IMPROVING THE FLOOD RESILIENCE OF BUILDINGS THROUGH IMPROVED MATERIALS, METHODS AND DETAILS

WORK PACKAGE 5 – LABORATORY TESTS

WP5C FINAL REPORT

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REPORT WP5C LABORATORY TESTS INTERIM REPORT

Report No.: WP5C

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1.INTRODUCTION

1.1 Background

This project, which investigates improvements into methods of mitigating the effects of flooding upon buildings, is divided into a number of Work Packages, as listed below:

- WP1 Establish steering group and project start up
- WP2 Review existing information and experience
- WP3 Consider health and safety implications
- WP4 Define draft procedure
- WP5 Conduct laboratory testing
- WP6 Collation and analysis of post-flood observational data
- WP7 Revise draft procedure
- WP8 Produce regulatory impact assessment
- WP9 Produce guidance document
- WP10 Publish guidance

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This report describes the experimental work carried out for WP5.

1.2 Purpose

The purpose of this work package (WP5) is to provide baseline experimental information on the performance of common building materials and construction elements (walls and floors) under simulated flood conditions. The scope of the work package and methodology were described in general terms in WP5a Method Statement, dated June 2005 and further developed in WP5b Interim Report, dated November 2005. It was noted then that changes to the initial testing methodology might be needed as a more in-depth appreciation of the testing requirements was gained during the detailed design of the test rig(s). This in fact proved true, and significant improvements were made to the proposed test rigs and instrumentation, as described in the present report.

1.3 <u>Scope</u>

The scope of Work Package 5 consisted of laboratory testing (informed by the recommendations of WP2) and involved the following stages, which were defined in the original proposal (dated November 2004) and confirmed at the Steering Group meeting (PSG 2) held on 20 June 2005:

- Stage 1 Common building materials
- Stage 2 Composite building construction (walls)
- Stage 3 Common floor types/coverings and details
- Stage 4 Identification of water resistant materials, methods and techniques.

One of the main requirements of the laboratory testing is to apply a consistent methodology for each stage of the test programme, in order to provide a comparable set of baseline parameters, which describe both the common construction elements and their constituent materials. Such a set of consistent data has not previously been available in existing sources.

1.4 Scope of report

This report covers the testing methodology, test rigs, testing and results as outlined in the project Specification (Report WP5a) and later further refined through discussions within the project team and consultations with the Project Steering Group members. The report includes discussion of the results and conclusions to be later incorporated in the Guidance Document (WP9).

2.SELECTION OF TEST MATERIALS/ARRANGEMENTS

2.1 Building materials

Stage 1 of the study was concerned with the investigation of the behaviour of common building materials under flood conditions. A list of proposed materials for testing was developed based on consultation at a CIRIA consultation Workshop on 20 May 2005 and further team discussions, and included bricks, blocks, stone, timber, mortar and plaster board. This list was further refined through a literature review and during the sourcing of materials, where it became apparent that certain types were not in common use while others not specified were. An agreement was reached to test the following types, which were typical for domestic constructions and widely available:

Bricks

- Class A Engineering bricks
- Class B Engineering bricks
- Facing brick type 1 Sand facing brick
- Facing brick type 2 Wire cut facing brick
- Hand-made facing brick brand name: Michelmersh Red Hampshire

Blocks

- 3.5N Fenlite
- 7.0N Concrete
- Autoclave Aerated Concrete, commonly known as Aircrete (brand: Durox)

Timber board

- SH Standard OSB2, 11mm thick
- SH BBA approved OSB3, 18mm thick

Ordinary gypsum plaster board, 9.5mm thick

Mortars

- Below DPC, 1:3 cement:sand ratio
- Above DPC, 1:6 cement:sand ratio

It should be noted that Engineering Class bricks are also used as Damp Proof Course (DPC) bricks. The testing of reconstituted stone was considered, but this material appears to be unusual and not representative of normal construction practices. Although brand names are given in the above list for completeness of information, in the remainder of this report the use of brand names was avoided wherever possible.

The materials were purchased from local building products suppliers. At least six units of each type of brick and four of each type of block were purchased to allow for repeat tests/damage. Their average characteristics are presented in Table 2.1:

		Nominal	size	Nominal weight			
Type of Material	Length	Height	Thickness	(dry)	Observations/description		
material	(m)	(m)	(m)	(kg)			
Bricks	1	1					
Engineering Class A	0.215	0.065	0.100	3.08			
Engineering Class B	0.215	0.065	0.100	3.29	Also used as DP2 (damp proof course bricks)		
Pressed Facing: sand- textured	0.215	0.065	<mark>0.100</mark>	2.08	Frogged		
Pressed	<mark>0.215</mark>	0.065	0.100	2.03	Fletton Rustic (London)		
Facing: spike- textured					Frogged		
Hand-made Facing	0.215	0.065	0.100	1.96	Michelmersh Red Multi Hampshire Stock		
					Frogged		
Blocks*		<u>I</u>	<u>I</u>	I			
3.5N (low density)	0.440	0.215	0.100	14.34	ARC block Fenlite L/W Aggregate Solid		
7.0N (high density)	0.440	0.215	0.100	18.65	Dense Concrete Solid		
Aircrete	0.620	0.215	0.100	8.32	DUROX Supabloc		
Timber board	1	1	I	I	1		
SH Standard OSB2, 11mm thick	2.440	1.220	0.011	0.110**	The board was cut into 216mm by 65mm rectangular specimens for testing		
SH BBA Approved OSB3, 18mm	2.440	1.220	0.018	0.184**	The board was cut into 216mm by 65mm rectangular		

 Table 2.1
 List of materials tested – general characteristics

thick			specimens for testing

* The blocks were cut into specimens of 210mm by 65mm by 100mm for testing

** Average weight of two rectangular testing specimens with dimensions 216mm by 65mm by 11mm (or 18mm)

*** Sand had been kept outdoors and was damp.

2.2 Wall arrangements

The wall arrangements to be tested were discussed and general types were agreed at the Steering Group meeting that took place on 20 June 2005. The proposed arrangements presented at this meeting were based on Robust Details (website <u>www.Robustdetails.com</u>) which are construction solutions complying with Approved Document E (sound insulation) of the Building Regulations (there are obviously no similar details for flood-related issues so the Robust details were considered to be the best basis for the testing programme). Further suggestions were presented at the Steering Group meeting that was held on 20 October 2005. The results of these discussions were presented in Interim Report WP5b. The detailed specification of the walls tested, see Table 2.2, evolved as the study progressed, reflecting the performance of individual materials and their performance once combined in composite constructions. These building elements were chosen on two counts: to allow investigation of the influence of the extremes in material properties such as permeability/sorptivity of the wall construction and at the same time to provide information on the performance of walls that could be considered for recommendation in flood-prone areas.

Wall Type	Cavity	Insulation	ion External face Internal face Ext		External facing material	Internal facing material	Test Wall
							no.
			Engineering brick Class A	Concrete block 3.5N	None	Plaster board (removed during drying phase)	Wall ME1
				Aircrete	None	Plaster board (removed during drying phase)	Wall ME2
Masonry	Empty	No insulation	Wire cut facing brick	Concrete block 3.5N	None	Plaster board (removed during drying phase)	Wall ME3
				Aircrete	None	Plaster board (removed during drying phase)	Wall ME4
			Wire cut facing brick	Concrete blocks 3.5N	Cement render	Plaster board (removed during drying phase)	Wall ME5

Table 2.2 General characteristics of walls tested

Wall Type	Cavity	Insulation	External face	Internal face	External facing material	Internal facing material	Test Wall
							no.
	Part fill	Rigid PU foam	Wire cut facing brick	Aircrete	None	Plaster board (removed during drying phase)	Wall MPF1
Masonry		Mineral fibre		Aircrete	None	Plaster board (removed during drying phase)	Wall MFF1
	Full fill	Blown-in insulation Wire cut facing brick		Concrete block 3.5N	None	Plaster board (removed during drying phase)	Wall MFF2
		Mineral fibre	ineral fibre		None	Internal lime plaster	Wall MFF3

Table 2.2 (cont.) General characteristics of walls tested

Wall Type	Cavity	Insulation	External face	Internal face	External facing material	Internal facing material	Test Wall
							no.
			Wire cut facing brick	1 course of Concrete 3.5N clocks, vapour control membrane, OSB18mm, polyethylene membrane	None	Plaster board (removed during drying phase)	Wall TF1
Timber frame	Empty	Mineral fibre insulation on the internal face	Wire cut facing brick	1 course of Concrete 3.5N clocks, vapour control membrane, OSB18mm, polyethylene membrane	Cement render	Plaster board (removed during drying phase)	Wall TF2
			Wire cut facing brick	1 course of Concrete 3.5N clocks, vapour control membrane, OSB18mm, polyethylene membrane	Cement/lime render	Plaster board (removed during drying phase)	Wall TF3

Table 2.2 (cont.) General characteristics of walls tested

3.TESTING METHODOLOGY

3.1<u>Aims</u>

The aim of the tests was to provide baseline information on the behaviour of materials and composite constructions during floods. This implies the need to collect information on seepage, water absorption, material integrity (structural), drying times and cleanability. Some of these parameters, such as seepage and water absorption, define the material's ability to resist water penetration and therefore are indicators of its ability (or lack) of being affected by flood water. On the other hand, the drying response and cleanability, together with other aspects such as conditions for mould growth, are parameters associated with the material's ability to "recover" from a flood. The testing programme covered the characteristics of materials and constructions which may contribute to flood resistance and resilience. However, it was agreed that investigation of cleanability, mould growth and other health-related aspects were outside the scope of this testing programme.

It was agreed to simulate realistic conditions relating to typical flood situations in UK; this essentially means that building materials and composites should be subjected to a 1m depth of water. It should be pointed out that the literature review carried out earlier during this project (WP2) indicated that structural failure can occur below this limit, depending on a number of factors. The 1m head of water limit should therefore be considered with caution as it may have structural implications.

In order to define the characteristics of building materials and composites both in terms of their exposure to flood water and during the drying phase, it is important to establish time-dependent relationships for the various parameters under study. Therefore the test programme needed to incorporate methods that allowed continuous monitoring.

The ultimate aim of the study was to obtain a better understanding of how buildings behave when subjected to flood water in order to develop guidance for the construction of buildings in flood prone areas. In order to achieve this it is necessary to first understand the relevant properties of the building constituents, i.e. building materials such as bricks, blocks, timber. This will help interpret the results from composite constructions (walls and floors). A literature search indicated that there is a significant amount of standard data on material properties such as water absorption (and to a lesser extent permeability) but information on drying characteristics and how the materials interact in composite construction is very sparse.

3.2 Preliminary assessments

Given the wide range of building materials available in the market, it was apparent that the properties of the testing materials would also vary significantly. The behaviour of the various materials in relation to water penetration, i.e. the rate at which they allow water through, was an important factor in the design of the testing methodology, the test rig and the instrumentation used for the monitoring. However, due to the lack of published data, it was not easy to quantify the range of permeabilities the test rig would have to cater for. Simple tests were therefore devised to help establish the range of permeabilities for the following materials prior to the actual resistance and resilience tests:

- Engineering brick Class B
- Hand-made facing brick
- Concrete block.

These preliminary tests were conducted in the following way, which was a simplified form of a permeability test. Each material was subjected to a column of water of approximately 1m height contained in a 50mm diameter vertical tube. This tube was sealed to the face of the brick/block using a proprietary flood sealant product that had been used successfully in previous testing by HR Wallingford. The water column level was monitored regularly and topped up to retain the required level. Time and volumes required to keep the level constant were recorded and a permeability coefficient was determined based on Darcy's law. The procedure was approximate as it assumed that the brick/blocks were fully saturated but provided a good insight into the extremely varying characteristics of the three materials tested. The permeabilities of these materials were found to be very different indeed, as can be seen from the descriptions below.

Engineering brick Class B

This brick was a typical Engineering brick Class B measuring 0.215m (length) by 0.065m (height) by 0.100m (thickness). It was subjected to a column of water of approximately 1m height for three days. During this period the ambient air temperature recorded varied between 14°C and 20°C and the water temperature between 14°C and 18°C. At the end of this period the brick was dry to the touch and no seepage was observed through the brick. The average permeability coefficient K (assuming the brick was fully saturated) was found to be 3.5×10^{-8} m/s. A lower permeability would be expected if the brick was not fully saturated. This agrees very well with published data for ceramic clay bricks (see University of Edinburgh notes), which gives K between 3.2 and 3.8×10^{-8} m/s.

Facing brick

This brick was referenced as Michelmersh 65mm Red Multi Hampshire and had the following dimensions: 0.212m (length) by 0.063m (height) by 0.103m (thickness). It was subjected to a column of water of approximately 1m height and the test lasted only 7 minutes because a constant seepage rate was reached very quickly. The ambient air temperature recorded was 15° C and the water temperature was 14° C. The seeped water was collected in a graduated beaker and the volume was measured during a fixed period of time. The permeability coefficient K (assuming the brick was fully saturated) was found to be 2.9×10^{-5} m/s, corresponding to a seepage rate of 1.92 litres/hr.

Concrete block

This block measured 0.440m (length) by 0.210m (height) by 0.100m (thickness). It was found that this material was so permeable that it was not possible to achieve a constant water level inside the tube as the rate of seepage was higher than the manual filling rate.

The three preliminary tests showed a range of permeabilities of at least 10³ and confirmed expectations that the test facility would need to be flexible to accommodate very different material performances. These tests also confirmed that a single method of collection and measurement of seeped water would not be appropriate due to the variation in the amounts of water to measure. It became apparent that for materials such as Engineering bricks, if any water seeped through, this would be in such small amounts that the only accurate method to use would be the weighing method, whereas for materials such as concrete blocks the test rig would need to be designed to allow for pumping large volumes of water to retain the required flood water levels. Also the test rig would need to be able to retain large amounts of seeped water behind the material/wall and therefore an arrangement which is open on one side (as suggested in the Method Statement in WP5A) would not be appropriate.

3.3 Test duration and general procedure

In order to expose the various test materials/composites to a simulation of flood conditions that could be practically reproduced within the time and budget constraints, it was agreed that the tests would comprise of:

- Wetting phase: a maximum of 3 days (72 hours) during which the testing units are exposed to still flood water providing 1m head of water; in the case of the testing of building materials and walls, this head of water was maintained on the external face whereas for the testing of floors this was provided as an uplift force exerting on the underside of the floor
- Internal wetting phase (only for walls): the testing of walls also involved wetting on the internal face of the wall for 1 day at a depth of 1m
- Drying phase: A maximum of 7 days (168 hours) during which the test units are allowed to dry naturally under laboratory ambient conditions. Walls were allowed to dry for a minimum of 6 days.

Although the various materials/arrangements required variations in the test procedure, the general procedure adopted can be summarised as follows.

Determination of base conditions:

For materials testing, the geometric dimensions were measured, the materials were weighed and their moisture reading was recorded to provide the "before the flood" conditions; no artificial drying of the materials was undertaken. In the case of walls and floors moisture readings were taken at various, pre-defined points on the surface.

Air temperature and relative humidity were recorded at the start of the test and photographs were taken to record the appearance of the material/composites.

Wetting phase:

The materials were exposed to 1m water depth as described above. The testing was carried out using the normal water supply to the models in the HR Wallingford laboratory which is obtained from boreholes. It was agreed by the PSG that reproduction of heavily silted water

was outside the scope of the tests as they were intended to represent river flooding rather than sewer flooding. The level of silt in UK flooded rivers is relatively low at about 100ppm (average typical value) and this does not vary greatly from the natural concentration of silt in the laboratory water. The additional internal wetting of the walls was intended to simulate conditions during a flood where water cannot escape and is retained inside the building.

Water that seeped through the material/arrangement was collected and the rate of seepage was measured using a method that depended on the permeability of the material/composite being tested. For small seepage rates (such as those of Engineering or Wire Cut bricks) the seeped water was collected in a container, the volume accurately weighed and the time recorded); for large seepage rates (such as those associated with some concrete blocks) the seeped water was allowed to collect in the test tank and the rate of increase in level was measured volumetrically with a scale positioned on one of the side walls of the tank and a stopwatch. For intermediate seepage rates a raingauge was used to collect the water and the data was sent to a datalogger. During the wet phase of testing, the water that leaked through the walls was not allowed to build up significantly on the internal face. The reasons for this were twofold: to obtain comparable results with those from materials testing and to allow measurement of equilibrium seepage rates (which would otherwise be affected by the slowing down caused by reducing differential pressures between the external and internal faces of the wall).

