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FIRE RESISTANCE OF A MASONRY WALL CONSTRUCTED FROM NOVEL UNITS COMPOSED ENTIRELY OF WASTE MATERIALS AND BOUND WITH WASTE VEGETABLE OIL

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ABSTRACT

An alternative masonry product comprised entirely of waste aggregates and binder is under development. As part of the new product's safety testing, the resistance to fire exhibited by the units in a wall has been investigated. An indicative fire test on a single leaf wall was performed in which the specimens were exposed to heating conditions laid out in British Standards 476:20. The wall remained self-supporting despite loss of material in the units and the temperature at the unexposed face was found not to exceed 85°C after 66 minutes of heating. Several specimens were also retrieved in order to test their residual compressive strength, which was found to be in the range of 4-11 MPa with an average value of 8 MPa. Supplemental studies of individual, fully exposed block units at elevated temperatures suggested a gain in strength at temperatures above 200°C and below 350°C but a sharp decrease in strength in line with the combustion of the binder above 350°C. The testing provides indicative data concerning the behaviour of the product under simulated fire conditions.

KEYWORDS: sustainable, fire, resistance, waste, wall

INTRODUCTION

The requirement to reduce the environmental impact of all industries has been mounting. This is especially noticeable in the construction industry, which despite contributing largely to the economy also has a significant impact upon the environment. The three concerns which the product in this paper addresses are:

- Reduction of primary aggregate extraction [1]
- Recycling of low value wastes into high value products
- Limiting or eliminating use of traditional cementitious binders

The Vegeblock concept revolves around the use of waste materials to create bricks and blocks which can be cured at a low temperature and as such have a low energy requirement [2]. Typical constituents include Incinerator Bottom Ash (IBA) as coarse and fine aggregate and Incinerated Sewage Sludge Ash (ISSA) as a filler; however, crushed bricks, crushed glass, steel slag, limestone and furnace bottom ash have also been used. This versatility stems from the use of Waste Vegetable Oil (WVO) as the binder, typically in proportions of 10-14% by weight. The WVO encapsulates the solids in a cold mixing process. Application of pre-determined static pressure forms a block or brick with a self supporting rigid matrix which is then cured in a convection oven, normally at 160°C for 24 hours. This process has previously been reported in detail [2]. The gain in strength upon heating is attributed to the furthering of a complex series of free radical oxidation and thermal polymerisation reactions that occur during the heating of vegetable oils when cooking foods [3-5].

BRICK MATERIALS

For the wall construction, brick samples containing less than 55% vertical voids of dimensions 214mm x 102mm x 65mm were prepared. A coarse, medium and fine fraction of IBA were used, along with ISSA as filler. The IBA fractions had been oven dried prior to sieving and storage. The WVO was used as collected. The mix proportions and grading are listed in Table 1.

Table 1: Mix design of brick samples.

Brick mixture	**IBA 10-5 mm**	**IBA 5-2.36 mm**	**IBA <2.36 mm**	**ISSA**	**WVO**
% by weight	20%	30%	40%	10%	12%

The IBA was obtained from Veolia UK, the ISSA from Yorkshire Water, and the WVO was collected in-house from Leeds University catering services. An image of a custom mould and an example brick are shown in Figure 1.

