Journal of
Flood Risk Management

Effect of long-term exposure and delayed drying time on moisture and mechanical integrity of flooded homes

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DOI: 10.1111/jfr3.12062

Key words
Degradation; disaster recovery; restoration; water.

Abstract

A housing flood unit (FU) and large wall section samples were constructed from conventional building materials and exposed to simulated flooding. Conditions resembling the flooding after Hurricane Katrina in New Orleans, LA, were mimicked, specifically long-term flooding (3 weeks) and standing periods (3 weeks). The effect of natural drying of the FU, followed by forced drying, on the moisture and mechanical integrity of building elements and components was studied. The results were compared with a similar study where the flood and standing times before drying were considerably shorter (3 and 5 days, respectively). The long-term flood exposure and delayed re-entry resulted in severe delamination and blistering of the gypsum board below water level on almost all the walls of the FU. Natural ventilation by opening windows was not effective in reducing the moisture content of the gypsum board. A combination of dehumidification and air conditioning dried the FU and test samples in about 1 week. Short-term (3 days) flood exposure and re-entry 5 days later caused significantly less visual damage to the walls of the FU in comparison with the long-term exposure. Mechanical testing of the interior wall samples yielded similar results for both the long-term and short-term studies. For both studies, the mechanical strength above and below the water line was similar after the prescribed drying period. This type of data is important in order to utilise most effectively the components of a structure affected by flooding, as well as for development of protocols for the restoration of building components.

Introduction

Floods are usually associated with excess moisture, long periods of heat and humidity, and ponding of water in affected structures. These factors will clearly affect the materials used for building construction, e.g. gypsum boards, wood framing, sheathing, siding and flooring systems. However, the extent of this effect has received only limited attention (Leichti *et al.*, 2002; Livengood and Aglan, 2003; Aglan *et al.* 2005; Melencion and Morrell, 2009). The early work performed by the first author and coworkers (Aglan and Livengood, 2003; Aglan *et al.* 2005) prior to Hurricane Katrina was for a short (3 days) flood exposure. Other researchers (Leichti *et al.*, 2002; Melencion and Morrell, 2009) studied individual components in laboratory settings. Additionally, none of these studies have mimicked the flooding situation that occurred when Hurricane Katrina caused severe destruction to many buildings, in New Orleans, LA, in 2005, constructed from conventional building materials such as gypsum boards and wood framing. These harsh conditions involved an extended period of flooding, high ambient temperatures and relative humidity typical of the south of the US in late summer, and contaminated flood water. Flood water contamination can occur from oil spillage or sewage pipes breakage during flooding. This can cause pollution of building components/materials that hinders their restoration. Additionally, there was a lack of ventilation due to power outages.

Some studies have focused on laboratory examinations of the effect of wetting and drying on the properties of individual building materials. Leichti *et al.* (2002) examined the mechanical properties of oriented strand board sheathing exposed to water for 7 days and then air-dried. A moisture metre was used to monitor the drying process. Changes in the embedment strength of the dried samples were noted within the first 48 h of drying. The changes in the shear strengths of the dried samples were not significantly different for the 7-day period of the experiment. Melencion and Morrell (2009) also examined wood building components, specifically the effect on the mechanical properties of wood infested with fungi. They demonstrated that the decrease in mechanical properties of the wood components was related to the type of fungus, as well as the type of wood substrate. Additionally, the damage caused by fungi required long periods of time relative to the time required for moisture damage alone. Aglan and Wendt (2004, 2006a,b) examined the mechanical properties of a range of flood-damaged building materials, including gypsum wallboard products (Fiberock, USG Co., Chicago, IL, USA). The gypsum products had been exposed to floodwater for a period of 3 days.

Conventional gypsum board is a plank of dried gypsum plaster pressed between two thick sheets of paper. Pure gypsum is a dihydrate of calcium sulphate, the most common sulphate mineral put into use today. It is a fine white powder that if moistened and allowed to dry becomes rigid (Olson, 2001). The United States Gypsum Company is the world's largest manufacturer of gypsum panels (USG). The gypsum market has produced an estimated 187 million tons in 2009 and is projected to grow to 264 million tons by 2014 (IntertechPira, 2010).

