.0
Cement: sand/Pumice					
8. (iii) 100%	14.0	1:5.5	5.3	1.89	10.5
Mas. cem.: sand/c.w.					
9. (iii) 100%	15.8	1:4.5	5.8	1.84	9.9
Mas. cem.: sand/pfa					
10. (iii) 100%	15.8	1:4.5	5.8	1.84	10.9
Mas. cem.: sand/bfs					
11. (iii) 100%	15.8	1:4.5	6.0	1.58	9.4
Mas. cem.: sand/Pum.					
12. (iii) 100%	15.8	1:4.5	6.6	2.08	9.0
Cem.: lime: sand/c.w.					
13. (iii) 100%	13.6/5.0	1:1:6	6.6	2.42	13.1
Cem.: lime: sand/pfa					
14. (iii) 100%	13.6/5.0	1:1:6	6.4	2.35	11.0
Cem.: lime: sand/bfs					
15. (iii) 100%	13.6/5.0	1:1:6	4.8	1.76	9.6
Cem.: lime:sand/Pum.					
16. (iii) 100%	13.6/5.0	1:1:6	5.3	1.94	11.5
Cem.: lime: sand/bfs plus air-entrainer					
17. (iii) 100%	14.5	1:4.25	4.1	1.43	10.5
Cem.: lime: sand/Pum. plus air-entrainer					
18. (iii) 100%	14.5	1:4.25	6.3	2.16	9.7

Nomenclature: c.w = coal waste
pfa = pulverized fuel ash
bfs = blast furnace slag
Pum = pumice

crete mix designs, where specific water: cement ratios are used, when producing a mortar mix the water content has to be sufficient to enable the mortar to achieve a dropping ball consistency of 10 mm ± 0.5 mm. The final column of Table 1 shows the consistency values obtained on the individual mortars.

EXPERIMENTAL PROCEDURE AND U-FACTOR DETERMINATION

The thermal conductivity (λ) of the mortars was measured in accordance with BS 874 (BSI 1988) using a plain hot-plate apparatus. A mold was available in which the samples could be cast vertically to required tolerances. Using this method, a mortar with a consistency conforming to BS 4551 proved to be too wet for thorough compaction to take place. When compacting the mortar samples using a tamping rod, it served only to induce air voids into the wet mix. Water also seeped out of the bottom of the mold. These combined effects made the samples unsuitable for thermal conductivity measurement in the plain hot-plate apparatus. To overcome these problems, an alternative method of compaction was used which still enabled mortars with a standard consistency to be produced. This method involved compacting the samples on a vibrating table, and any tendency of bleeding was reduced by sealing the edges of the mold with a silicone sealant prior to filling with mortar. This method of sample preparation was chosen over using an artificially dry mix because insufficient water affects such factors as moisture content, porosity, and density, all of which have an effect on thermal conductivity. Prior to undertaking the thermal conductivity measurement, all the test samples were conditioned to an air-dry equilibrium moisture content in a controlled laboratory whose environment was maintained at 65% relative humidity (RH), 20°C. They were deemed to be in equilibrium with this psychrometric condition when three successive weekly weighings were the same. The sample weight before and after thermal conductivity measurement was recorded so as to later determine the moisture content of the sample during the test. The oven-dry weight of the samples was determined by drying samples at 105°C for approximately 48 hours. After this time, they were removed from the oven and allowed to cool to ambient temperature in a desiccated atmosphere before weighing.

In total, the thermal conductivity of 18 different mortar mixes was selected for presentation in the paper. The thermal conductivity values were then substituted in place of the standard thermal conductivity value for mortar recommended in CIBSE Guide A3 when calculating the U-factor of four typical wall constructions. Figure 1 shows a section through the walls.

RESULTS AND DISCUSSION

The density and thermal conductivity values adjusted to an equivalent 3% moisture content, measured on the various lightweight mortars, are given in Table 2. These were then used to calculate the U-factors of the wall constructions shown in Figure 1. For purposes of comparison, the U-factors of the walls were then recalculated excluding the mortar joint. The columns containing the U-factors have been subdivided to show the U-factor obtained by including and excluding the mortar joint.