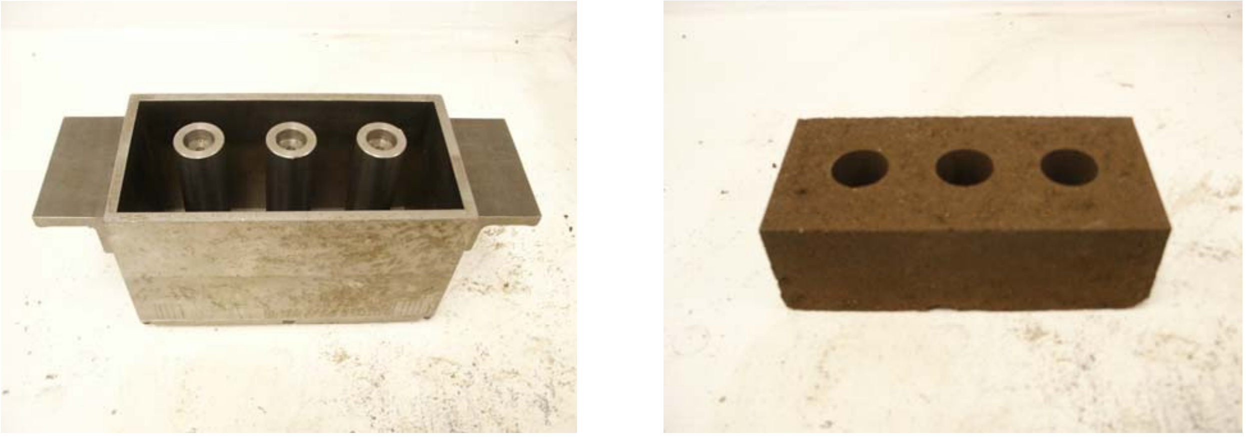

Figure 1: A custom brick mould and an example of a brick complete with perforations.

FIRE TESTING OF WALL

The wall testing was performed at Bodycote Warringtonfire, Warrington, U.K. A single leaf wall of 1000mm height, 1000mm width and 100mm thickness was built using a 3:1 (by volume) sand cement mortar. The wall was effectively divided into two halves, Side A and Side B. Side A was layered with 12.5mm thick standard plasterboard (viewable in Figure 2a). Both sides were exposed to the same conditions. This was Bodycote's recommendation and allowed a comparative analysis of protected and unprotected bricks.

Both halves of the wall had five thermocouples attached to the unexposed face using a high temperature adhesive. The maximum allowable rise in temperature for the test process was to be 140°C above the ambient temperature. In addition, three internal gradient thermocouples were inserted into pre-drilled holes 25mm, 50mm and 75mm deep from the unexposed surface and closed off with a fire resistant cement. The gradient thermocouples were inserted high on the assembly where the heat would be most intense. The construction formed the front face of a one metre cubed gas fired furnace chamber. The setup is viewable in Figure 2b.

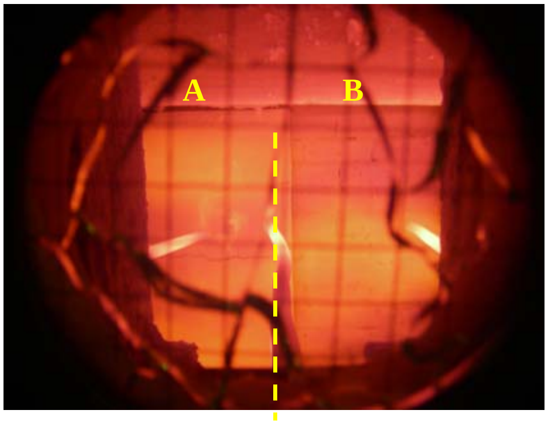

Figure 2a): View of the inside of the furnace and the plastered and unplastered side of the exposed face.

Figure 2b): The unexposed face of the test wall with thermocouples as it appeared attached to the furnace.

The temperature of the furnace was raised in line with the conditions specified in the British Standard [6]. The thermocouples took readings at two minute intervals which were recorded by a computer. The curve showing the relationship between the specified temperatures and the actual, monitored furnace temperatures over time is shown in Figure 3.