Mechanical properties of gypsum are relatively well known. Although gypsum sheathing alone is not part of the structure that supports buildings, the shear strength provided by gypsum is considered in building codes (McGowan, 2007). Failure of gypsum sheathing is mostly related to wet gypsum sheathing, one of the most common ways to damage gypsum boards (McGowan, 2007). Gypsum sheathing is an especially permeable material; it has been shown to hold up to 200% of its weight in water. The water held in the gypsum at any given time could weaken components next to the sheathing (e.g. wood or metal framing) (McGowan, 2007). When gypsum boards are exposed to prolonged conditions of humidity and high temperatures, the material undergoes a series of complex chemical and physical changes. Some of the changes that occur when gypsum is exposed to water are the reduction in tensile strength and in shear strength. These changes are attributed to the water's modification of surface tension, lubrication, and chemical changes that take place in the core. Weakening of the adhesion of gypsum and the paper outer layers weakens the composite strength of a conventional gypsum wallboard (Gypsum Association, 2002)

The purpose of the present work is to study the effect of long-term and short-term flooding on the wetting and drying behaviour of flooded homes. The ultimate goal of this work is to provide recommendations on reuse of flooded materials. The effect of flooding on the mechanical integrity of gypsum board exposed to flooding was examined.

Materials and methods

Flood unit

Construction materials included 2 in. × 4 in. (50.8 mm × 101.6 mm) wood southern pine studs, southern pine plywood panels, gypsum board, house wrap, insulation (R-13) and roofing shingles.

Construction

The 12 ft × 12 ft × 8 ft (3.66 m × 3.66 m × 2.44 m) flood unit (FU) was a wood frame house with a concrete-slab foundation (Figure 1). Plywood panels were placed to the outside of the frame and gypsum boards to the inside, with the insulation between these panels. Vinyl siding was used to complete the outside, and the gypsum boards were painted with two coats of a semi-gloss. Vents were placed on the south and north face of the unit. A single window was placed on the north, east and west sides. The door was on the south side. Interior wall section test samples were mounted to the floor of the FU to provide additional replicates of flooded interior walls (Figure 2).

Flood testing

The FU was built in a basin adjacent to an agricultural lake located on the George Washington Carver Experimental Station, Tuskegee University, Tuskegee, Alabama, USA. The lake is adjacent to an area to raise cattle and hence introduces manure contamination of the lake water by run-off. Water from the lake was pumped into the basin using a high-flow rate pump and applied as a curtain of water through a longitudinal slit in a 4 in. (101.6 mm) PVC pipe. The FU was exposed to 2 ft (0.61 m) of water from the floor level for a period of 3 weeks (10 May 2010 to 31 May 2010) (Figure 3). The water level was kept constant using a make-up pump

Figure 1 Flood unit before testing.

Figure 2 Wall section panels (test samples) placed in the flood unit for flood testing.

Figure 3 Flood unit submerged up to 2 ft (0.61 m) of water for 3 weeks during flood testing.

and an overflow pipe. The water was then drained, and the unit was kept closed for another period of 3 weeks (1–21 June 2010). Late May and June weather is typically hot and humid in central Alabama, where the field flood testing was performed. Temperature and relative humidity sensors were installed in the FU under the ceiling. The wiring from these sensors went through the vents on the south walls of the unit to a control room located in proximity to the FU. Handheld moisture sensors (Navigator Pro, Delmhorst Instrument Co., Towaco, NJ, USA) were used to measure the moisture in the sheetrock after re-entry. The FU was opened for visual observations of the interior and to provide ventilation on 21 June 2010.