The relationship between thermal conductivity and density of the lightweight mortars given in Table 2 is shown in Figure 2, where thermal conductivity is plotted as a function of density. A standard curve, which is com-

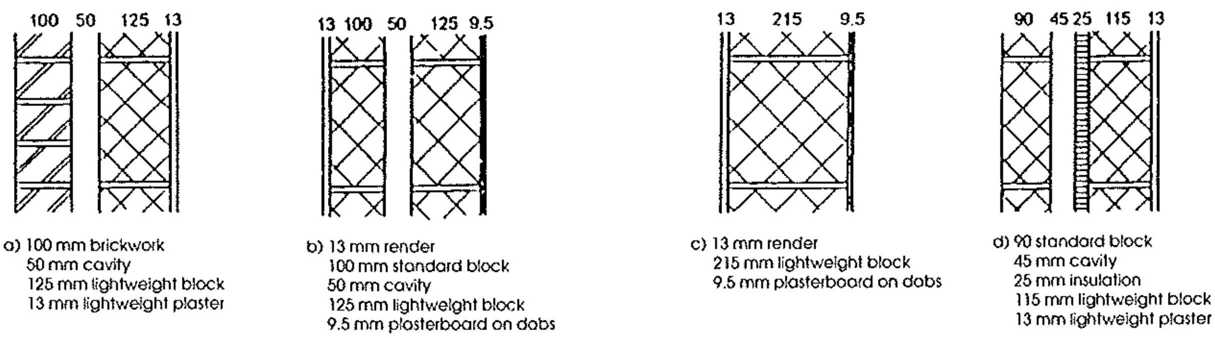

Figure 1 Four typical wall constructions.

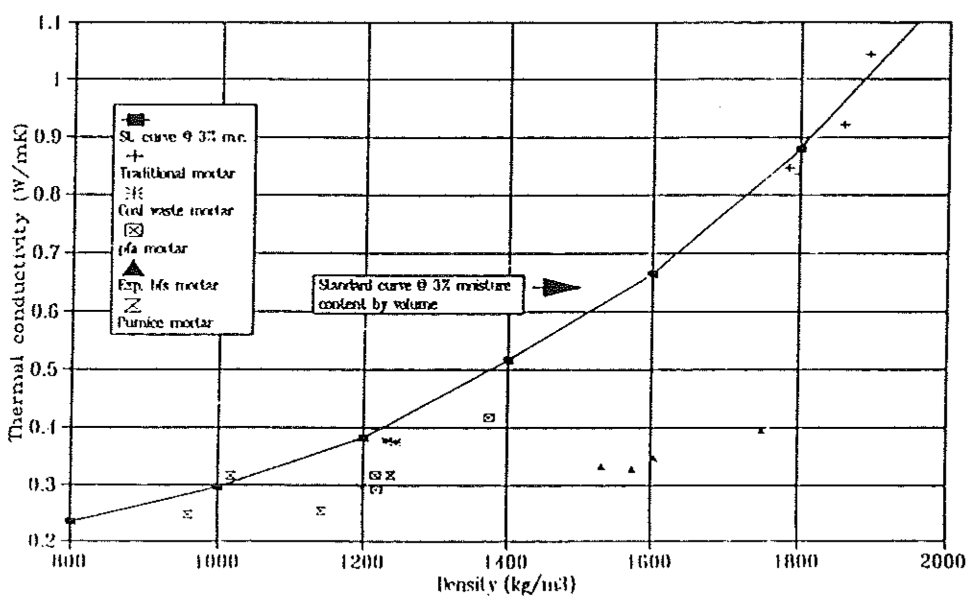

Figure 2 Thermal conductivity, corrected to 3% moisture content by volume, vs. density.