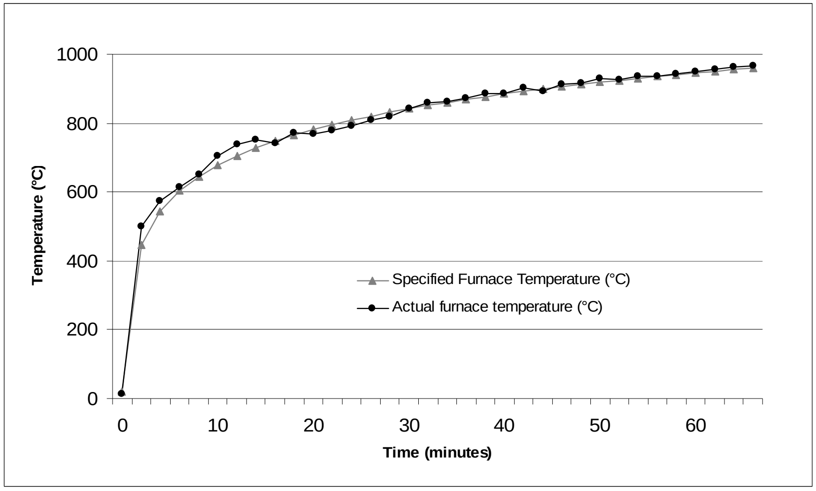

Figure 3: Plot of the temperature curve specified in the British Standards fire resistance test guidelines versus the monitored furnace temperature during the test.

STRENGTH TESTING OF DAMAGED SAMPLES

Of the samples retrieved from the wall construction, several were selected based on their condition (i.e. bricks which had not suffered extensive damage upon removal) and the mortar was removed from both the surfaces and the voids. Prior to crushing, the thickness of the specimens was measured in arbitrary 40mm increments in order to provide a realistic profile with which to determine the reduced cross-sectional area. Completely combusted material was not factored into the measurements as it provided no strength. Profiles of both the top and the bed faces of the bricks were measured. Figure 4 shows an example of how measurements taken from one specimen. The vertical perforations are shown.

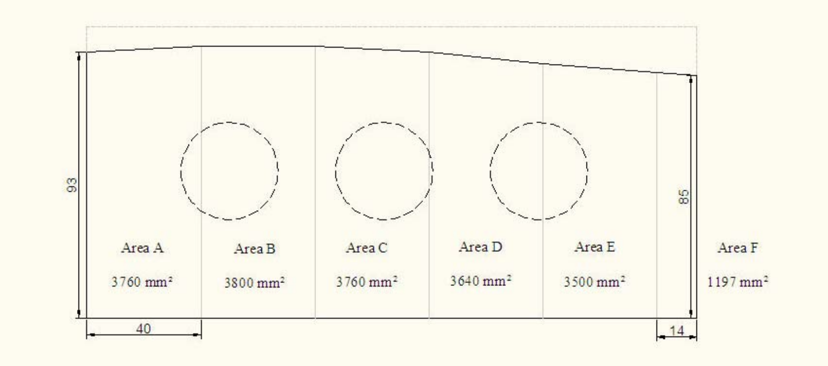

Figure 4: Illustrative diagram of the sections of the top face of one fire tested brick that were measured in order to determine the remaining cross-sectional area.

Compressive strength tests of bricks retrieved from the wall were performed according to the British Standard specification [7]. The testing apparatus was a Tonipact 3000 cube crusher that uses the Servocon Digital Control computer programme. The load was applied at a rate of 6.75 kN/sec. Pieces of 6mm plywood were placed both on top of and underneath the specimens, in order to ensure a uniform application of load by the testing apparatus. The peak load values given by the failure detection mechanism of the machine were recorded. Figure 5 shows the equipment set up to crush a specimen.


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Figure 5: Configuration of the compressive strength tests.

INDIVIDUAL BLOCK TESTING

Block samples of dimensions 100mm x 100mm x 65mm were prepared. The coarse fraction was once again IBA, however in this mixture the medium and fine fractions consisted of crushed glass. The mix proportions and grading are listed in Table 2.

Table 2: Mix design of block samples. (CG – Crushed Glass.)

Block mixture	**IBA 10-5 mm**	**CG 5-2.36 mm**	**CG <2.36 mm**	**ISSA**	**WVO**
% by weight	25%	25%	35%	15%	10%

Preparation of the block specimens was performed similarly to the brick specimens. The moulds however, were of a smaller size, and the blocks were cured at 120°C rather than 160°C in the convection oven. This was to observe any possible effect of additional curing when the bricks were exposed to relatively lower temperatures in the furnace. An image of the mould and a typical block sample is shown in Figure 6.

Figure 6: 100mm mould and block.

Blocks were individually tested in an Elite Economy Chamber furnace to 100, 200, 300, 350, 400 and 450°C. They were placed in the furnace and once the desired temperature had been reached it was kept constant for an arbitrary period of 30 minutes. The mass lost during the heating was measured and the compressive strengths were obtained using the cube crusher described earlier. The results were taken in duplicate and the mean strengths reported later in this paper.