Observations of the internal face of the material/arrangement were continually made through the use of webcams. These took snap shots every 15 minutes throughout the day and the night periods.

Floor arrangements were subjected to an uplift pressure of 1m and water that would eventually seep through could be measured using point gauges.

Air temperature and relative humidity were recorded at regular intervals for all the materials/walls/floors tested.

Drying phase:

With regard to material testing, the materials were removed from the test rig at the end of the wetting phase, the sealant and cling film were removed and the materials were allowed to dry on a rack under laboratory ambient conditions. The materials' weight was monitored during the drying phase. During this phase the materials were allowed to dry through their six faces, as opposed to two faces, when the materials are part of a composite construction, which gives a maximum drying rate. The reasons for this procedure were linked with the need to weigh the materials before and after the wet test and also the mounting of the materials on the test rig to withstand the pressure of 1m head of water: this required careful sealing before and after installation onto the bulkhead, which then needed to be removed for the weighing during the drying phase.

With regard to walls, the water accumulated behind the wall or floor was drained and the composites were allowed to dry naturally inside the test tank under laboratory ambient conditions.

With regard to floor arrangements, the water accumulated above the floor was drained. The floors were then removed from the test rig to allow testing of other units and placed on a bed of damp sand to dry naturally thus simulating real building conditions.

Measurements were taken of the moisture in the materials/walls/floors at regular intervals during the 7 day drying phase (for the materials) or 6 days (for the walls).

Air temperature and relative humidity were recorded at regular intervals. Observations were made of the materials/arrangements appearance during this phase and this was recorded photographically.

It was agreed at the start of the test programme that tests should be carried out only once unless suspicious results were obtained, in which case a repeat test would be undertaken. No repeat tests were necessary, although several tests were required until the test set-up was considered satisfactory.

4.TEST RIGS

Upon consideration of the aims of the project, it was decided that at least two types of test rig were required for the laboratory testing: Test Rig type A for testing of materials and possibly composites (i.e. walls) and Test Rig type B for testing of floors and joints.

The design of Test Rig A was carried out so that it could accommodate both the testing of materials and walls; these had similar but more stringent requirements than the materials testing because it involved flooding not only on the external face but also on the inside face of the walls.

The design of Test Rig B required simulating an uplift force on concrete floors subjected to 1m water depth.

4.1 Test Rig A - Testing of Common Building Materials and Walls

In order to be able to carry out the testing within the allocated timetable, it was decided to construct two separate but identical test rigs to allow simultaneous testing of two different materials/walls. The design of these test rigs had to make allowance for the following aspects:

- Access for a builder for construction of walls
- Observation of the flow seeping through the materials/walls
- Water-tightness of the overall test rig as well as the method of fixing the materials/walls
- Retention of 1m depth of water at the front and back of the testing unit.

Figure 4.1 is a schematic of Test Rig A (plan and side elevation). The main features of this test facility are:

- Removable front wall to allow access for in-situ construction of walls
- Transparent back wall to allow observation of seeped flow and any changes to the appearance of the materials
- Removable bulkhead with openings for simultaneous testing of two specimens of building materials
- Removable stiffening T- elements to allow construction of walls against a fixed surface and to prevent any deformation of the walls and floor of the test rigs from exceeding 1mm deflection
- Drains that could be closed to retain water in the tank on the inside face of the building materials and thereby allow measurement of large amounts of seepage by volumetric means.



Figure 4.1 Schematic diagram of Test Rig A – Plan and Side elevation

Figure 4.2 shows a schematic side view of Test Rig A with a sample of building material being tested.



Figure 4.2 Typical arrangement for testing of building materials in Test Rig A

4.2 Test Rig B - Testing of floors

Figure 4.3 is a schematic of Test Rig B (plan and side elevation). It shows the general layout used for testing of single slabs. The main features of this test facility were:

- Supply tank made of steel, connected to test tank by flexible hose
- Test tank made of steel, 0.52m by 0.52m (base) and 0.60m (wall height) with weir to allow overflow. A metal angle was placed around the internal perimeter of the tank to allow sitting of the pre-cast slabs. At the base of the tank a grid and geotextile were introduced to prevent sand loss through the supply pipe
- Air vent pipe connected to the test tank to allow escape of air from the sand base
- Fixing metal frame to counterbalance uplift forces caused by 1m head of water (not shown in Figure 4.3).

Alterations to the inside of the test tank were undertaken for the testing of floor/wall junctions to permit the construction of foundation walls.



Figure 4.3 Schematic layout of Test Rig B showing set-up for floor slab testing

4.3 Types of measurement and instrumentation

During the testing programme the following types of measurement/observations were taken:

• General ambient conditions

Temperature and relative humidity at regular intervals both during the wetting and drying phases of the tests.

Observations

Photographs of the tested materials before and after testing to illustrate changes in appearance/structural integrity and use of web cams to record changes in appearance during night test periods.

Water absorption

Weighing of individual materials at the start and end of the wet testing phase to determine the water absorption ratio.

· Seepage volume and rate - evolution with time

Measurement of volumes of seepage/leakage through the materials/walls/floors during the wetting phase using a variety of measuring techniques (volumetric and weighing methods and use of raingauge/datalogger). These depended on the rates of seepage, which were extremely variable.

Drying – evolution with time

Weighing with high accuracy scale (materials only) and use of a multi-purpose moisture meter to detect changes in moisture on the materials surface, walls and floors at regular intervals during the drying period

Leaching

From timber materials only - chemical analysis of seepage water to detect chemicals.

The measuring equipment and collecting devices were checked and connected, and software was written/installed to allow collection of data from the web cams, the raingauge, the weighing scales and the hygrometer.

A range of measuring equipment was selected and purchased for this study or sourced within HR Wallingford. A list is presented below:

- Two network web cams (Axis 205)
- Two high-accuracy weighing scales (6kg and 30kg) NTEP Approved Ohaus Trooper Industrial bench scales
- Thermohygrometer Lufft
- Pinless Moisture Meter and calibration plate Electrophysics CT100
- Three raingauges Casella 0.2mm
- PC for physical modelling, containing card for data collection
- Datalogger for use with the raingauges
- Photographic digital camera Olympus C-700, also used to produce video clips.

As described later in Section 9, the testing of floors and floor/wall junctions required specific sets of measurements/observations.

4.4 Measurement of moisture

The accurate measurement of moisture in building materials is a complex subject which is the subject of ongoing research. Achieving accurate measurements on composites, such as walls, is further compounded by the presence of different materials and their varying behaviours in relation to the presence of moisture.

When the specification for the instrumentation to be used under the present project was defined, it was decided to take a pragmatic approach and specify a general-purpose moisture meter that could be easily used to measure surface moisture in a "before-and-after" type comparison study. Values would be recorded at the start of the test prior to beginning of the wet phase to give the baseline conditions, then at the end of the wet phase and during the drying phase. Absolute values of moisture were not required and therefore more sophisticated methods were considered not necessary.

Generally, three types of moisture meter are employed by surveyors and the flood repair industry:

 A surface resistance moisture measuring device ("Protimeter" or similar) that measures %WME (wood moisture equivalent) of surface materials, using either two short probes or a sensor plate on the back – a pinless moisture meter of this type with a sensor plate was used in the present laboratory tests

- Long relative humidity probes (such as manufactured by Vasala) for use in cavities
- A Calcium Carbide device ("speedy moisture meter") which measures the amount of gas given off by a weighed sample (normally concrete or brick) in proportion to the amount of moisture present.

In the past, GE Industries, who produce the Protimeter, used to provide generic tables relating WME to actual moisture values. However, because the information was being misused, the normal practice within the flood repair industry now is to only quote %WME. A value of 16% WME is generally accepted as separating dry materials from those that are at risk, since it has been found that biological attack, such as dry rot, starts to take place above this threshold. Using wood moisture equivalent values means that if a set of wall elements was found to have the same % WME of, say 20%, the wood would be at 20%EMC (equilibrium moisture content), plaster at 1-3%EMC, bricks at 2-5%EMC, and cement mortar at 5-7%EMC.

As mentioned above, and for reasons related to the use non-invasive methods, the measurements of moisture undertaken in the present laboratory work are given in terms of WME and refer to surface moisture. As such, they can give some approximate indication of the status of dryness of a wall but cannot provide quantitative information on the drying status of the interior, particularly for walls formed by different materials. It should be noted also that the presence of salts in building materials, e.g. bricks, can also mask the readings of surface moisture that are based on WME.

Given the above drawbacks, it was decided to investigate whether there exist any alternative methods that would provide more reliable data. However, information gathered during the study showed that several promising methods are currently in a research and development phase. These were deemed unsuitable for the present study as they could not be easily used in the test rig and would also not guarantee the level of confidence/accuracy that they in theory should provide once all the research and development work is finished. Information gathered from several sources on these new methods and other existing techniques is summarised below:

Thermal probe - research at University College London:

The system being developed at UCL is a thermal probe which appears at this stage to require calibration for every material; the status of the development work is not sufficiently advanced to allow meaningful results if the probe were to be used in the current project.

TDR based probe - research at Glasgow Caledonian University:

The system being developed at Glasgow Caledonian University is based on time-domain reflectometry (TDR), using a radio signal and a computer to detect and collect data on moisture. The probe being developed is an improvement on a German probe, with 100mm long prongs which need to be inserted into the wall/floor through two parallel 2mm diameter holes. The research work is looking at reducing the length of the prongs from 100mm to 50mm (but some loss of accuracy is expected, which will need to be evaluated); there are also concerns about the feasibility of drilling the parallel holes on site, particularly in concrete which can have very hard aggregate. The probe provides an average moisture value through the 100mm length of the prongs and readings can be affected by the presence of metallic or magnetic elements in the materials. Due to its complexity, this system is not expected to be used by the average surveyor but by specialist ones only. Trials are planned on some Historic Scotland sites in 2007. The system is quite sophisticated and, as it was still in a development stage, the advice received was that it was inappropriate for use in the Resilience project.

Timber dowel technique:

Experience of using the "timber dowel technique" has shown that this technique tends to absorb more water than the surrounding brick/block and that there is also a hysteresis effect, which can induce misguided conclusions. The lag time with dowels depends on the relative characteristics of the dowel and substrate. So, for example with sandstone, a lag of about 3 days was noted whereas with a particular clay brick the lag was estimated to be several weeks. Also, if dowels get very wet they can swell with the result that in the short term they become difficult to extract, and in the long term will decay. The technique is not very reliable and can only provide a trend in terms of whether a wall/floor is drying or getting wetter but not useful absolute values. The advice given by researchers in this applied area was that it would not be useful for the Resilience project.

Core drilling:

The use of core drilling to obtain samples from the whole wall thickness was considered as a possible way to complement the information provided by surface moisture readings. The samples would need to be removed intact in order to give a qualitative idea of their internal moisture level. The collection of core samples in concrete materials such as those used in rendered, hard brickwork and blockwork walls requires the use of diamond head core drills which normally use water as a cooling system. Since the cooling water affects the moisture content of the core sample the information provided by this technique would be misleading. Drilling without cooling water could be attempted but the heat generated would also impact on the moisture of the core samples. This confirms the information obtained through Glasgow Caledonian University that collecting data on internal moisture currently is difficult, ultimately unreliable and is still in research stage.

5. TESTING OF BUILDING MATERIALS

5.1 Preparation of materials for testing

Two specimens of each of the building materials listed in Table 2.1 were mounted on purpose-built mounting plates and fixed to the bulkhead in the test rig (see Figure 4.1). Great care was taken to seal the mounting plates and the individual materials: silicone sealant was liberally applied around the materials and rubber strips were placed between the plates and the materials to provide a water-tight joint. As well as sealant, cellophane film was used to wrap the four faces of the materials not directly exposed to the water in order to avoid leakage through these faces. The cellophane and silicone sealant were chosen because they were found to be effective at sealing from preliminary tests and they could also be very easily peeled off at the end of the wet phase to allow accurate measurements of the weight of the materials during the drying phase. The two specimens were fixed to the mounting plates on a work bench (see Photo 5.1) and the sealant was allowed to dry before the mounting plates were fixed to the bulkhead in the test rigs (Photos 5.2 and 5.3). **NB. All photographs are presented in Annex A, which has been produced as a separate volume.**

The specimens were submitted to 1m depth of water during three days (72 hours); at the end of this period, the mounting plates with the specimens were removed from the test rig, the sealant and cellophane were pealed off and the building materials were placed on a rack to dry naturally under the laboratory ambient conditions for a period of seven days.

The openings of the mounting plates allowing exposure to water were determined by the size of the face of the bricks and were kept fixed for all the materials tested. This meant that some larger materials such as the blocks and boards needed to be cut to brick size for the tests. This was carried out with a disk cutter, which produced a clean cut. Care was taken to ensure that the face of the material normally used on the face of a wall was the one exposed to water in the test rig so that local changes to porosity caused by the cutting of the material would not adversely influence the results.

Due to their nature, the preparation of the mortar specimens and fixing arrangements differed from those used for self-standing materials. The amounts of sand and cement used were weighed, the amount of water used was measured and these quantities were recorded. The mixtures were set within metal shuttering so that the thickness of the specimens was 10mm.

5.2 Testing

The testing of building materials was carried out between August and October 2005. Once the materials were installed in the test tanks and the sealant had time to go off, water was pumped into the external compartment at a slow rate to avoid creating excessive pressure forces on the exposed faces of the materials. In most cases, seepage through the materials was only observed after the water depth had reached the required level of 1m above the exposed face of the material. However, in the case of Concrete Blocks 3.5N and 7N, seepage in large quantities started occurring as the tank was being filled, as can be seen from Photo 5.4. This behaviour was expected from the results of the preliminary tests, described in Section 3.2, which had revealed the extreme permeability of this type of material.

All materials, apart from the hand-made Michelmersh brick and the plaster board, were tested for the full duration of the wet phase. Even in cases where the seepage rate was thought to have achieved a constant value before the three day period was over, it was decided to leave the materials in place in the tank as this would produce comparable conditions in terms of the final wet weight of the specimens.

The hand-made brick developed a leak at about 30hrs after commencement of the test which is attributed to breakage of the seal. The seepage rate had, however, reached approximately constant values after 22 hours of testing and the results were considered satisfactory, so the test was not repeated.

During the wet phase of testing of the oriented strand boards (OSB), samples of seepage water were collected and sent out for analysis to assess any potential health hazards that could be associated with chemicals released by the boards. TRADA, the Timber Research and Development Association was contacted for information and revealed that OSBs as purchased from building merchants were not treated with preservatives but that glue of the type phenol formaldehyde was used in the fabrication of the boards. Samples were collected from the two test set-ups with OSB2 and OSB3 and sent to Mountainheath Services Ltd for two separate chemical analyses: for phenol and for formaldehyde. Five samples in total were analysed: one of the water used in the tests to provide base conditions (control sample), and two from each of the timber boards corresponding to the first and last days of wet testing.

The plaster board suffered collapse after 4 minutes of testing and the test was therefore terminated. During the filling up of the tank to 1m water depth in preparation for the wet phase, the two board specimens revealed no seepage and no seepage or wetting was observed during the first minute but water soon started seeping through at a high rate. After about 4 minutes of testing, one specimen was ripped through the centre and the other detached at one of the sides.

Photos of the materials tested are presented in Photos 5.5 to 5.11 (Bricks), Photos 5.12 to 5.15 (Blocks), Photos 5.16 and 5.17 (Timber board), Photo 5.18 (Plaster board) and Photos 5.19 and 5.20 (Mortars).

5.2.1 Results

The tests revealed, as expected, a wide variation in the properties measured for the various building materials. For each material, the water absorption, evolution with time of seepage rate and drying weight were determined and are presented in Table 5.1, which gives a summary of the results, and in Figures 5.1 to 5.24.

It should be noted that, for clarity of presentation, it was not possible to present the graphs using the same scale for the y-axis due to the wide variability of seepage rates (and weights). This should be borne in mind when comparing the results for the various materials.

It should also be noted that the seepage results presented for the materials are the average of the two specimens tested in each case.