Moisture removal from the FU was attempted by natural drying starting on 21 June 2010. This involved opening the windows and the door to allow natural movement of the air through the FU. After 2 July, forced drying was applied based on the measurement of the moisture of the gypsum wallboards remaining 100% to that date. This involved the use of a dehumidifier and a portable air-conditioning (AC) unit. The AC was used to control the temperature of the FU.

A previous study (Aglan *et al.* 2005) conducted at the same test facility, under short (3 days) exposure, was reviewed and used for comparison with the current long-term (3 weeks) flood exposure. For the long-term flood exposure study, both natural and forced drying was used, while for the short exposure, only natural drying was used. The drying behaviour of the south walls of both FUs will be compared in the current study.

Test samples

The materials for the supplemental wall section test samples for the flood testing were similar to those for the FU. The house wrap was the Lowe's brand rather than DuPont's Tyvek. Wall section test samples of two sizes were constructed and attached to the concrete slab floor of the FU (Figure 2). These sizes are 4 ft × 4 ft (1.22 m × 1.22 m) and 4 ft by 6 ft (1.22 m × 1.83 m).

Mechanical testing

A Sintech 5D (MTS Systems Co., Eden Prairies, MN, USA) was used for the flexural strength measurements. A four-point bend test specimen having the dimensions 8 in. long, 1 in. wide and 0.5 in. thick (203.2 mm × 25.4 mm × 12.7 mm) was used. The overall span was 6 in. (152.4 mm) and the loading span was 2 in. (50.8 mm). The crosshead speed was 0.05 in. (1.27 mm) per minute.

Results and discussion

Moisture removal from FU

Natural drying of the FU occurred from 21 June 2010 to 2 July 2010. This involved natural movement of the air through the FU by opening the windows and the door. The rationale for not using forced drying immediately after re-entry of the FU was to mimick power outage after flooding. On 2 July, it was decided that forced drying was needed. This was determined from measurement of the moisture content (100%) of all walls and ceiling.

Measurements of the water removed from the FU by forced drying are shown in Figure 4. This represented the amount of water collected daily by the dehumidifier. As can be seen (Figure 4), the moisture removal occurs in two zones; up to about day 15, the collected moisture decreased with time. After that, a plateau was reached. The water collected after day 15 appears to be from the dehumidification

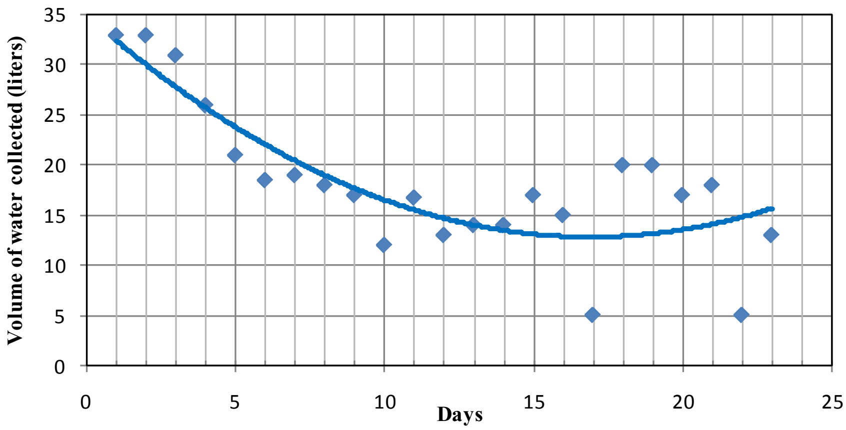

Figure 4 Volume of water removed from the flood unit during dehumidification and air conditioning.