RESULTS AND DISCUSSION

Several visual observations were made during the testing of the wall. The wall retained self-supporting throughout, and smoke issue was observed through the mortar joints on Side A at the 10 minute mark [8]. This is not unusual. The temperature monitoring of the unexposed face of the wall is shown in Figure 7.

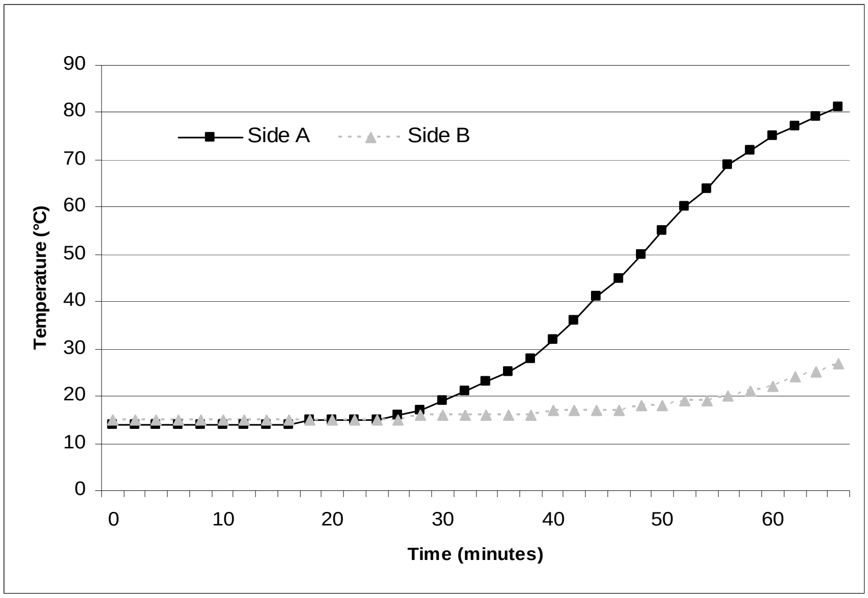

Figure 7: Mean temperatures from five thermocouples distributed on both Side A and B of the unexposed face of the wall construction.

The temperature of Side A did not show a significant increase until around 26 minutes into the test. After this point, it steadily increased until the termination time of 66 minutes. The temperature at termination was 81°C. As expected, the plasterboard protection on Side B of the wall delayed the heat transfer. Some cracking of the plasterboard was observed at 30 minutes and this disruption was probably responsible for the slight temperature rise observed from that point onwards. The plasterboard protection was not noted as having completely detached until 55 minutes.

It is reasonable to assume that after this point the temperature on Side B's unexposed face would rise in a similar fashion to that of Side A, which would allow any protected brickwork an additional 50-60 minutes to reach the peak temperature noted on the unprotected side. This is substantiated by the sharper rise in temperature observed on Side B in the 10 minute period after the removal of the protective layer.

The results obtained from the internal gradient thermocouples were as expected. Those placed deeper into the specimens recorded higher temperatures, and the temperatures obtained from Side B of the wall were lower on average. The plots are shown in Figures 8 and 9.