		Ar	nbient condit	ions			Seepage rate			
Material	Ave Air Te	erage mp. (°C)	Ave Rel. Hun	rage nidity (%)	Average Water Temp. (°C)	Water absorption (%)				Drying
	During wet phase	During dry phase	During wet phase	During dry phase	During wet phase		Max. value (l/hr)	Time of max. value	Limit value*(l/hr)	Weight at end of dry phase/ dry weight
Bricks										
Engineering Class A	16.8	18.7	79.0	80.9	16.7	0.3	0	NA	NA	1.001
Engineering Class B	17.2	19	82.3	82.6	17.0	4	0.005	End of test – still increasing	0.005 and increasing	1.013
Sand facing	19.3	18.5	79.1	79.2	18.4	16	0.292	End of test – still increasing	0.292 and increasing	1.034
Wire cut facing	19.3	18.5	79.0	85.4	18.8	11	0.020	End of test – still increasing	0.020 and increasing	1.052
Hand-made facing	19.2	18.6	82.4	83.5	17.4	16**	22.3	Start of test	3.5	1.106
Blocks										
3.5N (low density)	18.5	17.2	84.7	84.1	17.3	9	52	After about 50 hrs	0.5	1.035
7.0N (high density)	18.8	16.8	83.9	82.3	17.3	8	606	Start of test	20	1.026

Table 5.1 Summary of test results for building materials
		T										
Aircrete	19.1	18.5	82.1	83.7	18.1	53	2.37	After 4.5hrs of testing	0.5	1.411		
Timber board												
SH Standard OSB2, 11mm thick	17.3	16.2	85.1	81.5	17.0	89	2.2	After 2hrs of testing	0.2	1.475 Increase in thickness to 13mm after wet phase		
SH BBA Approved OSB3, 18mm thick	17.3	16.2	85.1	81.5	16.9	80	4.38	After 3hrs of testing	0.2	1.474 Increase in thickness to 21mm after wet phase		
Plaster board												
Plaster board 9.5mm thick***	16.1	-	80.5	-	15.4	61	70.9	First minutes of testing	-	1.134		
Mortars												
Below DPC, 1:3 cement:sand	14.8	16.2	84.2	87.6	15.1	0.3	0.0008	After 30 hrs of testing	0.0002	1.000		
Above DPC, 1:6 cement:sand	14.8	16.2	84.2	87.6	15.1	0.3	0.0032	After 25 hrs of testing	0.0028	1.000		

* This is the value reached at the end of the wet phase

** The wet phase lasted less than 3 days due to development of leak

*** The wet phase lasted only 4 minutes due to collapse of the specimen



Figure 5.1 Engineering Brick Class A; Drying - Evolution with time

NB. No graph is provided for the seepage through Engineering Brick Class A as none was detected.





Figure 5.2 Engineering Brick Class B; Seepage - Evolution with time

Bricks - Engineering Class B Drying



Figure 5.3 Engineering Brick Class B; Drying - Evolution with time



Figure 5.4 Sand facing bricks; Seepage – Evolution with time



Bricks - Sand facing Drying phase

Figure 5.5 Sand facing bricks; Drying – Evolution with time

Bricks - Wire cut Seepage rate



Figure 5.6 Wire cut facing bricks; Seepage – Evolution with time



Wire cut Brick - Drying phase

Figure 5.7 Wire cut facing bricks; Drying – Evolution with time

Bricks - Michelmersh Seepage rate







Michelmersh facing brick - Drying

Figure 5.9 Hand-made facing bricks; Drying – Evolution with time



Figure 5.10 Concrete blocks 3.5N; Seepage – Evolution with time



Concrete Block 3.5N - Drying

Figure 5.11 Concrete blocks 3.5N; Drying – Evolution with time



Figure 5.12 Concrete blocks 7N; Seepage – Evolution with time



Concrete block 7N - Drying

Figure 5.13 Concrete blocks 7N; Drying – Evolution with time

Block - Aircrete Seepage rate





Blocks - Aircrete Drying



Figure 5.15 Aircrete block; Drying – Evolution with time

Timber board - OSB2 11mm



Figure 5.16 OSB2; Seepage – Evolution with time



Timber board OSB2 11mm - Drying

Figure 5.17 OSB2; Drying – Evolution with time



Figure 5.18 OSB3; Seepage – Evolution with time



Timber board OSB3 - Drying

Figure 5.19 OSB3; Drying – Evolution with time



Plasterboard 9mm Drying

Figure 5.20 Plaster board 9mm; Drying – Evolution with time



Figure 5.21 Mortar 1:3; Seepage – Evolution with time

Mortar 1:3 - Drying phase



Figure 5.22 Mortar 1:3; Drying – Evolution with time



Mortar 1:6 - Seepage rate



Mortar 1:6 - Drying phase



Figure 5.24 Mortar 1:6; Drying – Evolution with time

The analysis of seepage water from the tests of Oriented Strand Board is presented below in Table 5.2.

Table 5.2 Results of chemical analysis of seepage water from tests using Oriented Strand Board (OSB)

	Concentrations (µg/l)					
Sample	Phenol	Formaldehyde				
Control	<10	<50				
OSB2 11mm						
20 Sept 05	<10	<50				
22 Sept 05	<10	98				
OSB3 18mm						
20 Sept 05	<10	63				
22 Sept 05	<10	310				

Phenol concentrations were all below traceable values (values of 4mg/l are allowed in US drinking water). Formaldehyde concentrations were higher for OSB3 18mm but still below US recommended levels in drinking water (1mg/l) (Source: Fact Sheets from website www.health-report.co.uk).

6. DISCUSSION OF RESULTS OF BUILDING MATERIALS

The discussion of the laboratory results presented in the next sections concentrates on resistance to water penetration and drying ability, and will be further developed and complemented in the discussion of the wall test results.

It can be seen from Table 5.1 that, although the ambient temperature and humidity conditions were not controlled, these did not vary greatly during the testing of all the materials. Hence this provided a reasonable common ground for comparisons to be undertaken between the various materials and strengthened the confidence on the test results and by consequence on any conclusions to be drawn from them.

6.1 Resistance to water penetration

It was mentioned before that the response of the various materials to exposure to 1m depth of water was extremely variable, even within each category of materials, e.g. bricks, blocks, etc. This variability was found both in terms of seepage rates and seepage behaviour, i.e. evolution with time. Whereas some materials showed the peak seepage rate at the start of exposure to 1m depth of water (or soon after) and a decline with time (e.g. hand-made brick (Figure 5.8), concrete block 7N (Figure 5.12), timber board (Figure 5.16)), others showed a gradual increase in rate with time, extending beyond the wet test duration (e.g. sand facing brick (Figure 5.4), concrete block 3.5N (Figure 5.10)). Figures 6.1 and 6.2 show a comparison of seepage rates for the brick types tested, in natural scale and logarithmic scale respectively (due to the wide range of seepage rates, logarithmic scales are required to allow comparisons to be made). Equivalent graphs are shown in Figures 6.3 and 6.4 for the blocks tested. Figures 6.5 and 6.6 were produced for comparison of the two types of timber board and mortar tested, respectively.



Figure 6.1 Comparison of seepage rates for the bricks tested (natural scale)

Bricks - Seepage rate (logarithmic scale)







Figure 6.3 Comparison of seepage rates for the blocks tested (natural scale)



Blocks - Seepage rate (logarithmic scale)

Figure 6.4 Comparison of seepage rates for the blocks tested (logarithmic scale)



Figure 6.5 Comparison of seepage rates through the timber boards tested







From a view point of resistance to water penetration, it is clear from Figure 6.2 that Engineering bricks offer the highest level of resistance, whereas hand-made bricks can offer the least amongst all the types of brick tested. With regard to blocks, Aircrete was found to offer the highest resistance to the ingress of flood water of all the blocks tested.

Figure 6.7 shows a graph of seepage rate evolution with time for all the materials tested. In general terms, concrete blocks showed the highest seepage rates whereas mortar and engineering bricks provide the lowest water penetration. Seepage rates varied by more than a factor of 10^6 .



Materials seepage rate (logarithmic scale)

Figure 6.7 Evolution of seepage rate with time for all materials tested

6.2 Drying ability

With regard to another aspect of resilience, the drying ability, Engineering bricks also present the best properties as they absorbed little water and became closer to their dry weight at the end of the drying phase than other types of brick (see Table 5.1 and Figure 6.8).

With regard to blocks, Aircrete showed the least favourable properties in terms of ability to regain its dry weight after wet testing (see Table 5.1 and Figure 6.9). This was due to a higher absorption rate. The two types of concrete block tested had comparable behaviour, in terms of their drying characteristics.

Both timber boards tested (OSB2 and OSB3) were found to have similar characteristics in terms of dry weight recovery (see Table 5.1 and Figure 6.10) but suffered an approximate 20% expansion in thickness due to exposure to water.

The two types of mortar samples tested showed similar behaviour as can be seen from Table 5.1 and Figure 6.11, recovering their dry weight before the seven day drying period was over.



Figure 6.8 Comparison of drying times for the bricks tested



Figure 6.9 Comparison of drying times for the blocks tested

Timber board OSB - Drying



Figure 6.10 Comparison of drying times of the timber boards tested



Figure 6.11 Comparison of drying times for the mortar samples tested

7. TESTING OF WALLS

7.1 Construction of walls

The walls were tested in Test Rig A (see Figure 4.1), which was adapted from its configuration for the materials testing by introducing two T pieces which provided the required additional stiffness to minimise deflection of the tank walls. In order to allow access for construction, the front panel was removed and later put in place once all the building work was carried out.

An experienced builder (AK Builders, based in Abingdon) was contracted to build the walls and he also provided valuable practical guidance on typical construction practice relating to location of damp proof course, number and location of wall ties, etc. Further information on the specification of the walls was obtained from the NHBC Standards and Robust details. The work of the builder was overseen by a Building Inspector, Ms Joanna Percy, of South Oxfordshire District Council who was satisfied with the standard of workmanship and construction practices adopted (see Appendix A).

The walls (1.14m high by 1m width) were built inside the test tanks. In order to provide better lateral bonding, a tie-in system for extension walls (Expamet Multi-Starter) was used on both ends of the walls. Also, as another precaution against structural failure, the walls were built with a larger number of wall ties than is common in typical construction: Starfix wall ties were placed every 3 courses of brick (in height) and every 3 bricks in width. This enabled separation of the effects of structural capacity and resilience to flood water. The NHBC Standards recommends maximum wall tie spacings as follows: in general wall areas maximum horizontal spacings of 900mm and 450mm vertically. In comparison with the maximum spacings recommended, the test walls were built with 40% more ties in the horizontal direction and 2.3 times more ties in the vertical direction.

The bricks and blocks were placed in a stretcher bond joint. Where applicable, bricks were used frog up because this is generally recognised as being the best way of achieving good bond between mortar and brick.

The wall cavity width was 100mm in the case of masonry walls and 60mm in the case of timber framed walls, as per NHBC Standards recommendations. No cavity trays were installed because this feature is used to collect any wind-driven rain that penetrates through the external face of the wall and return it to the outside. For the present tests no weep holes were provided as they would allow the ingress of water into the cavity.

A damp proof course (DPC) membrane was placed above the third course of bricks and first course of blocks. Below DPC level a mortar mix of 1:3 (cement: sand) was used and above this level a mix of 1:6 was used, as per recommendations. A mortar plasticiser (Jewson, complying with BS4887) was added to the mix for workability for both the 1:3 and 1:6 mortar mixes. Plasticiser is not usually recommended for 1:3 mixes but in the present case it was considered useful by the builder to improve workability. The amounts of water used for the mortar mix and plasticiser were recorded as well as the ambient conditions during construction (see Table 7.1 – in this table the amounts of plasticiser and water are given as percentages of the weight of concrete, assuming density of 1000kg/m³). In the present case,

walls built of wire cut bricks did not include Engineering bricks below the DPC. This was intended to facilitate analysis of behaviour of different types of brick and reflects ordinary practice, although the use of Engineering bricks below DPC is also common.

In the test walls it was decided to use the same two types of mortar mix (1:3 and 1:6, respectively for below and above DPC level) for walls built with engineering bricks and with soft bricks. It is appreciated that mortar mixes should be suitable for the type of masonry involved, i.e. they should reflect the suction properties of the bricks they are joining. However, in the present case, this approach would introduce another variable in the study and therefore make any conclusions on performance of the walls more difficult to draw.

The construction of the timber framed walls involved the use of more components than the cavity masonry walls and these were:

- External face consisting of a standard masonry wall formed by bricks (or blocks) and mortar;
- 60mm wide cavity;
- Wall ties and nails for timber framed walls.
- Internal face on a base of concrete blocks 3.5N, followed by two layers of 6in by 2in timber; the internal face is a composite construction made of (moving from the cavity to the internal face): a vertical layer of breathable membrane (Kober Permo forte), timber board sheathing OSB3 18mm thick, mineral fibre insulation, a vertical layer of vapour control membrane (500 gauge polyethylene) and gypsum plaster board 9mm thick.

	Air	Ambient		r mix 1:3		Mortar mix 1:6				
Wall*	Temp.	Rel. (cement : sand)				(cement : sand)				
	(°C)	Humidity	Cement	Sand	Plasticiser	Water	Cement	Sand	Plasticiser	Water
		(%)	(kg)	(kg)	(% weight of cement)	(% weight of cement)	(kg)	(kg)	(% weight of cement)	(% weight of cement)
ME1	14.3	84.3	18.98	56.96	1.0	36	12.56	72.82	0.8	60
ME2	14.3	84.3	18.98	56.96	1.0	36	12.56	72.82	0.8	60
ME3	15.6	85.4	19.76	59.30	1.0	35	9.95	59.70	1.0	67
ME4	15.6	85.4	19.76	59.30	1.0	35	9.95	59.70	1.0	67
MFF1	9.1	75.4	15.18	45.54	0.6	48	10.01	60.06	1.0	50

 Table 7.1
 Wall construction – characteristics of the mortar used

MFF2	9.1	75.4	15.18	45.54	0.6	48	10.01	60.06	1.0	50
MPF1	10.2	80.9	21.45	64.36	0.5	41	14.44	86.63	1.4	45
TF1	10.2	80.9	21.45	64.36	0.5	41	14.44	86.63	1.4	45
TF2	8.6	83.4	21.20	63.58	0.5	43	11.6	69.60	1.7	40
TF3	8.6	83.4	21.20	63.58	0.5	43	11.6	69.60	1.7	40
ME5	7.6	76.9	15.16	45.48	0.6	41	10.56	63.38	1.9	62
MFF3	7.6	76.9	15.16	45.48	0.6	41	10.56	63.38	1.9	62

* Please refer to Table 2.2 (Section 2.2 for description of wall types)

The walls (i.e. the mortar) were left to cure for seven days, which was agreed was the maximum length of time that was practically compatible with the test programme. Information concerning masonry walls is not readily available but observation of the walls indicated that the mortar was dry in appearance before the seven day curing period was over - this suggests that the mortar was likely to have achieved sufficient strength and bonding characteristics to produce representative results. It is known that concrete reaches a strength value very close to its ultimate value at the end of 28 days but this was impossible to accommodate within the project timeframe. After four days curing, where a plaster board was specified, this was fixed to the internal face of the walls.

Some wall arrangements involved the application of external renders, the specification of which followed recommendations in the Building Regulations Approved Document C. This document suggests that for severe exposure "the exposed face of the bricks or blocks should be rendered or be given no less protection. Rendering should be in two coats with a total thickness of at least 20mm". This is confirmed in the NHBC Standards, which states that initial undercoats should not be less than 10mm and not more than 15mm thick, and finishing coats generally between 6 and 10mm. The mixes should comply with recommendations of BS5262.

Lime plaster was applied to one of the walls tested (MFF3). The use of lime in buildings is known to be a specialist field which can require a high level of skill and experience. Without attempting to cover the finer details of the lime application trade, an Internet literature search was carried out to obtain a suitable specification for internal lime plaster and practical information on application methods. In terms of specification, mixes of one part lime to three or three and a half parts sand were found to be most common. It was decided to use a one to three proportion for the present case. In order to minimise shrinkage (and consequent cracks) as the water evaporates, suggestions to use well graded sand, to thoroughly wet the wall before application and to apply thin coats (of less than 13 mm) were followed. The lime and sand were mixed with water, taking the precaution to protect the builder's face with a dust mask, resulting in a mix with the appearance and consistence of thick porridge. The first coat was applied by throwing the lime plaster from a trowel onto the well wetted wall and then roughly levelling. This coat was scratched to produce a diamond effect intended to promote

bonding with second coat. The second coat was applied 4 days later and allowed to dry for 7 days before the test started. A few small cracks were observed to form in the first coat but not in the second and the surface looked quite even and fairly smooth. The application of the lime plaster was carried out by a member of HRW's building team who, although experienced in wall rendering, had no previous familiarity with lime plastering. The result was very satisfactory nevertheless, and, after conquering his initial reluctance to use lime due to unfounded fears about its hazardousness and difficulty in application, his feedback on the experience was quite positive.