TABLE 2 Summary of Test Results

Mortar constituents, designation, sample no. and percentage aggregate replacement	Density (kg/m³)	λ @ 3% m.c. by vol. (W/mK)	U-Factors; Figure 1a		U-Factors; Figure 1b		U-Factors; Figure 1c		U-Factors; Figure 1d	
			Inc. joint	Exc. joint	Inc. joint	Exc. joint	Inc. joint	Exc. joint	Inc. joint	Exc. joint
Traditional mortars										
Cement: sand										
1. (iii)	1893	1.043	0.67	0.59	0.51	0.44	0.56	0.45	0.35	0.33
Mas. cem.: sand										
2. (iii)	1858	0.922	0.67	0.59	0.51	0.44	0.55	0.45	0.35	0.33
Cement: lime: sand										
3. (iii)	1783	0.846	0.67	0.59	0.51	0.44	0.55	0.45	0.35	0.33
Cement: sand plus air-entrainer										
4. (iii)	1798	0.836	0.67	0.59	0.51	0.44	0.55	0.45	0.35	0.33
Lightweight mortars										
Cement: sand/c.w.										
5. (iii) 100%	1245	0.373	0.63	0.59	0.48	0.44	0.50	0.45	0.34	0.33
Cement: sand/pfa										
6. (iii) 100%	1374	0.418	0.64	0.59	0.48	0.44	0.51	0.45	0.34	0.33
Cement: sand/bfs										
7. (iii) 100%	1750	0.393	0.63	0.59	0.48	0.44	0.50	0.45	0.34	0.33
Cement: sand/Pumice										
8. (iii) 100%	1239	0.318	0.64	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Mas. cem.: sand/c.w.										
9. (iii) 100%	1232	0.376	0.63	0.59	0.48	0.44	0.50	0.45	0.34	0.33
Mas. cem.: sand/pfa										
10. (iii) 100%	1218	0.317	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Mas. cem.: sand/bfs										
11. (iii) 100%	1604	0.345	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Mas. cem.: sand/Pum.										
12. (iii) 100%	1018	0.316	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Cem.: lime: sand/c.w.										
13. (iii) 100%	1199	0.298	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Cem.: lime: sand/pfa										
14. (iii) 100%	1219	0.291	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Cem.: lime: sand/bfs										
15. (iii) 100%	1532	0.331	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Cem.: lime: sand/Pum.										
16. (iii) 100%	960	0.248	0.62	0.59	0.46	0.44	0.48	0.45	0.34	0.33
Cem.: lime: sand/bfs plus air-entrainer										
17. (iii) 100%	1574	0.328	0.63	0.59	0.47	0.44	0.49	0.45	0.34	0.33
Cem.: lime: sand/Pum. plus air-entrainer										
18. (iii) 100%	1143	0.254	0.62	0.59	0.46	0.44	0.48	0.45	0.34	0.33

Nomenclature: c.w = coal waste
pfa = pulverized fuel ash
bfs = blast furnace slag
Pum = pumice

monly used in the UK to relate thermal conductivity to density at 3% moisture content by volume (as proposed by Arnold [1970]) also is shown in the figure. The thermal conductivity of the traditional mortars agrees closely with this curve, although the majority of the lightweight mortars fall significantly below it. On average, the traditional mortars were 0.5% above the standard curve and the lightweight mortars were 32% below it. The mortars containing pumice were the least dense, with an average density of 1,090 kg/m^3. Relative to density and the standard curve, the mortars containing an aggregate made from expanded blast furnace slag (exp bfs) showed the greatest reduction in thermal conductivity. On average, the thermal conductivity of such mortars was 51% less than that expected from the standard curve. These results illustrate that the thermal performance of different mortar mixes can vary significantly and that individual aggregates cause significantly different thermal properties.

The air-entrained mortars (those containing masonry cement and those with the addition of an admixture) had thermal conductivity values that followed a trend similar to that of the other mortar mixes. The addition of air entrainer did not appear to reduce thermal conduc-