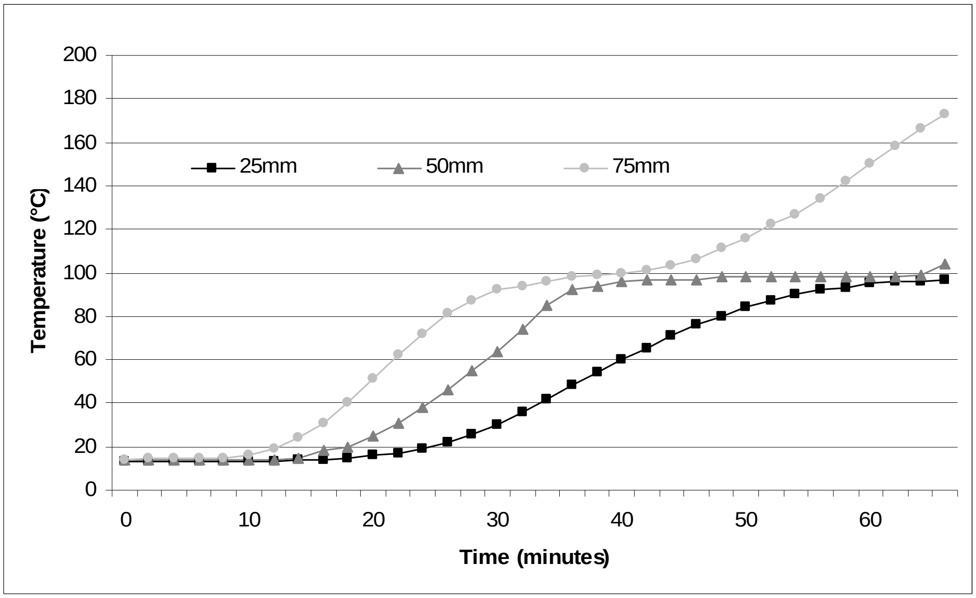

Figure 8: Temperatures monitored by internal thermocouples inserted at varying depths into Side A of the wall.

Within the first 20 minutes of the test, the furnace temperature reached approximately 800°C. The 75mm probe at Side A of the wall (Figure 8) exhibits the sharpest increase in temperature as expected; however the peak temperature reached was far lower than the furnace temperature despite being only 27mm from the surface. However, it is possible that if the test had been prolonged this thermocouple would eventually have been exposed fully to the furnace heat as the surface was damaged. The trend of the readings in the last 20 minutes or so of the test suggest this.

The 50mm and 25mm thermocouple readings in Side A are lower as is to be expected, and looking at the plots indicates a ‘staggering’ of the heat transfer. A stable phase of slow increase in temperature was recorded by the 50mm probe from 36 minutes and by the 25mm probe from 54 minutes; this may be due to the air in the voids acting as a heat sink and slowing the progress of the transfer. These periods are probably beneficial to the areas of the brick not directly affected by the furnace heat since they would provide additional curing to the waste vegetable oil binder.

The three probes on Side B all recorded a very similar pattern to that of the external thermocouples (see Figure 9), albeit with a larger temperature increase in line with depth. The temperature monitoring shows that the wall remains a reasonable barrier to heat throughout simulated fire conditions. This is supported by the deepest internal thermocouple recording an increase of temperature under the maximum rise of 140°C above ambient, even when unprotected by plasterboard.

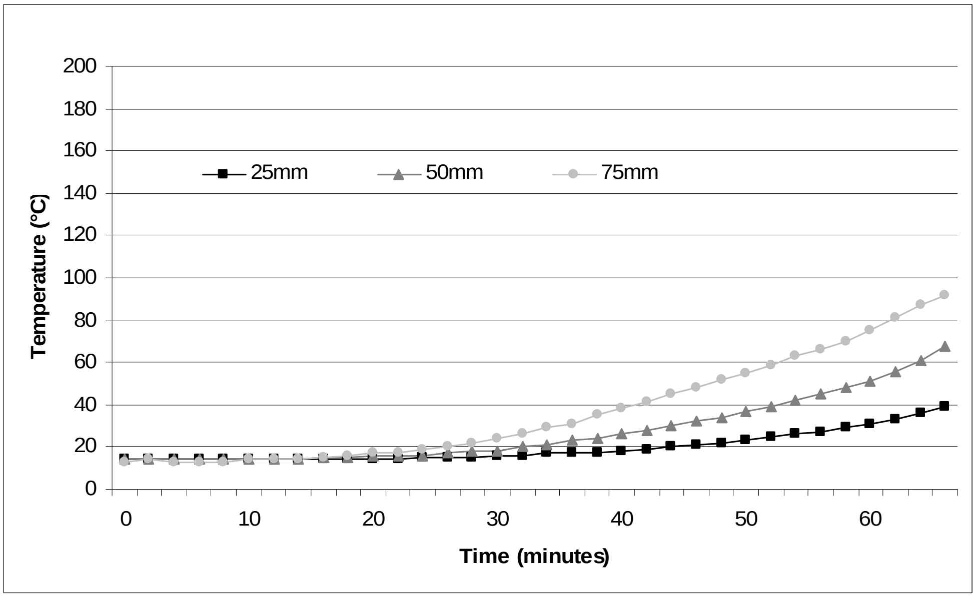

Figure 9: Temperatures monitored by internal thermocouples inserted at varying depths into the wall on Side B.