The characteristics of the external renders applied to walls TF2, TF3 and ME5 are summarised in the following Table (Table 7.2), as well as the characteristics of the internal lime plaster applied to wall MFF3:

Wall	Air	Ambient	Thickness	Cement	Sand	Lime	Water				
	Temp.	Rel.	(mm)	(kg)	(kg)	(kg)	(I)				
	(°C)	Humidity									
		(%)									
Wall TF2 – Cement render (1 cement : 6 sand)											
1 st coat	8.1	82.2	10	9.57	57.42	-	6.5				
2 nd coat	7.8	86.8	10	10.11	60.68	-	6.5				
Wall TF3 –	Wall TF3 – Lime render (1 cement : ½ lime : 4 sand)										
1 st coat	8.1	82.2	10	15.78	63.12	7.89	9.0				
2 nd coat	7.8	86.8	10	14.40	57.58	7.2	9.0				
Wall ME5 -	Wall ME5 – Cement render (1 cement : 4 sand)										
1 st coat	8.8	77.2	12	7.70	46.03	-	6.0				
2 nd coat	6.1	86.5	10	11.6	46.4	-	6.0				
Wall MFF3 – Internal lime plaster (1 lime : 3 sand)											
1 st coat	8.8	77.2	10	-	30	10	8				
2 nd coat	6.1	86.5	10	-	37.2	12.4	8.5				

Table 7.2 Characteristics of the renders tested (according to BS 5262) and lime plaster

The following photos illustrate the construction and testing of the walls:

ME1 - Photos 7.1 to 7.3

ME2 – Photos 7.1, 7.2, 7.4 and 7.5

ME3 - Photo 7.6

ME4 – Photo 7.7

MFF1 – Photo 7.8

MFF2 - Photos 7.9 and 7.10

MPF1 - Photos 7.11 and 7.12

TF1 - Photos 7.13 to 7.16

TF2 – Photo 7.17

TF3 - Photo 7.17

ME5 – Photo 7.18

MFF3 – Photo 7.19.

7.2 Results of masonry walls

The results of the wet and drying test phases are presented in Figures 7.1 to 7.31, which include graphs of leakage through each masonry wall type, the variation with time of water depth inside the wall cavity and drying of the external and internal faces of the walls. The leakage rate was determined by measuring the water that accumulated on the internal side of the tank, which represented the combined seepage through the internal and external wall units. The measurement frequency was determined during the actual test, according to the amount of water getting through the wall, since this could not be anticipated prior to the test. As mentioned in Section 3.3, the seeped water was not allowed to accumulate behind the internal face of the walls. The drying data in the various graphs are given as evolution of moisture with time in terms of % WME (wood moisture equivalent) – refer to Section 4.4.

It should be noted that, for clarity of presentation, it was not possible to present the graphs using the same scale for the y-axis due to the wide variability of seepage rates (and moisture values). This should be borne in mind when comparing the results for the various walls.

7.2.1 Walls ME1 and ME2

Walls ME1 and ME2 were empty cavity walls built with Engineering Class A bricks on the external face and Concrete blocks 3.5N (ME1) or Aircrete blocks (ME2) on the internal face.

As can be seen from Figure 7.1, wall ME1 developed a leak between 10 and 25 hours after the start of the wet test (this occurred during the night period; study of the web cam photos did not provide conclusive answers as to the start time of the leak). It was not possible to ascertain where the leak originated but it produced a marked increase in the leakage rate through the wall. It is considered that the long term (steady state) leakage rate through ME1 was achieved before this leak occurred and this value was comparable to the long term rate through ME2 (compare Figures 7.1 and 7.2). However, it has to be acknowledged that cracking or some other failure could be the long term performance of the wall subjected to flood water for several days.



Figure 7.1 Wall ME1; Leakage rate – Evolution with time



Figure 7.2 Wall ME2; Leakage rate – Evolution with time

The drying tests revealed that, as expected because they were similar, the external faces of the two walls had very comparable behaviour (see Figures 7.3 and 7.4), with an increase of 15% in moisture (WME) from their dry state. This is higher than expected, based on the bricks performance alone (which had water absorption of only 0.3% based on increased weight) and is therefore to be concluded that it must be due to the combined effect of bricks and mortar joints. However, it must be noted that different techniques have been used to determine the water absorption of materials as opposed to the walls, so the results are not entirely compatible. Also, the drying of the walls in their constructed state is necessarily different to the drying of the materials.



Figure 7.3 Wall ME1; External face – Evolution of drying with time



Figure 7.4 Wall ME2; External face – Evolution of drying with time

With regard to the internal faces (compare Figures 7.5 and 7.6), the concrete block wall (in ME1) returned to its dry state moisture value after less than 160 hours, whereas the Aircrete wall (in ME2) retained about 5% moisture.

50 1m above ground 0.5m above ground At ground level 45 1m and 0.5m above ground initial 40 moisture value Moisture (%WME) 35 30 Ground level initial moisture value 25 20 20 40 60 80 100 120 140 180 200 160 0 Time (hour)

ME1 Internal face - Drying

Figure 7.5 Wall ME1; Internal face – Evolution of drying with time



ME2 Internal face - Drying

Figure 7.6 Wall ME2; Internal face – Evolution of drying with time

Figures 7.7 and 7.8 show the increase in water depth inside the cavity wall for the two walls, respectively. The depth of water reached a constant level of about 0.120m for ME1 (after the leak developed this increased to about 0.450m) and 0.420m for ME2.



Wall ME1: Water Depth in wall cavity

Figure 7.7 Wall ME1; Depth of water in wall cavity – Evolution with time

Wall ME2: Water Depth in wall cavity



Figure 7.8 Wall ME2; Depth of water in wall cavity – Evolution with time

On this first set of walls tested, the results are consistent with the results obtained for the building materials used in their construction but it was evident from the leakage rates measured that these exceeded those determined for the building materials in isolation. This points out to the influence of joints between the bricks/blocks as preferential paths for the water.

From the above graphs it can be concluded that wall ME1 had only marginally better overall performance characteristics than wall ME2, in terms of leakage and drying rates. This seems to be linked with the presence of concrete blocks in ME1 which have a slightly better ability to dry rapidly than Aircrete. However, final conclusions will only be possible when the test results for all the walls can be assessed as a whole.

7.2.2 Walls ME3 and ME4

Walls ME3 and ME4 were empty cavity walls built with Wire cut facing bricks on the external face and Concrete blocks 3.5N (ME3) or Aircrete blocks (ME4) on the internal face.

Figures 7.9 and 7.10 show the evolution with time of the leakage rate through walls ME3 and ME4, respectively. Both walls show a similar leakage curve, with maximum values of leakage rate at the start of the test and then declining to a constant rate of about 25 l/hr. The initial leakage from Wall ME3 was larger than for wall ME4.



Figure 7.9 Wall ME3; Leakage rate – Evolution with time



Figure 7.10 Wall ME4; Leakage rate – Evolution with time
The drying tests revealed that, although the external wall face was constructed with the same materials in both walls ME3 and ME4, wall ME3 retained more moisture than ME4 during the drying phase (see Figures 7.11 and 7.12), with an increase of up to 50% in WME from its dry state (compared to about 10% for wall





ME3 External face - Drying

Figure 7.11 Wall ME3; External face – Evolution of drying with time



Figure 7.12 Wall ME4; External face – Evolution of drying with time

With regard to the internal faces (compare Figures 7.13 and 7.14), the concrete block wall (in ME3) returned to its dry state moisture value after 160 hours, whereas the Aircrete wall (in ME4) retained up to about 10% moisture. This finding is similar to the case of walls ME1 and ME2 as described in Section 7.2.1.

ME3 Internal face - Drying



Figure 7.13 Wall ME3; Internal face – evolution of drying with time





Figure 7.14 Wall ME4; Internal face - evolution of drying with time

Figures 7.15 and 7.16 show the increase in water depth inside the cavity wall for the two walls, respectively. The depth of water appeared to have reached a constant level of about 0.5m for ME3 but the level was still rising at the end of the wet phase of testing for wall ME4. Overall, the depth of water inside the cavity was substantially higher in Wall ME4. This must be due to the smaller seepage through Aircrete blocks when compared with Concrete blocks (as shown during the materials testing described in Section 5.2.1) which allows the build-up of water inside the wall cavity.



Wall ME3: Water Depth in wall cavity

Figure 7.15 Wall ME3; Depth of water in wall cavity – Evolution with time



Figure 7.16 Wall ME4; Depth of water in wall cavity – Evolution with time

7.2.3 Walls MFF1 and MFF2

Walls MFF1 and MFF2 were full fill cavity walls built with Wire cut facing bricks on the external face and Aircrete blocks on the internal face. The cavity insulation in wall MFF1 consisted of mineral fibre and of loose "blown-in" insulation in wall MFF2 (Dupre MICAFIL lightweight expanded mineral).

As can be seen in Figures 7.17 and 7.18, the leakage through these walls was very different, the leakage rate being one order of magnitude larger in wall MFF1. This finding was at first thought unexpected as the two walls were similar in all respects apart from the insulation used inside the cavity. Substantiated by observations of the condition of the insulation, it is believed however that this is due to the different water retention characteristics of the two types of fill. The blown-in fill was found to absorb water and become wet to the touch during the wet phase of the test, whereas the mineral fibre was less absorbent. By absorbing the water that leaked through the external face of the wall, the loose fill did not allow the water to build up inside the cavity and create the head necessary to produce a large seepage rate.

When comparing with ME4 (see Figure 7.10), which is similar in construction to MFF1 and MFF2 but had an empty cavity, it is apparent that the evolution of seepage with time observed for MFF1 is similar to that of ME4, although the maximum leakage rate in MFF1 was somewhat higher. This indicates that using mineral fibre as cavity insulation has little effect on the leakage into the interior of the building.



Figure 7.17 Wall MFF1; Leakage rate – Evolution with time

MFF1 - Leakage Rate



Figure 7.18 Wall MFF2; Leakage rate – Evolution with time

The drying tests revealed that, as expected, the two external walls had very similar behaviour (compare Figures 7.19 and 7.20). The two internal faces (compare figures 7.21 and 7.22) also revealed similar behaviour.



MFF1 External face - Drying

Figure 7.19 Wall MFF1; External face – Evolution of drying with time

MFF2 External face - Drying



Figure 7.20 Wall MFF2; External face – Evolution of drying with time



MFF1 Internal face - Drying

Figure 7.21 Wall MFF1; Internal face – Evolution of drying with time



MFF2 Internal face - Drying

Figure 7.22 Wall MFF2; Internal face – Evolution of drying with time

7.2.4 Wall MPF1

Wall MPF1 was a part fill cavity wall built with Wire cut facing bricks on the external face and 3.5N concrete blocks on the internal face. The cavity was part insulated with rigid foam (Kingspan Siteline) nominally 50mm thick (actual thickness was 48mm).

As can be seen in Figure 7.23, the maximum leakage rate through this wall was below 0.100m³/hr. This value is intermediate between the rates measured for walls MFF1 and MFF2 which were similar to MPF1 in all respects apart from the insulation used inside the cavity. By absorbing some of the water that leaked through the external face of the wall, the part-fill plaque did not allow the water to build up inside the cavity and create the head necessary to produce a large seepage rate.

When comparing with ME4 (see Figure 7.10), which is similar in construction to MPF1 but has an empty cavity, it is apparent that the evolution of seepage with time observed for MPF1 is similar to that of ME4, although the maximum leakage rate in MPF1 is only about a third of that of ME4. This indicates that using cavity insulation has some effect on reducing leakage into the interior of the building.

With regard to drying, a comparison of Figures 7.12 (Wall ME4) and Figure 7.24 (Wall MPF1) shows very little difference between the behaviour of the external faces of the empty cavity wall and the part fill wall. With regard to the internal wall, Figure 7.14 (Wall ME4) and Figure

7.24 (Wall MPF1) the part fill wall retained a slightly less moisture (1% less) at the end of the dry phase.



Figure 7.23 Wall MPF1; Evolution of leakage with time



MPF1 External face - Drying

Figure 7.24 Wall MPF1; External face - Evolution of drying with time



MPF1 Internal face - Drying

Figure 7.25 Wall MPF1; Internal face - Evolution of drying with time



Figure 7.26 Wall MPF1; Cavity – Water depth evolution with time

7.2.5 Wall ME5

Wall ME5, together with wall MFF3, were the last in the series to be tested. Wall ME5 was an empty cavity wall built with Wire cut facing bricks on the external face and Concrete blocks 3.5N on the internal face. The external face was rendered with a cement-based render. As recommended in the NHBC Standards, in order to give key to the first coat of render, the joints of the external brick wall were raked out 15mm. The second coat was applied three days after the first coat.

The main objective of testing Wall ME5 was to compare its performance with that of wall ME3, which was similar to ME5 in all respects apart from the lack of external render. Figure 7.27 shows the evolution with time of the leakage rate through wall ME5. At the start of the test, no leakage was observed and the rates were several orders of magnitude smaller than those observed for wall ME3 (see Figure 7.9) – note the different scales in the two graphs.



Figure 7.27 Wall ME5 - Evolution of leakage with time

With regard to drying, the external face (with cement render) appeared to retain significantly less moisture than the equivalent non-rendered masonry wall (Wall ME3) at the end of the dry phase: approximately 4% of the dry state moisture at ground level (see Figure 7.28) compared with 27% for the non-rendered wall (see Figure 7.11). With regard to the internal wall, the moisture levels went back to the pre-test condition, i.e. the wall actually dried very effectively during the tests. This is due to the fact that in the first place, very small amounts of water leaked through the external wall and built up inside the cavity (see Figure 7.30).

ME5 External face - Drying



Figure 7.28 Wall ME5; External face – Evolution of drying with time

ME5 Internal face - Drying



Figure 7.29 Wall ME5; Internal face – Evolution of drying with time

Wall ME5: Water Depth in wall cavity



Figure 7.30 Wall ME5; Depth of water in cavity – Evolution with time

7.2.6 Wall MFF3

Wall MFF3, together with wall ME5, were the last in the series to be tested. Wall MFF3 was a cavity masonry wall with mineral fibre insulation, built with Wire cut facing bricks on the external face and Concrete blocks 3.5N on the internal face. The internal face was rendered with a lime-based plaster.

The main objective of testing Wall MFF3 was to investigate the behaviour of lime plaster, in particular to compare its performance with that of standard gypsum plaster board. Soon after the wet phase test started (1m head of water on external face) the lime plaster cracked and detached from the wall; this occurred at the level of the damp proof course (see Photo 7.20). Large leakage rates were observed, as can be seen in Figure 7.31. When exposed to water on both the external and internal sides, the lime plaster started to crack also at the surface water level, as shown in Photo 7.21. The lime plaster disintegrated completely and therefore it was impossible (as well as irrelevant) to take moisture readings relating to the drying phase. It is appreciated that lime plaster requires several months (or even years) to reach its full properties and the timeframe of the testing programme would not allow for that. Further discussion is given in Chapter 8.



Figure 7.31 Wall MFF3 - Evolution of leakage with time

7.3 Results of timber framed walls

The results of the wet and drying phases of tests carried out on timber framed walls are presented in Figures 7.32 to 7.42, which include graphs of leakage through each wall type, the variation with time of water depth inside the wall cavity and drying of the external and internal faces of the walls. The leakage rate was determined by measuring the water that accumulated on the internal side of the test tank, which represented the combined seepage through the internal and external wall units. The measurement frequency was determined during the actual test, according to the amount of water getting through the wall, since this could not be anticipated prior to the test. As mentioned in Section 3.3, the seeped water was not allowed to accumulate behind the internal face of the walls. The drying data in the various graphs are given as evolution of moisture with time in terms of % WME (wood moisture equivalent) – refer to Section 4.4.

It should be noted that, for clarity of presentation, it was not possible to present the graphs using the same scale for the y-axis due to the wide variability of seepage rates (and weights). This should be borne in mind when comparing the results for the various materials.