Table 1 Moisture content (%) during drying of flood unit north wall gypsum board exposed to flood water during 2010; natural drying occurred from 21 June until 2 July; dehumidification began on 2 July

Elevation from floor	Days after opening flood unit						
	Natural drying				Forced drying		
	+2 (23 June)	+4 (25 June)	+7 (28 June)	+11 (2 July)	+15 (6 July)	+16 (7 July)	+17 (8 July)
6 in	100	100	100	100	100	72	0
1 ft	100	100	100	100	95	26	0
1 ft 6 in.	100	100	100	100	45	20	0
2 ft	100	100	100	100	42	8	0
2 ft 6 in.	100	100	100	100	31	2	0
3 ft	100	100	100	100	11	0	0
3 ft 6 in.	100	100	100	100	10	0	0
4 ft	100	100	100	100	8	0	0
4 ft 6 in.	100	100	100	100	0	0	0
5 ft	100	100	100	100	0	0	0
5 ft 6 in.	100	100	100	100	0	0	0
6 ft	65	65	68	96	0	0	0

1 in. = 25.4 mm and 1 ft = 0.3048 m.

of the air of the FU as the moisture content of all walls and ceiling reached the preflooding value. Zero moisture content represents as received dry wall; 100% represents full saturation. Some scatter in the volume of water collected at the end of the drying period is observed in Figure 4. This was due to a combination of rain, which artificially increased the amount of water collected and power failure due to storms, which artifically decreased the amount of water collected.

During both the natural and forced drying procedures, the moisture content of the gypsum boards of the interior walls was measured at 6″ (152.4 mm) intervals of the height of the wall. In this paper, only the data for the north and south walls are reported. The north wall represents the slowest drying wall.

The north wall measurements clearly show the effect of natural drying versus forced drying (Table 1). For 11 days of natural drying, all moisture content measurements were 100% up to a height of 5 ft 6 in. (1.68 m) from the floor. This indicates that the walls to this height were fully saturated with water. By the 15th day of drying, representing 4 days of forced drying conditions, only the heights of 6 in. (152.4 mm) and 1 ft (304.8 mm) from the floor still had a 100% and 95% moisture content, repectively. However, they dried precipitously during the fifth and sixth day of forced drying (see Figure 5). All other heights from the floor showed a sharp, linear decrease in moisture content throughout the period of forced drying (Figure 5).

Thus, it can be seen that natural drying is not an effective drying method for long-term flooding. Forced drying should be started as soon as possible after re-entry in order to minimise water damage to building materials.

The south wall measurements show the effect of natural drying versus forced drying (Table 2). For 11 days of natural drying, similar to the north wall, all moisture content meas-

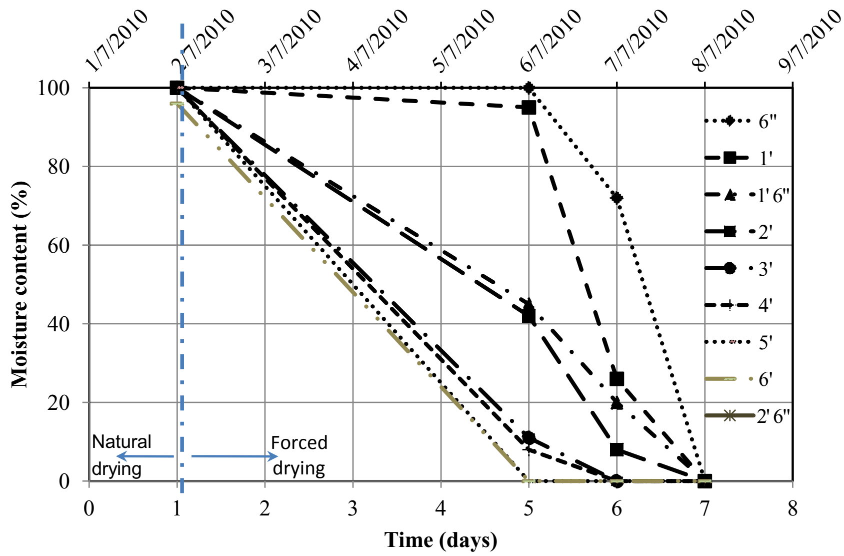

Figure 5 Moisture content in the flood unit north wall gypsum board during natural and forced drying after exposure to flood water (zero moisture content represents as received dry wall; 100% represents full saturation).