The strength values of several bricks that were recovered from the construction are reported in Table 3. It is important to note that the staff at the testing facility removed the bricks without labelling their original situation in the construction. This makes attributing strength properties based upon the extent of the fire damage extremely difficult. Some inference with regards to the relationship between the extent of damage and the residual strength can however be made from the reduction in surface area, which is displayed as a percentage alongside the strength values in Table 3.

Table 3: Percentage reduction of cross-sectional area and compressive strengths of 9 bricks recovered from the test wall.

Sample number	Reduction in cross-sectional area (%)	Compressive strength (MPa)
1	13.47	11.33
2	17.07	4.64
3	27.21	9.58
4	15.40	10.05
5	16.43	7.06
6	20.59	7.86
7	30.09	4.91
8	20.85	8.98
9	15.67	10.47

Typically, the compressive strengths of intact brick samples of the same mixture averages 10.3 MPa with a standard deviation of 0.38. The range of specimens obtained here exhibited a significant deviation in strengths. The bulk of the specimens (1,4,6-9) follow a pattern whereby the reduction in area is inversely proportional to the strength. If the extent of fire damage and the according reduction in area is large enough to reach the voids in the bricks then the strength will be somewhat compromised, particularly in the damaged half. If the test had been performed upon bricks lacking perforations, it is expected that the deviation in strength values would be far less significant. Another factor to consider is the additional curing which the heat from the fire test provides. Samples with low-medium heat penetration may have actually gained a small amount of strength analogous to extra curing time.

Specific samples such as 5 require closer examination. Despite the reduction in area being relatively low for this sample, the strength was also quite low. This can be attributed to extensive damage on the top left hand side which would compromise the void area, despite the measurements being high elsewhere on the sample. Additionally, there may have been some damage to certain bricks during their retrieval and removal of the remaining mortar.

Considering the block samples, the typical compressive strength of these before fire testing was determined to be 5.5 MPa. Ordinary block samples cured at 160°C and prepared from a similar mix to the brick samples exhibit higher strengths than this [2]. The strengths of the samples after the various treatments in the furnace are shown in Table 4. The sample retrieved after heating at 200°C actually showed a decrease in compressive strength. This is considered an anomaly due to variation in the quality of the block. The 300°C sample increased in strength quite significantly. This is attributed to both additional curing and the stiffening of the sample edges as it started to char. Some mass loss also occurred; this is likely due to the evolution of volatile species from the oil.

Table 4: Data obtained from individual, fully exposed samples heated in a furnace.

Furnace Temperature (°C)	Mass lost (%)	Compressive strength (MPa)
100	0.09	5.50
200	0.09	4.60
300	1.18	8.90
350	2.06	8.35
400	8.95	1.18
450	9.23	1.10

At 350°C a decrease in strength is noted, alongside an increase in mass loss. Given the typical flash point of vegetable oils and inspection of the sample it is suggested that the mass loss and decrease in strength are both due at least in part to combustion of the binder. Both the sample heated to 400 and 450°C exhibited a significant drop in strength and increase in mass lost. These temperatures cause major removal of the binder element from the blocks and leave them as dry samples with minimal remaining strength.

CONCLUSIONS

- The results presented in this paper provide promising preliminary, indicative data regarding the performance of vegeblock under simulated fire testing conditions.
- The wall acted suitably as a barrier to heat transfer in that the rise in temperature recorded at any of the data loggers was less than 140°C above ambient.
- The bricks retrieved from the wall had promising residual strengths despite being fire damaged, albeit with a larger than desirable variation between samples.
- The removal of the binder upon heating is clearly a concern, particularly in fully exposed block samples that were heated individually in a small furnace.

ACKNOWLEDGEMENTS

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