7.3.1 Wall TF1

Wall TF1 was a timber framed wall with Wire cut facing bricks on the external face and empty cavity (other components are listed in Section 7.1). Lower leakage rates were measured (see Figure 7.32) when compared with a typical masonry wall such as Wall ME4 (see Figure 7.10). This is likely to be attributed to the presence of the OS Board on the internal wall construction, which has lower seepage characteristics than concrete blocks (see Table 5.1). Photo 7.16 shows the installation of insulation within the timber frame. It is worth noting that, although representative of general practice, the workmanship appears poor from an insulation viewpoint as relatively large gaps can be seen. However, this is unlikely to impact on flood performance.



Figure 7.32 Wall TF1; Evolution of leakage with time

TF1 External face - Drying



Figure 7.33 Wall TF1; External face - Evolution of drying with time



Figure 7.34 Wall TF1; Internal face - Evolution of drying with time [measurements taken on the wooden frame (0.5m and 1m above ground) and on the concrete block layer (ground level); no initial moisture level was taken at 1m above ground]

TF1 Internal face - Drying

7.3.2 Wall TF2

Wall TF2 was a cement-rendered timber framed wall with concrete blocks on the external face and empty cavity (other components are listed in Section 7.1). As can be seen from Figure 7.35, the leakage rate was much reduced compared with non-rendered typical external masonry walls, i.e. walls using facing bricks such as wire cut (see Figure 7.10). The effect of renders will be discussed in more detail in Section 8.

With regard to drying, the external face (with cement render) appeared to retain slightly less moisture than a typical masonry wall such as Wall ME4 at the end of the dry phase: approximately 16% of the dry state moisture (see Figure 7.36) compared with 17% (see Figure 7.12).



Figure 7.35 Wall TF2 - Evolution of leakage with time

TF2 External face - Drying







TF2 Internal face(Block and Wood Frame) - Drying

Figure 7.37 Wall TF2; Internal face - Evolution of drying with time [measurements taken on the wooden frame (0.5m and 1m above ground) and on the concrete block layer (ground level)]



Figure 7.38 Wall TF2; Internal face (OSB) - Evolution of drying with time

7.3.3 Wall TF3

Wall TF3 was a lime-render timber framed wall with concrete blocks on the external face and empty cavity (other components are listed in Section 7.1). As can be seen from Figure 7.39, the leakage rate was much reduced compared with non-rendered typical external masonry walls, i.e. walls using facing bricks such as wire cut (see Figure 7.10). The effect of renders will be discussed in more detail in Section 8.

With regard to drying, the external face (with lime render) appeared to retain significantly less moisture than a typical masonry wall such as Wall ME4 at the end of the dry phase. Measurements of WME do not necessarily enable direct comparisons between different types of surface material but a difference of 10% appears significant: 7% WME for TF3 (see Figure 7.41) compared with 17% WME for ME4 (see Figure 7.12).



Figure 7.39 Wall TF3 - Evolution of leakage with time

TF3 External face - Drying







TF3 Internal face(Block and Wood Frame) - Drying

Figure 7.41 Wall TF3; Internal face - Evolution of drying with time [measurements taken on the wooden frame (0.5m and 1m above ground) and on the concrete block layer (ground level)]



Figure 7.42 Wall TF3; Internal face (OSB) - Evolution of drying with time

8. DISCUSSION OF RESULTS FROM WALL TESTS

The ensuing discussion of results from the wall tests has been split into two categories: leakage and drying behaviour. The main results are summarised at the end of this section.

It should be borne in mind that the tests were carried out on test panels which, although large for laboratory work, had necessarily smaller dimensions than the walls of real domestic dwellings. For this reason, and the constraints at the edges of the test tanks, the test panels would not have the same cracking behaviour of real structures. Also, as the testing programme was carried out on young walls, long term drying shrinkage and/or settlement, which can lead to cracking, were not possible to observe.

8.1 Leakage through cavity walls

Empty cavity walls

During tests of empty cavity walls (walls ME1, ME2, ME3, ME4 and timber framed walls) it was possible to observe and measure the build up of water inside the wall cavity. The increase with time of the water level inside the cavity is shown in the graphs presented in Figures 7.7, 7.8, 7.15 and 7.16. It is clear from the graphs that walls incorporating Engineering Bricks Class A on their external face (ME1 and ME2) were associated with lower levels of water inside the cavity due to lower leakage rates. Reasonably low levels of water inside the cavity were also measured at wall ME3 but this is primarily due to high leakage rates through the concrete blocks. When comparing all the graphs, it is interesting to note that the walls that comprised concrete blocks on the internal face (ME1 and ME3) led to lower levels of water accumulation inside the cavity as the 3.5 N concrete blocks allowed easier leakage through than Aircrete blocks (compare water depths of around 0.5m inside wall ME3 to 0.9m inside ME4 at the end of the wet phase).

Due to the accumulation of water inside the cavity it was not possible to ascertain the precise point(s) of entry into the cavity of the leaked water if this occurred below the level of water in the cavity. Dye was injected to help visualisation but was not helpful. However, it is possible to say, that in tests of walls ME1 and ME2 (which used Engineering bricks Class A) the leakage path was through the bottom part of the wall rather than the middle or top. As the maximum water pressure occurs at the base of the wall, this finding is not surprising but it also reveals that no cracks were found to develop across the height of the wall which would create preferential paths for the water. In the case of walls ME3 and ME4 (using wire cut bricks) water was seen to leak through mortar joints above the water level in the cavity, to about 0.5m height. A possible explanation for this (not backed up by any quantitative evidence) is that the higher porosity of the wire cut bricks compared with Engineering bricks enables more water to be drawn from the mortar, which then dries too fast with the possible development of small/micro cracks and holes. It was noted in Section 7.1 that, for reasons related to minimising the variables in the test programme, the same mortar mix was used for all the test panels regardless of the type of brick/block used, only varying the mix above and below DPC. Normally the mortar mix would match the bricks as the water content of the mix can have an effect on the suction exerted by the brick, which was not covered in the present research.

Full-fill cavity walls

Tests carried out on full-fill cavity walls MFF1 and MFF2 indicated that mineral fibre in batts (used in wall MFF1) did not slump during the wet test whereas the blown-in insulation (used in wall MFF2, i.e. expanded mica) slumped by an average of 40mm (or about 3.5% of the height) at the end of the three day test with water on the external wall face. At the end of the one day test with exposure to water on both faces the average slump measured was 50mm (or about 4.4% of the height). These measurements were taken from the top of the brick external wall.

At the end of the wet test (three days plus one day), observation of the characteristics of the cavity insulation material showed that:

- The mineral fibre was dry to the touch above the 1m water level whereas the blown-in expanded mica insulation was wet
- Both materials were wet below the water level.

It should be noted that there is a range of mineral fibre products and performance may vary. In particular high density mineral fibre batts may suffer less from slumping than the material tested under the current project.

Part-fill cavity walls

Tests carried out with part-filled cavity (wall MPF1, which contained a rigid foam plaque) showed that the board absorbed some water but retained its structural integrity.

Effect of external renders

The two types of external render tested (cement render and lime-cement render) were found to be very effective in reducing leakage through the external wall into the cavity. This in turn creates advantageous conditions, i.e. lower driving head, for reduction of leakage through the internal face. The overall effect was very positive, with a reduction of maximum leakage rates to less than 3% of the corresponding leakage rate through typical masonry walls constructed with facing bricks. Figure 8.1, comparing Walls ME3 and ME5 (ME3 with wire-cut bricks on the external face and ME5 with wire-cut bricks plus external cement render) illustrates the benefits of external renders in terms of minimising water ingress, which in turn is reflected in better drying performance. However, it is important to note that trying to stop water ingress may induce excessive pressures on masonry walls for which they need to be structurally checked.





Figure 8.1 Effect of external render on leakage through brick walls

The cement render was found to be more effective than the lime-cement render in terms of leakage reduction with the added benefit of being simpler and cheaper to mix and apply.

Behaviour of gypsum plasterboard

During the tests carried out on walls, the behaviour of the plaster board fixed to the inside wall was monitored. The plaster board was present during the wet testing phase, when the walls were exposed for three days to water on the external face and to water on both faces for one day. At the end of this phase the plaster board was removed.

During the wet phase the plaster board was found to remain sound in appearance. However, when the board was being removed it disintegrated into small pieces, only held by the backing paper sheets.

The tests enabled some conclusions regarding capillary action. Above the level of the standing water (1m) the board was visually wet and this profile was drawn on the paper backing of the plaster board. The average rise in moisture was 25mm, with a maximum of 35mm).

Behaviour of lime plaster

Tests carried out on young lime plaster (seven days old, based on date of second and last coat applied) showed that it did not have sufficient strength to withstand the high leakage rates associated with brick and block non-rendered walls. The result was collapse of the lime

plaster and total disintegration. It is appreciated that a different behaviour might have been observed had the lime plaster attained its full properties, normally at the end of several months or even months. However, there is no known published information on the structural ability of lime plaster to resist the force of 1m head of water leaking through very porous materials such as ordinary bricks and concrete blocks. The current research project unfortunately does not provide opportunity to investigate this issue further.

8.2 Drying characteristics

When attempting to draw conclusions on the drying behaviour of walls it is necessary to bear in mind that the data collected during the test programme (surface moisture levels) only provided an indication of the moisture status of the wall surfaces and its evolution with time. The data was useful, in particular, for indicating whether the surface of a composite is able to go back to the original moisture levels, measured at the start of the wetting phase. A discussion of the advantages and limitations of the moisture measuring technique used in the present tests is presented in Section 4.4. Measurements of WME do not necessarily enable direct comparisons between different types of surface materials, such as rendered walls and brickwork but significant differences were found in the tests which allow some general conclusions.

The information collected from the tests on the drying characteristics of walls is summarised in the following sub-headings where a distinction is made between empty, full-fill and part-fill cavity walls. Insulation materials and renders are also covered. A further sub-heading is included in this section describing the analysis carried out to estimate the time required for a wall to reach its pre-flood moisture conditions. This information will then allow comparisons to be made between natural drying and forced drying (as implemented by flood damage specialists) both in terms of time and cost.

Empty cavity walls

External face

In spite of their higher leakage rate, the walls constructed with wire cut facing bricks (walls ME3 and ME4) did not show better drying characteristics when compared with walls constructed with Engineering bricks Class A (walls ME1 and ME2) as can be seen from graphs presented in Figures 7.3 and 7.11, for example. None of the walls was found to return to the original moisture levels, measured at the start of the tests.

Internal face

Both walls constructed with concrete blocks 3.5N (walls ME1 and ME3) returned to their original moisture levels at the end of the drying phase whereas those constructed with Aircrete (walls ME2 and ME4) still retained some moisture (compare for example Figures 7.5 and 7.6).

Full-fill cavity walls

External face

The effect of having full cavity insulation on the drying ability of the external face of the wall can be appreciated by comparing the performance of walls MFF1 and MFF2 with ME4. A comparison of Figures 7.12 and 7.19 indicates that the mineral fibre insulation in MFF1 might have hindered the drying of the external face. Comparison of Figure 7.20 with 7.12 shows that the blown-in insulation did not have much effect.

Internal face

The presence of mineral fibre insulation in the cavity of wall MFF1 appeared to have little or no effect on the drying of an internal face formed by Aircrete blocks (compare Figures 7.21 and 7.14). The presence of blown-in insulation appears to aid the drying process to a small extent, particularly at ground level (compare Figures 7.22 and 7.14).

Part-fill cavity walls

External face

The effect of having part full cavity insulation on the drying ability of the external face of the wall can be appreciated by comparing the performance of wall MPF1 with ME2. A comparison of Figures 7.4 and 7.24 indicates that the PU foam insulation in MPF1 might have hindered the drying of the external face.

Internal face

The effect of having part full cavity insulation on the drying ability of the internal face of the wall can be appreciated by comparing the performance of wall MPF1 with ME2. A comparison of Figures 7.6 and 7.25 indicates that the presence of PU foam insulation in the wall cavity has little effect on the drying of the internal face.

Insulation

Full-fill - Mineral fibre

At the end of the drying phase, both the middle and top layers of the mineral fibre insulation were dry to the touch but the bottom layer was still wet. This material, regardless of whether it had been used in masonry wall cavities or in timber framed walls, was quite fragile and remained wet for a long time afterwards, namely after three months.

Full-fill - Blown-in

When the walls were demolished at the end of the wet and drying phases, the blown-in insulation material retrieved from the cavity was notably wetter at the base than at the top. At the base this loose material had gained the consistency of a wet pulp. Samples of the loose material taken from the base, middle level and top of the wall were left to dry on a plastic sheet in the laboratory. After one month of drying, it was found that all the samples were damp to the touch, but no longer wet as was the case of the samples taken from the bottom parts of the cavity immediately after the tests. The weights of two samples, taken at ground and top levels, were also monitored for over a month and a half after the end of the drying phase. The evolution with time is presented in Figure 8.2, which shows the percentage

increase in weight in relation to the dry weight (the gap in the data is due to the Christmas period, when no measurements were taken).



Blown-in insulation - percentage increase in weight from dry value

Figure 8.2 Drying of Blown-in insulation beyond end of drying phase - Evolution with time

Part-fill

After removal from the test rig, the part-fill insulation tested (rigid PU foam) was regularly weighed to determine its drying characteristics. During the whole of this drying period the plaque retained its structural integrity. The evolution of its weight per unit of volume was plotted in Figure 8.3 together with the dry weight per unit volume. It can be seen from this Figure that after 35 days the material had not recovered its original weight and little change was observed after 25 days.

Rigid PU Foam insulation - drying



Figure 8.3 Drying of part-fill insulation (Rigid PU foam) beyond end of drying phase - Evolution with time

External renders

The two types of external render tested (cement render and lime-cement render) were found to have different drying behaviours, with the lime-cement render drying more quickly than the cement render. The cement rendered wall tested was comparable with typical non-rendered masonry walls, whereas the lime-cement rendered wall retained about 10% less moisture than a typical masonry wall at the end of the drying phase. Figure 8.4 illustrates some positive effects of introducing an external render: not only does the rendered wall absorb less moisture but it goes back to almost its original moisture value in less than a week of drying.



Comparison of drying of external walls without and with render

Figure 8.4 Effect of external render on drying of external walls

Natural drying times for walls

As mentioned before, most of the walls tested did not manage to go back to their original moisture levels within the time allocated for the drying phase of the tests (7 days, or approximately 170 hours). Possible reasons for this were presented earlier and are associated with the presence of certain insulation materials and the amount of water ingress that the walls allowed in the first place.

An analysis was carried out of the drying data collected on the internal face of the walls to estimate the time required for the wall to achieve its pre-test moisture levels. Only the internal faces were analysed as these are typically used for assessments of moisture levels by surveyors undertaking flood damage repair in properties. The data collected during the tests included moisture values at three different levels (at ground level and at 0.5m and 1m above ground) but it was decided to use the ground level data for the analysis as this would provide the most conservative conclusions. In all cases the data was collected on the internal face after the plaster board was removed.

It should be noted again, that this analysis assumes that surface moisture is a reasonably adequate indication of the level of dryness of a wall and is based on data collected using standard surveying equipment. The drying process was undertaken in laboratory uncontrolled ambient conditions. The air temperature during the drying tests ranged between 7°C and 17.5°C and the relative humidity between 60.2% and 95%. The results of the analysis are presented in Table 8.1.