Table 2 Moisture content (%) during drying of flood unit south wall gypsum board exposed to flood water during 2010; natural drying occurred from 21 June until 2 July, and dehumidification began on 2 July

Elevation from floor	Days after opening flood unit						
	Natural drying				Forced drying		
	+2 (23 June)	+4 (25 June)	+7 (28 June)	+11 (2 July)	+15 (6 July)	+16 (7 July)	+17 (8 July)
6 in	100	100	100	100	40	0	0
1 ft	100	100	100	100	20	0	0
1 ft 6 in.	100	100	100	100	0	0	0
2 ft	100	100	100	100	0	0	0
2 ft 6 in.	100	100	100	100	0	0	0
3 ft	100	100	100	100	0	0	0
3 ft 6 in.	100	100	100	100	0	0	0
4 ft	100	100	100	100	0	0	0
4 ft 6 in.	100	100	100	100	0	0	0
5 ft	100	100	100	100	0	0	0
5 ft 6 in.	77	75	73	99	0	0	0
6 ft	74	72	62	92	0	0	0

1 in. = 25.4 mm and 1 ft = 0.3048 m.

urements were about 100% up to a height of about 5 ft (1.52 m) from the floor. The natural drying of the south wall was slightly more effective than the natural drying of the north wall. By the 11th day, when natural drying ended and forced drying began, the gypsum board of the south wall was still saturated with water. At 5 ft 6 in., the moisture content of the south wall was 99%. The effect of the forced drying of the FU also varied from the north to the south walls. Except for low levels of moisture content at the 6 in. (152.4 mm) and 1 ft (304.8 mm) levels from the floor, the south wall was dry within 4 days of forced drying (Figure 6 and Table 2). The north wall required nearly 7 days of forced drying to dry completely. The greater sun exposure of the south wall probably contributed to this faster drying rate of the south wall.

Effect of flooding exposure period

The differences between long-term and short-term flooding exposure are quite dramatic. The building materials of the FU were exposed to flood water for 3 weeks in the long-term exposure. In an earlier study (Aglan *et al.*, 2005), a similar FU was exposed to flood water for 3 days in the short-term exposure. In this section, data for short- and long-term exposures of the south walls are compared.

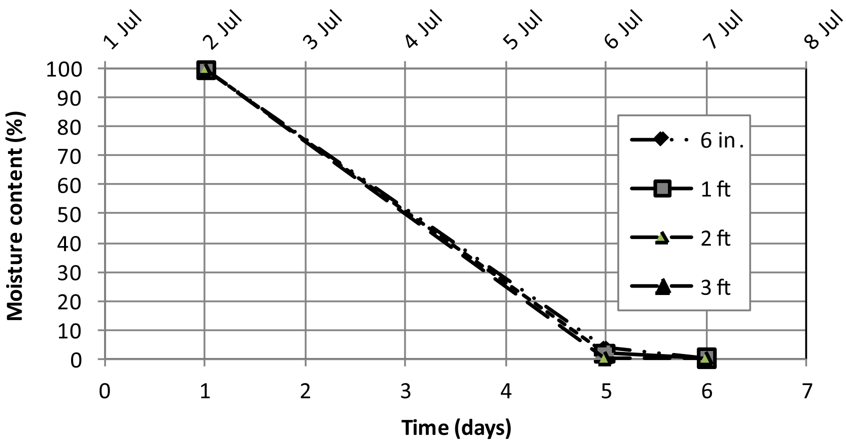

Figure 6 Moisture content in the flood unit south wall gypsum board during natural and forced drying after exposure to flood water (zero moisture content represents as received dry wall; 100% represents full saturation).

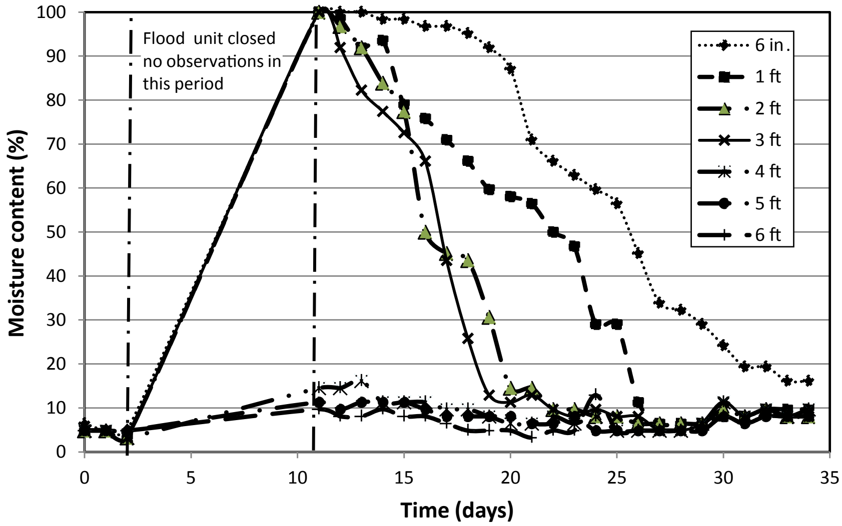

Figure 7 Moisture content versus time for the gypsum board on the south wall of the short-term exposure study. Day 2 is the beginning of flooding, day 5 is the draining of the basin, day 10 is the re-entry into the module and the beginning of observation and measurement and day 33 is the end of the drying period.

In the short-term exposure study (Aglan *et al.*, 2005), the FU was exposed to water for a considerably shorter time (three days) and opened 5 days later. Drying of the short-term study, FU was done entirely naturally (Figure 7). Day 21 of Figure 7 would be comparable with the time when forced drying was begun in the current long-term exposure study, 2 July in Figure 6. Clearly, a significant degree of drying had occurred naturally in the short-term study by that time, in contrast to the observations for the current long-period (3 weeks) flooding study. Moisture contents at the 6 in. (152.4 mm) and 1 ft (304.8 mm) height from the floor of the short-term flooded unit were still high at day 21. It took the bottom of the wall, 6 in. (152.4 mm) from the floor, almost 25 days from re-entry to dry naturally, as shown in Figure 7. This indicates that forced drying is recommended for both short- and long-term flood exposure of buildings. The sooner the forced drying starts, the faster the water is removed from wet walls. This will expedite the restoration and can save some of the building components of flooded homes, allowing faster return of home owners.

The effect of delaying the re-entry time has a major impact on the general appearance of the interior of FUs. This is manifested in severe mould growth and stain on the gypsum board walls of the long-time re-entry delay, 3 weeks versus 5 days. In addition, severe blistering of the paper face of the gypsum board is associated with the long-term delay. This was not the case for the short re-entry delay.

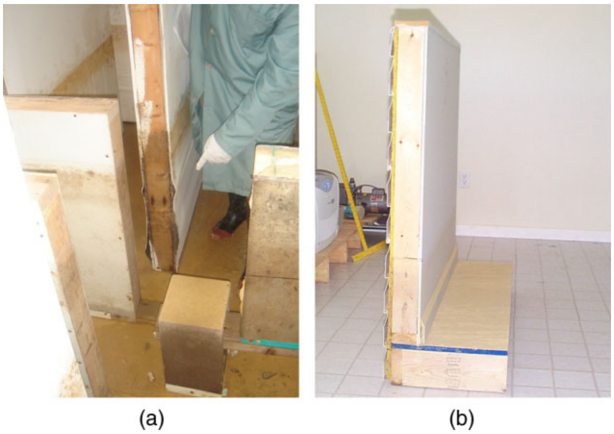

Figure 8 Effect of flooding period exposure on wall section test samples: (a) long-term flooding (3 weeks) and (b) short-term flooding (3 days).

Figure 9 Effect of long-term (3 weeks) flooding on two walls; (a) south and (b) west of the flood unit and (c) one test sample.