Wall type	Time to recover original moisture levels*	Observations
Masonry, empty cavity		
External face: Engineering bricks		Measured
Internal face: Concrete blocks	160 hrs	
	(approx. 7 days)	
Masonry, empty cavity		
External face: Engineering bricks		Extrapolated
Internal face: Aircrete	300 hrs	
	(approx. 12.5 days)	
Masonry, empty cavity		
External face: Wire cut bricks		Measured
Internal face: Concrete blocks	160 hrs	
	(approx. 7 days)	
Masonry, empty cavity		
External face: Wire cut bricks		Extrapolated
Internal face: Aircrete	851 hrs	
	(approx. 35.5 days)	
Masonry, empty cavity		
External face: Wire cut bricks		Measured
Internal face: Concrete blocks	160 hrs	
External cement render	(approx. 7 days)	
Masonry, part-fill insulation		
External face: Wire cut bricks		Extrapolated

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Internal face: Aircrete	628 hrs	
	(approx. 26 days)	
Masonry, mineral fibre full-fill insulation External face: Wire cut bricks		Extrapolated
Internal face: Aircrete	3764 hrs	
	(over 5 months)	
Masonry, blown-in full-fill insulation		
External face: Wire cut bricks		Extrapolated
Internal face: Concrete blocks	240 hrs	
	(10 days)	
Timber frame		
External face: Wire cut bricks		Extrapolated
Internal face: Concrete blocks	331 hrs	
	(approx. 14 days)	
Timber frame		
External face: Wire cut bricks		
Internal face: Concrete blocks (at	225 hrs	Extrapolated
External cement render	(approx. 9.5 days)	
Timber frame		
External face: Wire cut bricks		
Internal face: Concrete blocks (at ground level)	386 hrs	Extrapolated
External cement/lime render		

* Based on date collected at ground level on the internal face of cavity walls

8.3 Summary of results

The following conclusions were drawn from the test results on walls (backed up by information collected from tests on individual building materials). It is recommended to refer to earlier parts of Section 8 for background. It should be borne in mind that the experimental work was carried out on test panels which, although large in laboratory terms, had necessarily smaller dimensions than the walls of real domestic dwellings. For this reason, and the constraints at the edges of the test tanks, the test panels would not have the same cracking behaviour of real structures. Also, as the testing programme was carried out on young walls, long term drying shrinkage and/or settlement which can lead to cracking, were not possible to observe. Limitations of the technique used for the measurement of moisture (in terms of wood moisture equivalent or WME) are given in Section 4.4. Measurements of WME do not necessarily enable direct comparisons between different types of surface materials, such as rendered walls and brickwork but significant differences were found in the tests which allow some general conclusions. The main conclusions are:

- The behaviour of a composite wall cannot be predicted solely from the behaviour of its components
- Engineering bricks on external walls are very effective at preventing leakage (any leakage was only observed at ground level) whereas standard facing bricks on external walls allow high rates of leakage at various heights
- Walls incorporating external cement-lime render were found to allow more leakage through than equivalent walls using cement render (approximately one order of magnitude higher but still very low rates) but they did recover their dry state conditions considerably more quickly
- Concrete block walls are more permeable than Aircrete walls but Aircrete dries more slowly
- None of the non-rendered walls tested were found to return to the pre-flood moisture levels (surface values) after 6 days drying thus indicating that forced drying may be required; externally rendered walls practically returned to their pre-flood levels in less than a week
- Measurements showed maximum leakage rates of 150 l/hr for a non-rendered typical brick wall compared with 0.3 l/hr for externally cement-rendered walls; these latter retained about 10% less moisture than typical masonry walls at end of 6 days natural drying. However, it is important to note that trying to stop water ingress may induce excessive pressures on masonry walls for which they should be structurally checked.
- Extensive mould growth was observed on sheathing (OSB) during the dry phase of testing (see Photo 7.22)
- Insulating materials

Mineral fibre in batts became totally soaked in contact with cavity water and fragile to handle; it appears to hinder drying of walls; the material remained wet after 3 months following the test

The blown-in insulation material tested (expanded mica) absorbed water (450% weight gain) and slumped by about 4% of height; compared with mineral fibre in batts, it was only marginally better that the mineral fibre tested in terms of promoting drying of the internal wall face (surface values); the expanded mica material was found to still retain 50% more weight than in dry state after 3 months

Rigid PU foam (for part-fill insulation) also absorbed some water but retained structural integrity

Internal plaster

Gypsum plasterboard remained sound in appearance during the wet phase but disintegrated into small pieces when removed, only being held by the backing paper sheets; the average rise in moisture by capillary action was 25mm, with a maximum of 35mm

Lime plaster applied on a concrete block wall collapsed and disintegrated under 1m water pressure. However the performance of the uncured plaster (seven days old) cannot be taken as indicative of the performance of relatively mature lime plaster. Further work would be required to fully investigate the flood resilience of this plaster material.
9. TESTING OF FLOORS

9.1 Construction of floors

The scope of the study allowed for testing several different arrangements of floors simulating the ground floor of domestic buildings. The final specification for these arrangements was the result of extensive consultation and discussions with the funding organisations, the Steering Group members, the Building Inspector and builder involved in the wall testing as well as with contacts at Taylor Woodrow. Lessons learnt from the initial testing of materials and walls were also important for the definition of the testing facility and test procedure. As recommended at Project Steering Group Meetings, the specification for the floors followed closely recommendations in the NHBC Standards. It was later suggested that, rather than referring to NHBC Standards, reference should preferably be made to British and European Standards such as the BS 8500 (which is a complementary British Standard to BS EN 206-1 on Concrete) and BS EN 197-1:2000 (which covers Cement) as this would be more readily taken up by consulting engineers. However, perusal of these documents and their subsidiary standards, only reinforced the importance of following simple guidelines like those given by the NHBC. The information in the British and European Standards is presented in a fairly complex form as it is intended to give guidance on concrete covering all types of application, from the simple bulk concrete floor slab to highly specialised reinforced concrete in tall buildings and bridges. Bearing in mind that the present work is aimed at simple guidance to builders and developers of domestic buildings, it was therefore decided to use the practical advice in the NHBC Standards on the types of concrete mix.

The different test arrangements were devised to cover the aspects considered to be most relevant by the members of the PSG and other consultees: effect of slab thickness, effect of concrete strength, moisture barrier (i.e. membrane) effectiveness, overlap in membranes and wall/floor joints.

Given the need to carry out a large number of long duration tests within a short timeframe, it was agreed that the best practical option was to pre-cast slabs of concrete, install them in the test rig on a base of sand and remove them after the wet test phase. In order to simulate realistic drying conditions, the slabs would then be removed and put on a bed of wet sand to dry.

It was decided to test 0.5m by 0.5m concrete slabs (not reinforced), with minimum thickness of 100mm, as per recommendations in NHBC standards. For tests investigating the performance of wall/floor joints, the size of the test slabs was reduced to allow placement of the section of wall within the test tank.

Table 9.1 lists the arrangements tested. This is the final result of a series of amendments to the original test programme which were made in view of interim test results. The justification for the different arrangements is as follows:

Arrangements 1 to 3 (baseline tests) provided data on seepage through the slab (effect of thickness and concrete strength);

Arrangements 4 and 5 investigated the suitability of current membrane installation practices when the available the floor impermeable membrane is not sufficiently large to cover the whole floor area and either a 300mm overlap or taping is required;

Arrangement 6 provided data on floor/wall junction;

Arrangement 7 used a modified arrangement of a floor/wall junction to limit water leakage;

Arrangement 8 provided data on the effectiveness of an improved floor/wall junction at a corner.

Table 9.1 Floor arrangements tested

Arrangement	Thickness of concrete	Concrete mix (cement strength*)	Moisture barrier/screed/joints	Adjacent wall
Arrangement 1	100mm	32.5 ^a	-	-
Arrangement 2	150mm	32.5 ^a	-	-
Arrangement 3	150mm	42.5 ^b	-	-
Arrangement 4	150mm	42.5 ^b	Polythene sheet below slab (300mm overlap) ^c	-
Arrangement 5	150mm	42.5 ^b	Taped lap in membrane (50mm overlap)	-
Arrangement 6 ^d	150mm	42.5 ^b	Polythene sheet below slab	Blockwork foundation (side wall only)
Arrangement 7 ^d	150mm	42.5 ^b	Polythene sheet below slab + foundation block course in concrete trench	Blockwork foundation (side wall only)
Arrangement 8 ^e	150mm	42.5 ^b	Polythene sheet below slab + foundation block course in concrete trench	Blockwork foundation (corner wall)

* NHBC Standards, Table 1 in Appendix 2.1B:

Standard Prescribed Mix ST2, Slump Class S2

a – 1 bag of 25kg cement; 50 litres fine aggregate; 75 litres coarse aggregate

b - 1 bag of 25kg cement; 55 litres fine aggregate; 80 litres coarse aggregate

Max aggregate size: 20mm

c - lap of 300mm in membrane (as min. recommended in NHBC Standards)

d - dimensions of concrete slab were 0.5m by 0.35m to allow construction of block wall in test rig

e - dimensions of concrete slab were 0.35m by 0.35m to allow construction of a corner block wall in test rig.

It is worth making a comment on the cement strength classes used for the test slabs. When the specification for the construction of the test slabs was being written, NHBC advised that cement of strength class 32.5 was the most common type for use in ground floor slabs, with class 42.5 being unusual. However, when sourcing the cement for the test slabs, it became apparent that cement 42.5 is very commonly used, but in most cases the actual strength class is not known because this information is not displayed on the cement bags. This is a potential source of confusion when bagged cement is used.

The floor slabs for Arrangements 1 to 5 were cast on 19 and 20 January 2006 (see Photo 9.1) and on 22 March 2006 for Arrangements 6 to 8 using wooden formwork and were left to cure for a minimum of 28 days before they were installed in the test rig. As they were going to be subjected to considerable uplift forces, it was considered that they should be allowed to reach very close to their ultimate strength; it is generally accepted that after 28 days the increase in strength is minimal. Hooks were embedded in the slabs to facilitate handling with a fork lift.

As mentioned earlier in Section 4.2, the floors and floor/wall junctions were tested in Test Rig B (see Figure 4.3 and Photo 9.2). At the start of the test programme it was necessary to undergo a series of preliminary tests before the test set-up was considered suitable. The need for these tests arose from difficulties in finding sealing techniques and materials that would withstand the uplift pressure force produced by 1m head of water acting on the base of the floor. Various sealants and sealing methods were used and it became apparent that using slabs with 150mm thickness, which are 50% heavier than those with 100mm thickness, greatly helped solve the sealing problem. For this reason, most tests were carried out with 150mm thick slabs.

9.2 Results

Arrangement 1 – 100mm thick slab; 32.5 class cement

Arrangement 1 slab was subjected to water uplift pressure for three days, during which no water was seen to seep through the slab but some leakage was observed through the sides; the test also included water pressure on the surface for one day combined with uplift pressure.

After the test was completed, the slab was removed from the test rig, weighed (see Table 9.1) and then a corner was broken off to allow inspection of the interior, to check whether water had penetrated through the slab thickness. The colour of the concrete (dark grey) indicated that the material had absorbed moisture but as the slab was dry to the touch, it was uncertain whether it had absorbed much moisture. A few days later the colour of the broken piece exposed surface was much lighter which confirmed that the slab had been wet and was now drying (see Photo 9.3). It is known that a light grey film develops on drying concrete surfaces on contact with air but the drying process was confirmed quantitatively by weighing the broken corner at regular intervals during the next six days.

Moisture readings taken on the surface of the slab were inconclusive.

Figure 9.1 shows the evolution of drying of a broken-off corner of the test slabs for Arrangements 1, 2, 3, 4 and 5.



Drying rates of concrete slabs - Arrangements 1 to 5

Figure 9.1 Evolution of drying (of sample of slab) for Arrangements 1 to 5

The test slabs were removed from the test rig at the end of the wet phase of testing and were weighed to evaluate their moisture absorption capabilities. Table 9.2 shows the increase in weight (absolute and in percentage terms) that the slabs experienced at the end of the wet phase of testing.

Table 9.2 Results of slab tests

Arrangement	Slab characteristics	Dry weight (kg)	Weight at end of wet phase (kg)	Percentage increase in weight (wet weight/dry weight)
Arrangement 1	100mm; 32.5 class cement	58.9	60.1	2
Arrangement 2	150mm; 32.5 class cement	91.2	91.55	0.4
Arrangement 3	150mm; 42.5 class cement	90.6	90.8	0.2
Arrangement 4	150mm; 42.5 class cement Membrane with 300mm overlap	88.8	89.1	0.3
Arrangement 5	150mm; 42.5 class cement Membrane with taped 50mm overlap	90.8	91.0	0.2
Arrangement 6	150mm; 42.5 class cement Wall/floor junction	NA	NA	NA From the start of the test, significant leakage was observed through the joint between the floor slab and the wall and the test was terminated
Arrangement 7	150mm; 42.5 class cement Improved	NA	NA	NA No leakage was

	wall/floor junction			observed
Arrangement 8	150mm; 42.5 class cement Corner wall/floor junction	NA	NA	NA No leakage was observed

NA – Not applicable

Arrangement 2 – 150mm thick slab; 32.5 class cement

Arrangement 2 slab was subjected to water uplift pressure for three days, during which no water was seen to seep through the slab and only very minor leakage was observed through the sides. The reduction in leakage through the sides when compared with the 100mm thickness slab is likely to be attributable to the greater weight of the slab, which better counterbalanced the uplift pressures.

The slab was weighed prior to installation in the test rig: its weight was 91.200kg. After the three-day wet test, the slab weight increased to 91.550kg. A corner was broken off to allow inspection of the interior and this showed that the material had absorbed moisture at the base but this moisture had not risen to occupy the whole thickness of the slab (see Photo 9.4). The evolution of drying of the broken corner is shown in Figure 9.1.

Arrangement 3 – 150mm thick slab; 42.5 class cement

Arrangement 3 slab was subjected to water uplift pressure for three days, during which no water was seen to seep through the slab and only very minor leakage was observed through the sides.

Prior to installation of the slab in the test rig the slab weight (dry) was 90.600kg. After the three-day wet test, the slab weight increased to 90.800kg. A corner was broken off to allow inspection of the interior. This showed that the material had absorbed moisture at the base but this moisture had not risen to occupy the whole thickness of the slab (see Photo 9.5).

Arrangement 4 – 150mm thick slab; 42.5 class cement; membrane with 300mm overlap

Arrangement 4 slab was subjected to water uplift pressure for three days, during which no water was seen to seep through the slab.

Prior to installation of the slab in the test rig the slab weight was 88.800kg. After the three-day wet test, the slab weight increased to 89.100kg. Water had been able to infiltrate into the overlap in the membrane and therefore the slab was in contact with water. A corner of the slab was broken off to allow inspection of the interior. This showed that the material had

absorbed moisture at the base but this moisture had been confined to the base of the slab and corners.

Arrangement 5 – 150mm thick slab; 42.5 class cement; taped membrane

Arrangement 5 slab was subjected to water uplift pressure for three days, during which no water was seen to seep through the slab.

Prior to installation of the slab in the test rig the slab weight was 90.8kg. After the three-day wet test, the slab weight increased to 91.0kg, which showed that the slab absorbed some moisture. A corner of the slab was broken off to allow inspection of the interior. This confirmed that the material had absorbed moisture at the base but this moisture had not risen to occupy the whole thickness of the slab (see Photo 9.6).

Observation of the membrane after removal from the test rig showed that it had suffered a small rupture at one of the edges of the slab. Although one cannot be certain whether this occurred during the test or only at the stage of removal of the slab from the test rig, this highlights the need for great care to be applied on site to minimise perforation of the membrane.

Arrangement 6 – 150mm thick slab; 42.5 class cement; wall/floor junction

A sketch of Arrangement 6 is given in Figure 9.2, which closely followed the NHBC details.

Arrangement 6 consisted of a standard wall/floor joint as shown in the NHBC details. It included a Damp Proof Membrane (DPM) of gauge 500 (which is lighter than typically recommended) in order to facilitate bending at the junction and other corners of the test tank.

When Arrangement 6 was subjected to the uplift pressure of 1m head of water leakage was immediately observed coming at the level of the joint between the floor slab and the blockwork wall (see Photo 9.7). The rate at which the water was leaking was very significant and it was decided to terminate the test to avoid overflow of the test facility. The test was repeated three times to try to understand the path of the water and to measure the leakage rate. The leakage rate measured was about 0.175m³/hr. Although water was first seen to ingress onto the slab at the DPC joint level joint, build-up of water behind the blockwork was also observed soon after (this build-up rate was measured as approximately 0.400 m³/hr).

Given the point of entry of the water onto the slab and the fact that the water gushed onto the slab as if there was a sudden release of pressure, it was suspected that the membrane was perforated at some point immediately after the test started. The junction between the slab and the wall represents a sudden change of direction for the membrane; furthermore, there are sharp elements of mortar and concrete (namely the mortar joint and the edges of the concrete block and of the slab) that can cause the membrane to rip when subjected to the very high pressure associated with 1m head of water. In order to test this hypothesis, the slab was carefully removed and the membrane was inspected for holes and rips. Small holes were found where the membrane turned into the wall mortar joint (at DPC level), which coincided with the observed point of ingress of the water. The membrane was also stretched at the

corners adjacent to the wall but no holes were visible. However, when water was poured over these points, leakage was observed.

This test helped identify weak points that can facilitate the ingress of water under 1m head pressure. These were: changes in direction of the membrane and porosity of the blockwork at foundation level.

An improved wall/floor detail was devised and tested as Arrangement 7.



Figure 9.2 Sketch of wall/floor junction (Arrangement 6)

Arrangement 7 – 150mm thick slab; 42.5 class cement; improved wall/floor junction

Arrangement 7 was developed as an improvement of Arrangement 6 with the objective of minimising the amount of leakage that was observed during the test of Arrangement 6. The first course of blocks (the foundation blocks) was set in a trench (below the test slab) filled with concrete which was prepared using water proofing additives. A higher gauge polythene membrane was used (1000 gauge, equivalent to equivalent to 250 microns). It was found that the membrane was easily placed in the test tank.

No leakage was observed through the junction between the wall and the floor slab or through the slab, indicating that this construction detail is satisfactory (see Photo 9.8).

Arrangement 8 – 150mm thick slab; 42.5 class cement; wall/floor corner junction

Arrangement 8 was intended to test the behaviour of a wall/floor corner junction with improvements identified during testing of Arrangement 7.

As for Arrangement 7, the first course of blocks (the foundation blocks) was set in a trench (below the test slab) filled with concrete which was prepared using water proofing additives.

An impermeable 1000 gauge membrane was placed under the test slab and over the first course of blocks as shown in Figure 9.2. At the corner, care was taken to fold the membrane in a neat manner to avoid excessive material at this joint and reduce the risk of ripping.

During the test no leakage was observed through the wall/floor corner junction or through the slab, indicating that this construction detail is satisfactory (see Photo 9.9).

After the test was completed, water was allowed to build up in the wall cavity (i.e. between the course of blocks and the wall of the test tank) and at a head of approximately 0.1m some localised leakage through the membrane was observed. Although the membrane was not actually ripped, it was locally weakened by friction with the test slab (particularly its sharp edge) and this was sufficient to allow water through. With insitu slab construction this problem is less likely to occur but it is worth stressing that shearing forces on the membrane can be detrimental, particularly under high water pressure.

9.3 Conclusions

Under the test conditions described in Section 9.1, the conclusions from the floor tests (unreinforced slabs of mass concrete) can be summarised as follows:

- Concrete slabs are effective at preventing water ingress under 1m head of uplift pressure; no seepage was observed through any of the slabs tested;
- Increasing the concrete slab thickness from 100mm to 150mm is beneficial to counterbalance uplift forces caused by 1m head of water and therefore a minimum thickness of 150mm is recommended in flood-prone areas. It should be noted that slab deformation in response to uplift loads can induce cracking and lead to the creation of preferential paths for water ingress. In the present tests this was not observed but could be due the fact that the tests were carried out on small test slabs which had a ratio perimeter/area considerably bigger than for typical real slabs and therefore could mobilise relatively larger friction forces.
- Water absorption by concrete floor slabs under the current test conditions (3 days exposure to 1m head of uplift pressure) was found to be a small percentage of their weight, typically less than 1% for 150mm thick slabs;

- As expected, it was found that the 100mm thick slab was easier to dry than the 150mm slabs. However, in view of the minimal water absorption of concrete slabs in general, this is considered to be of less importance than achieving sufficient weight to counterbalance severe uplift forces;
- The strength of the cement used in the concrete mixture (32.5 or 42.5) appears to be of little relevance with regard to flood resilience and therefore standard cement is considered adequate;
- The use of an impermeable polythene membrane of gauge less than 1000 (250 microns) is not recommended as it can tear easily;
- There was little difference between overlapping the membrane by 300mm and taping it with a 50mm overlap;
- Visually a membrane may not show perforation but weak points, caused by shear forces at the contact with the floor slab and at changes in direction, can induce leakage. It is recommended to take care when placing the membrane around sharp corners;
- In order to prevent leakage at wall/floor junctions it is important to carefully fold the impermeable membrane at the DPC level and to set the wall foundation in concrete or use an alternative impervious material to prevent water ingress into the wall cavity through porous blockwork foundation.

10.TESTING OF PROMISING/IMPROVED WALL TYPES - STAGE 4

Some useful conclusions were drawn from the series of tests carried out on standard types of wall (described in Section 7) with regard to materials and/or construction processes that are likely to improve the flood resilience properties of buildings and are, in principle, easy to implement in practice. In addition to identifying more resilient materials and construction processes, an assessment was also made of methods that are currently in use and are seen as having significant potential for expansion in the near future. Examples of these promising methods, which have been investigated with regard to insulation, water absorption and structural properties but not yet in terms of their flood resilience characteristics, include: single wall construction (as opposed to cavity wall construction), use of external insulation, "thin layer mortar joints" and use of water-splash boards on internal wall faces. Following discussions, and with the agreement of the Project Steering Group, Stage 4 of the testing programme was developed to investigate the above-mentioned wall types/materials.

During Stage 4 the following types of wall were constructed and tested:

- Thin layer mortar joint on solid block wall (Wall S4.1)
- Solid masonry wall with external insulation (Wall S4.2)
- Masonry cavity wall with external and internal renders (Wall S4.3)
- Timber frame cavity wall using splash-proof board (Wall S4.4).

The characteristics of these walls are summarised in Table 10.1. All walls tested under Stage 4 followed exactly the same test procedure adopted for the standard wall testing, i.e. exposure to 1m head of water on the external face for three days, followed by exposure on both sides for 24 hours (wet phase) and drying for six days (drying phase).

10.1 Wall S4.1 - Thin layer mortar solid masonry wall

"Thin layer mortar" is a type of mortar specified in the European Standard BS EN 998 Part 2 (BSI, 2003) for masonry walls (both brick and block). Being more widely established in Scandinavian and other northern European countries, thin layer joint construction has gained some popularity in recent years in the UK. Although the market share of thin layer mortar (or thin joints, as is also commonly known) is still small, the system is being promoted for its speed and ease of construction. These characteristics make it a potential competitor to timber frame construction.

Since the mortar layers are very thin, only a few millimetres thickness compared to about 10mm in standard construction, the system's curing time is much reduced compared with standard masonry walls. It requires, however, low tolerance in the dimensions of the blocks/bricks used so that these need to be fabricated and cut with high levels of precision. Due to their construction process, Aircrete blocks are particularly suitable for this type of system.

Wall Type	Cavity/solid	Insulation	Wall materials	External face covering	Internal face covering	Test Wall no.
Masonry Thin layer mortar solid wall	Solid	No insulation	Aircrete blocks 300mm thick with thin layer mortar Block dimensions: 600mm long; 215mm high; 300mm thick Below DPC: 600 density blocks Above DPC: 460 density blocks	Lime-cement render 1 lime : 1 cement :6 sand Two coats: 20mm thick (total)	Lime-cement render 1 lime : 1 cement :6 sand One coat:11mm thick Second coat: 2mm thick gypsum plaster	Wall S4.1
Masonry Solid wall with external insulation	Solid	External insulation (polystyrene - proprietary)	Concrete blocks 200mm thick (3.5N)	Proprietary render (various layers)	Proprietary render (minimum two layers, with gypsum)	Wall S4.2

Table 10.1 General characteristics of walls tested under Stage 4

DCLG BUILDING REGULATIONS (SANITATION) FRAMEWORK

Masonry Cavity wall with external and internal renders	Cavity 100mm wide	PU rigid insulation (50mm thick) in the cavity	Concrete blocks – external wall Concrete blocks – internal wall	Cement render 1 cement : 6 sand Two coats: 20mm thick (total)	Cement render 1 cement : 6 sand	Wall S4.3
Timber frame Cavity wall using splash resistant internal board	Cavity 75mm wide	PU rigid insulation (50mm thick) in the cavity	Concrete blocks – external wall 75mm wide cavity Internal timber frame using Fermacell 15mm thick board as sheathing (otherwise standard timber frame construction)	Cement render 1 cement : 6 sand Two coats: 20mm thick (total)	Fermacell board (10mm thick)	Wall S4.4

Following discussions with a representative of H+H Celcon to agree on the specification details, Wall S4.1 was built in Test Rig A by a demonstrator from this company, who also supplied the materials. The external and internal renders were cement-lime renders to take advantage of lime's properties as a plasticiser. The mortar used for the masonry joints was supplied as a bagged dry mixture of cement, fine sand and polymers. The test wall was built on 4 and 5 May 2006, with the blockwork and first coat of render being built on the first day (given the thinness of the joints in this wall, only two hours are needed before the first coat of render can be applied), and the second coat and plaster finish on the second day.

Photos 10.1 to 10.3 show various stages of construction.

The tests showed very little leakage through the bottom of the wall during the wet phase, which was below measurable limits (see Photo 10.4).

With regard to drying, it can be seen from Figures 10.1 and 10.2 (and Photo 10.5) that both the external and internal faces of the wall dried very effectively, practically reaching their initial moisture values well before the end of the drying phase. At ground level it took about 115 hours and 90 hours, for the external and internal faces, respectively.



S 4.1 External face - Drying

Figure 10.1 Wall S4.1 Thin layer mortar - External face (cement-lime render) - Evolution of drying with time



S 4.1 Internal face - Drying

Figure 10.2 Wall S4.1 Thin layer mortar - Internal face (cement-lime render with plaster finish) - Evolution of drying with time

10.2 Wall S4.2 - Solid masonry wall with external insulation

Wall S4.2 was a solid masonry wall where the insulation is provided on the external face. This type of wall construction is carried out normally by specialist companies, who have developed specific construction techniques and use proprietary materials. Discussions with company Alsecco led to an agreed specification for Wall S4.2. This was built in Test Rig A by a demonstrator from this company, who also supplied most of the materials used for the insulation and for the various layers used on the external and internal wall faces. In this very well detailed system, care is taken to use different insulation materials below and above DPC level (damp proof course) and a proprietary sealing strip is placed at DPC level. Also several layers are applied of adhesive and reinforcement to form the wall rendering system. It was decided that the test wall should be constructed as normally, with no especial provision against flooding.

The test wall was built on 5, 8 and 12 May 2006 and Photos 10.6 to 10.9 show various stages of construction.

Measurable leakage of the order of 25 l/hr was observed through this wall but this ceased after 57 hours (see Figure 10.3). The maximum leakage rate observed was one order of magnitude higher than that measured for other rendered walls and this behaviour may be associated with the sealant at DPC level which was not necessarily designed to withstand 1m head and be fully watertight. Some limited crumbling of the internal proprietary render was also observed (see Photo 10.10).



Figure 10.3 Wall S4.2 Wall with external insulation - Evolution of leakage with time

With regard to drying, it can be seen from Figures 10.4 and 10.5 that the wall did not return to the original moisture levels during the drying phase (except at 1m above ground). This applied both to the external and the internal faces of the wall (please note that moisture readings were not taken at ground level on the external face as this was of different construction to the rest of the wall.

S 4.2 External face - Drying









Figure 10.5 Wall S4.2 Wall with external insulation - Internal face (rendered) – Evolution of drying with time

10.3 Wall S4.3 - Masonry cavity wall with external and internal renders

Wall S4.3 was a cavity masonry wall consisting of two faces built of concrete blocks and rendered using cement render (1 cement : 6 sand). The renders were applied in two coats: first coat 10-15mm thick and second coat about 10mm thick. Rigid PU foam insulation (Kingspan) was placed in the 100mm wide cavity. As for other walls, the DPC was placed above the first course of blocks, using mortar of 1cement : 3sand below and a ratio of 1:6 above DPC. Wall S4.3 was built in one of Test Rigs A by an experienced member of HR Wallingford's Building Team. The test wall was built on 22 and 23 June 2006 and Photos 10.11 and 10.12 show two stages of construction.

Maximum leakage rates of 42 l/hr were measured at the start of the test but these reduced sharply with time and at the end of the second day the leakage was reduced to only about 2 l/hr and later to 1 l/hr (see Figure 10.6). The maximum leakage rate observed was higher than expected, at about three times higher than for Wall ME5 (a brick wall with external render).



Figure 10.6 Wall S4.3 Masonry wall with external and internal renders - Evolution of leakage with time

With regard to drying, it can be seen from Figures 10.7 and 10.8 that the wall returned to the original moisture levels during the drying phase (except at ground level for the external face). This indicates that, in spite of the higher than expected leakage rate, the wall had the ability to dry quite effectively.

S 4.3 External face - Drying



Figure 10.7 Wall S4.3 Masonry wall with external and internal renders - External face (rendered) - Evolution of drying with time

S 4.3 Internal face - Drying



Figure 10.8 Wall S4.3 Masonry wall with external and internal renders – Internal face (rendered) - Evolution of drying with time

10.4 Wall S4.4 – Timber frame wall with splash resistant board

Wall S4.4 was a timber frame wall with a 75mm wide cavity. The external face was built of concrete blocks and rendered using cement render (1 cement : 6 sand). The renders were applied in two coats: first coat 10-15mm thick and second coat about 10mm thick. Rigid PU foam insulation (Kingspan) was placed in the cavity. As for other walls, the DPC was placed above the first course of blocks, using mortar of 1cement : 3sand below and a ratio of 1:6 above DPC. Fermacell board 15mm thick was introduced as a replacement to timber sheathing and Fermacell 10mm thick was used as internal board. In order not to perforate the Fermacell board, no wall ties were used. Wall S4.4 was built in one of Test Rigs A by experienced members of HR Wallingford's Building Team who followed instructions previously given by the Fermacell representative. These instructions related to the fixing of the boards, such as: the use of proprietary screws provided by Fermacell, required fixing spacings and order of fixing starting from the mid level to avoid distortions of the board. The test wall was built on 22 and 23 June 2006 and Photos 10.13 and 10.14 show stages of the construction.

During the wet test it was noticed that the external face of the wall moved towards the cavity and this induced excessive leakage in comparison with what would be expected from a rendered masonry wall. It is thought that this structural problem was the cause of the very high leakage rates (600 l/hr) that were measured at the start of the test and remained very high during the wet test phase (see Figure 10.9). The rendered external wall was expected to provide an effective barrier to the water but having failed, the rest of the timber frame construction had little chance of containing the leakage. It seems therefore that the structural failure must have been linked with the lack of wall ties and these elements might have reduced the leakage considerably. It was also found that the splash proof board on the inside wall warped with the water pressure, developing a wavy profile (see Photo 10.15). The capillary rise on the board was nil.

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Figure 10.9 Wall S4.4 Timber frame wall with splash resistant board - Evolution of leakage with time

With regard to drying, it can be seen from Figure 10.10 that the external face returned to the original moisture levels during the drying phase (except at ground level). This indicates that, in spite of the higher than expected leakage rate, the wall had the ability to dry quite effectively. However, the internal face remained considerably moist (Figure 10.11) in spite of the fact that the water inside the cavity leaked out during the drying phase. It should be noted that these measurements were taken on the splash resistant board which, contrary to other tests with plaster board, was not removed at the end of the wet phase.

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S 4.4 External face - Drying



Figure 10.10 Wall S4.4 Timber frame wall with splash resistant board - External face (rendered) - Evolution of drying with time



Figure 10.11 Wall S4.4 Timber frame wall with splash resistant board - Internal face (rendered) - Evolution of drying with time

11. CONCLUSIONS

11.1 General

In the report produced for Work Package 2 "Review of Existing Information and Experience" (Wingfield et al, 2005) the authors pointed out that there was a striking lack of scientificallybased research on flood resilience of buildings and building materials in the literature. The current work has provided substantial new data and qualitative information which will enable improved decisions on the specification, application and use of building materials and methods for new builds in flood-prone areas.

The programme undertaken covered the testing of thirteen different building materials commonly used in domestic house construction, twelve types of cavity wall (both masonry and timber) and eight different arrangements of ground floors/wall joints. Further tests were carried out on four types of walls that had improved resilience characteristics and/or had potential for growth in the construction market. As extensive as the programme was, it is obvious that many building materials readily available on the market were not studied and therefore any conclusions from the present work programme will necessarily have to take this into account. It should also be noted that further work is required for the development of construction details for resilient buildings.

It was reassuring that the results of the testing programme confirmed the general recommendations contained in the Scottish Planning Advice Note PAN 69 (Scottish Executive, 2004) - with the exception of the last conclusion regarding lime plaster which, as a young material, the present study found not to be a flood resilient material:

- Masonry and concrete are unlikely to be severely damaged by contact with floodwater.
- Renders containing cement are unlikely to suffer damage.
- Wall cavity insulation such as mineral fibre or other absorptive materials will retain water and can lose their insulating properties or disintegrate with time.
- Timber materials can swell and distort when wet.
- [Lime-based plaster is preferable to gypsum which softens when wet.]

For reasons relating to the tight timetable, the testing of walls was carried out on young walls (7 day minimum). However, it should be noted that the behaviour of older walls could be substantially different due to continuing curing mechanisms and wetting/drying/thermal/hydration shrinkage and expansion effects. Evidence of the effects of shrinking and settlement on loss of airtightness in buildings collected by Wingfield et al (2006) indicates that older walls may be more vulnerable to water ingress than new walls if cracking develops at the lower levels of the building.

11.2 The concept of Resilience

In the LPS 2026 standard, developed by BRE (BRE, 2004), qualitative performance requirements are given to achieve different grades of resilience, in descending order from "Flood Proof" to "Flood Resilient" and "Flood Repairable". "Flood resilient" is defined as a medium level of performance where modest amounts of water enter the property and are then drained rapidly. The materials should not be damaged by water and can be decontaminated and dried quickly. Furthermore, materials used in walls and floors should not suffer irreversible degradation and wall linings, insulation and other materials should be easily replaced or repaired (see Wingfield et al, 2005). According to this definition, resilient materials/composites are those which are resistant to water penetration to a certain extent (the concept of totally preventing water ingress by the use of materials alone, i.e. without other measures such as locating the building on raised ground, is considered unrealistic by many, as water is likely to leak through air bricks and door frame joints). In addition to this, resilient materials/composites should be able to dry within fairly short periods of time.

The present work adopted this general definition of resilience, whereby "resilience" is a composite property formed by the ability to minimise water penetration, to dry effectively (i.e. within days or weeks rather than months) and to retain pre-flood dimensions and structural integrity.

The rationale adopted here for classification of materials/composites according to their resilience characteristics assumes that separate measures will be taken to minimise water ingress through any openings in the building (e.g. flood proofing of air bricks, doors and windows). The recommendations resulting from this testing programme were based on flood levels set at 1m above ground level. This is a rather severe load and should provide an upper limit for any further work on flood resilience.

11.3 Recommendations for resilient building materials

The main flood resilience characteristics of the materials tested were summarised in Table 5.1 and discussed in Chapter 6. In the following table (Table 11.1) the materials are classified by their characteristics in terms of good, medium or poor performance with regard to the properties tested. An overall rating for resilience performance is given in the table in an attempt to produce a classification system. It is clear that there are other factors that affect the choice of building materials, namely their insulating properties, ease of handling, availability, aesthetics, cost, etc. and these should also be borne in mind when specifying materials for construction in flood-prone areas. These issues are however outside the scope of this work package/project.

	Resil	stics*					
Material	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	Overall resilience performance			
Bricks	Bricks						
Engineering bricks (Classes A and B)	Good	Good	Good	Good			
Facing bricks (wire cut, sand facing)	Medium	Medium	Good	Medium			
Handmade bricks	Poor	Poor	Poor	Poor			
Blocks							
Concrete (3.5N, 7N)	Poor	Medium	Good	Medium			
Aircrete	Medium	Poor	Good	Medium			
Timber board							
OSB2, 11mm thick	Medium	Poor	Poor	Poor			
OSB3, 18mm thick	Medium	Poor	Poor	Poor			
Gypsum plaster b	oard						
Gypsum Plasterboard, 9mm thick	Poor	Not assessed	Poor	Poor			
Mortars							
Below DPC 1:3(cement:sand)	Good	Good	Good	Good			
Above DPC 1:6(cement:sand)	Good	Good	Good	Good			

Table 11.1 Flood resilience characteristics of building materials

* Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth

11.4 Recommendations for resilient walls and floors

Given that a comprehensive test programme was undertaken to obtain baseline information on the resilience characteristics of various building materials and of various cavity walls, it is useful to determine whether the behaviour of a composite wall can be predicted from an assessment of the behaviour of its components. This becomes more accurate if one uses the maximum leakage rate as the chosen parameter rather than drying times or moisture levels, where the levels of uncertainty are higher. In the table below, Table 11.2, a comparison is made for masonry walls and timber frame walls, all of which had empty cavities so that the effect of the insulation material would not mask the results. It can be seen that the maximum leakage rate through a wall cannot easily be predicted from its components and can, in some cases, exceed the rate associated with the "worst" component. However, there appears to be a good correlation between the use of "good" materials and a low overall leakage rate through the wall. In particular, specifying materials that are rated as "good" for the external face of cavity walls appears to be an important step towards achieving resilience, as this provides the first barrier to the flood.

Building unit	Maximum leakage rate of component (I/hr)	Maximum leakage rate of wall (l/hr)	Observations
Masonry Wall ME1		0.017	The maximum leakage rate through
Eng. Bricks A	0		the wall is intermediate between
Mortar 1:3	<0.001		that of its components, but
Mortar 1:6	0.003		closer to the values associated with the
Concrete blocks 3.5N	55		external wall components
Masonry Wall ME2		0.037	The maximum leakage rate through
Eng. Bricks A	0		the wall is intermediate between
Mortar 1:3	<0.001		that of its components, but
Mortar 1:6	0.003		closer to the values associated with the
Aircrete blocks	2.4		external wall components
Masonry Wall ME3		400	The maximum leakage rate through
Wire cut bricks	0.02		the wall is one order of magnitude bigger

Table 11.2	Effect of components	of maximum	leakage rates	s of walls	tested
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Mortar 1:3	<0.001		than that of "worst" component,
Mortar 1:6	0.003		indicating that the mortar joints had a
Concrete	55		significant effect
blacks 2 5N	00		- 9
DIOCKS 3.5IN			
Masonry Wall ME4		320	The maximum
		020	lookogo roto through
Wire cut	0.02		the wall is one order
bricks			of magnitude bigger
Briefee			then that of "worst"
			than that of worst
 Mortar 1:3 	<0.001		component,
			indicating that the
Mantan 4-0	0.002		mortar joints had a
Inortar 1:6	0.003		montal joints had a
			significant effect
	24		
• Andrete	2.7		
DIOCKS			
Masonry Wall ME5			
			· · · ·
Cement	0.003	1.6	The maximum
render			leakage rate through
			the wall is one order
<i>,</i> , , , , , ,			
(assumed similar			of magnitude bigger
to mortar 1:6)			than that of "worst"
			component
			component,
			indicating that the
			mortar joints had a
			significant effect
			signilioant cheot
 Wire cut 	0.02		
bricks			
2			
	0.001		
 Mortar 1:3 	<0.001		
Mortar 1:6	0.003		
	0.005		
Concrete	55		
blocks 3 5N			
DIOCKS 3.3IN			
Timber frame wall		0.3	The maximum
TF2			leakage rate through
··· -			the well is
 Cement 	0.003		intermediate between
render			that of its
			components
,			components
(assumed similar			

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to mortar 1:6)		
Concrete blocks 3.5N	55	
• OSB 18mm	4.4	

The main flood resilience characteristics of the walls tested and their components were summarised in Chapter 8. In the following table (Table 11.3) various wall components are classified by their characteristics in terms of good, medium or poor performance with regard to the properties tested. An overall rating for resilience performance is given in the table in an attempt to produce a simplified classification system.

	Resil	stics*			
Material	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	Overall resilience performance	
External face					
Engineering bricks (Classes A and B)	Good	Good	Good	Good	
Facing bricks (wire cut, sand facing)	Medium	Medium	Good	Medium	
Internal face			•		
Concrete blocks	Poor	Medium	Good	Medium	
Aircrete	Medium	Poor	Good	Medium	
Cavity insulation	n				
Mineral fibre	Poor	Poor	Poor	Poor	
Blown-in	Poor	Poor	Poor	Poor	
Rigid PU foam	Medium	Medium	Good	Medium	
Renders/Plaste	Renders/Plaster				
Cement render – external	Good	Good	Good	Good	
Cement/lime render – external	Good	Good	Good	Good	

Table 11.3 Flood resilience characteristics of walls

Gypsum Plasterboard	Poor	Not assessed	Poor	Poor
Lime plaster	Poor	Not assessed	Poor	Poor

* Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth

From the types of wall and sample materials tested, the following suggestions can be made to improve the flood resilience of new domestic buildings. These suggestions resulted from an extensive test programme on: 13 typical building materials (two samples of each), 16 walls of composite construction (one test panel for each) and 8 floor arrangements (one test slab for each). Consultation of Sections 7 to 9 of this report and in particular Sections 8.3 and 9.3 is recommended to provide background to the recommendations made. These were developed on the basis of adequacy for flood resilience and are not meant to exclude certain materials from general domestic housing construction in areas where consideration of flood resilience is less relevant.

- Where possible use engineering bricks up to 1m above ground level to increase resistance to water penetration
- Concrete blocks compare well against aircrete blocks in terms of drying; in terms of water penetration aircrete blocks have lower resistance to leakage. These two opposite types of behaviour means that specification of blockwork walls should take into account the design context, namely whether the wall is solid or cavity and includes renders and other finishes.
- <u>External renders</u> are very effective at reducing water penetration and should be used wherever possible for the first metre above ground. However, it should be noted that trying to stop water ingress may induce excessive pressures on masonry walls and structural checks may be necessary to ensure stability. The extent to which render prevents drying of the substrate is not currently clear and may be important to consider particularly for solid wall construction.

Walls lined with cement render (1 cement : 6 sand) were found to have less than 3% of leakage observed through non-rendered walls and drying characteristics remained largely unchanged

Walls lined with lime-cement render (1 cement : ½ lime : 4 sand) were found to allow less than 3% of the leakage observed through non-rendered walls; the drying characteristics were better than for cement render, with 10% less retained moisture

External render can provide a beneficial additional cover to imperfect mortar joints, thus reducing existing preferential paths for water ingress and can also help remedy bad workmanship; this benefit may however decline over time

Suitable construction details concerning the damp proof course (DPC) in conjunction with the use of external renders for flood resilient constructions need to be developed. At present, typical DPC details assume that external render layers are applied only above DPC level thus leaving the most vulnerable part of the wall (its base) unprotected against flood waters.

- Cavity insulation with rigid PU foam offers better flood resilience performance than other insulating materials such as mineral fibre or blown-in expanded mica as it retains integrity and has lower moisture take-up
- Internal cement renders are effective at minimising water ingress into a property and also appear to promote rapid drying of the surface of the wall. The extent to which the render prevents drying of the substrate is not currently clear and may be important to consider, particularly for solid wall construction; this applies also to external renders
- Standard gypsum plaster board should be avoided in flood resilient construction as the internal material disintegrates when immersed in water, only being held by the paper backing; use of sacrificial gypsum plaster boards may however be a suitable option. A splash proof board tested was found not to offer the required protection against flood water as it warped under lateral pressure and did not dry effectively. The use of this material as a replacement to timber sheathing could not be properly evaluated during the test programme due to structural failure of the external face of the wall. It is possible that the behaviour of the splash proof board would have been more positive if the wall had remained stable.
- Internal lime plaster/render should be avoided until further investigation of its long term behaviour can be established since young internal lime plaster was found to crumble very easily under high water pressure
- <u>Concrete slabs</u> with a minimum of 150mm thickness should be specified for ground floors;

Where impermeable polythene membranes are used underneath a concrete floor slab, a minimum 1000 gauge should be used; overlaps of 300mm and taped membranes with overlap of 50mm are adequate for joining membrane sections provided care is taken not to stretch the membrane; at junctions with walls the membrane should be folded (at corners) or gently laid into the blockwork to avoid perforation

Foundation details need to take into consideration that any concrete blocks placed below the level of ground floor slabs provide a preferential path for water to ingress into wall cavities. Use of concrete or another impermeable material to seal the blocks was found to resolve this problem during laboratory investigations but further work on foundation detailing is required.

12. RECOMMENDATIONS FOR FURTHER RESEARCH

The present report is a comprehensive description of the tests carried out under Work Package 5 and it is believed that the scope of the work has been fully covered. The work has provided many answers but inevitably has also prompted more questions that are considered important to complement the knowledge already acquired. A summary of recommendations for future research is given below:

- <u>Assessment of behaviour of lime plaster/render</u>. The limited testing undertaken in this project identified some flaws associated with the use of young lime plaster in flood prone buildings; this contradicts current published guidance which favours lime plaster to the detriment of cement render or gypsum plaster boards (as far as could be ascertained, the current published guidance is unsubstantiated by scientific evidence). Given the limitations of the tests, further investigations on well cured lime renders and plasters should be undertaken. Such testing should explore a range of conditions and identify the critical parameters, for example age, substrate and thickness, which may be relevant to flood resilience.
- <u>Evaluation of modern methods of construction</u>. During Stage 4 of the work programme some modern methods were tested; however, this field is very extensive and methods involving off-site construction are of particular interest due to their increasing popularity as time saving techniques.
- Investigation of the effect of variability of materials and construction quality on flood resilience properties. Variability between batches and manufacturers of building materials can impact on the expected performance and should be assessed to establish confidence limits and determine the robustness of flood resilient designs. Assessment of the impact of construction quality on resilient performance is also recommended.
- <u>Flood resilient materials for existing buildings.</u> The present work focused on new dwellings but a large proportion of constructions in the flood-plain are existing buildings, many of them over a century old. These have specific requirements in terms of architecture, age, materials, aesthetic value that are not necessarily relevant to new build and therefore need to be addressed separately.
- <u>Protection of dwellings against sewer flooding.</u> It was decided that the current research programme would simulate the effect of floods using fresh water, thus reproducing particularly river flooding. Sewer flooding has its own characteristics and would require the study of possible mould/bacteria growth. It is proposed that this should be investigated in the set up described in the item below.
- <u>Assessment of the behaviour of a full (small) house subjected to flood water.</u> Having established the behaviour of individual materials and composites, the next logical step is to reproduce a whole dwelling and investigate the effects of junctions and construction details not covered in the present test programme as well as the human environment created by a flood. This could include the reproduction of heavily silted waters, the study of mould growth in highly humid conditions and the presence of

chemicals with any associated potential health impacts. Furthermore, it could also allow comparison of natural and forced drying and of the various types of forced drying currently in use in the UK as well as of any new systems.

- <u>Protection of dwellings against flash floods.</u> The current research programme investigated typical flood conditions such as those occurring on flood plains. It is well known, however, that houses in many narrow catchments are at risk of flash floods, where the flow velocities can achieve high values and large debris can be carried by the flow and cause severe structural damage by impact on properties in their path. Bow waves generated by large floating solids that are carried by flood waters are also known to cause damage to buildings. Measures to improve the resilience of these houses should be the subject of research.
- <u>Development of construction details for flood resilient construction.</u> The present project identified materials and types of wall and floors suitable for specification in flood-prone areas. There is a need to develop the work further to provide builders, architects and engineers with guidance and drawings giving appropriate construction details. Examples include: specification of DPC materials and construction layout for use in conjunction with external renders or other dry proofing methods; and methods of blocking the path of water through blockwork foundations.

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14. ACKNOWLEDGEMENTS

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Finally, all the comments and views of the PSG members are gratefully acknowledged.

APPENDIX A BUILDING INSPECTOR REPORT

Building Control Head of Service: Adrian Duffleld



Visiening Leathing Leading

Ms M Escarameia Principal Engineer HR Wallingford Howbery Park Crowmarsh Wallingford Oxon OX10 8BA

MANAGING DIRECTOR

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> > Optiref; JP)R05 1274/X9ac

1 March 2006

Dear Ms Escarameia

RE: ODPM RESEARCH ON RESILIENCE OF BUILDINGS

This office has been asked to assist H R Wallingford by monitoring the construction of sample masonry/external wall panels while under construction at HR Wallingford.

Loonfirm that either myself or a colleague from the Building Control team have observed the panels under construction on the following dates:- 11 October 2005, 31 October 2005, 12 December 2005, 23 January 2006 and 27 February 2006.

The relevant panels have been under construction using conventional methods and best practice to satisfy current regulations on each occasion.

I trust this is helpful and adequate for your purposes.

Yours sincerely

NO CAMA

従 Joanna Percy (Miss) Building Control Surveyor

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