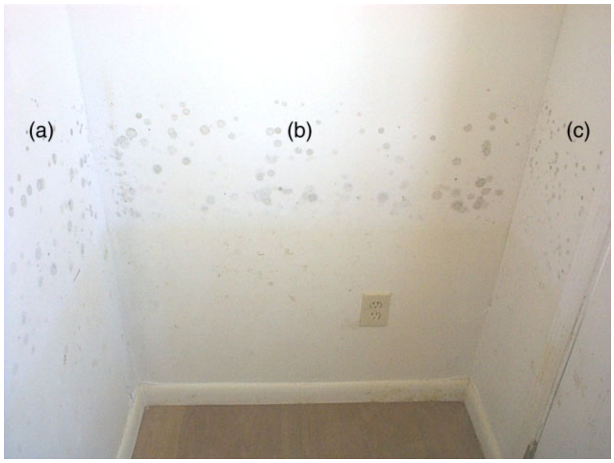

Figure 10 Effect of short-term (3 days) flooding on three walls: (a) south exterior, (b) west exterior and (c) interior wall (Aglan *et al*. 2005).

Integrity analysis of flooded gypsum board walls

The stark difference in the effect of long-term and short-term flooding on gypsum board can be seen in Figures 8–10. The test samples that were replicates of the interior walls (Figure 2) were exposed to long-term flooding (3 weeks), as described in the Materials and methods section. Figure 8(a) illustrates the effect of exposure to long-term flooding on the test samples that were replicas of interior walls (Figure 2). The swelling and peeling of the paper from the gypsum board of these test samples can be seen in Figure 8(a). The integrity of these samples has clearly been diminished, particularly below the water line. It is clear from Figure 8(a) that long-term exposure to moisture has weakened the adhesion of the outer paper face to the gypsum. This, in turn, can weaken the strength of the composite gypsum board. It is not clear from these observations whether the gypsum core has been compromised. This will be addressed in the mechanical properties section below. On the other hand, the wall section sample shown in Figure 8(b) was exposed to 3 days of flood testing (Aglan *et al*. 2005). Figure 8(b) clearly illustrates that the gypsum board was intact. The integrity of the wall section after 3 days of flood exposure had not been compromised.

The gypsum board of the exterior walls of the FU for the long-term flooding study was also examined. Figure 9 shows two of these exterior walls (south and west walls) as well as a test sample (right wall of Figure 9). Significant mould is seen on the walls, especially on the exterior walls of the FU. The swelling of the gypsum board and the delamination of the paper face of the gypsum board can clearly be seen for both exterior walls and the test sample.

Figure 10 is a view for the short-term flooding (3 days) and 5 days of delaying re-entry taken at the same location as in Figure 9 (Aglan *et al*. 2005). Only very isolated portions of paint peeling was observed. Slight staining is visible below the water line. Additionally, mould is visible above the water line. However, no significant damage is seen to the gypsum board in Figure 10 (3 days of flood exposure) that could not be remediated by simple cleaning and repainting. In fact, the FU of this short-term flooding study was remediated and restored to its original condition with minimal effort (Aglan *et al*. 2005). On the other hand, the gypsum wallboard with the long-term flooding exposure FU is not repairable because the face paper of the gypsum composite has been detached.

Mechanical properties of flooded gypsum board

In order to examine more quantitatively the integrity of the gypsum boards from the long-term flooding study

Table 3 Flexural strength of gypsum board walls

Gypsum sample	Maximum stress, MPa			Percent change	
	As received	Below water	Above water	Below water	Above water
Long-term flooding*	1.17	1.07	1.11	–8.5	–5.1
Short-term flooding (Aglan *et al*. 2005)	3.68†	3.56	3.68	–3.3	0.0

*The paper was removed prior to testing these samples.
†The 'as received' values were not available; they were assumed to equal the 'above-water' values for the samples.

(3 weeks), the flexural strengths of the gypsum boards of the FU of the current long-term study were determined. These results were compared with flexural strength data obtained in a previous flood study (Aglan *et al*. 2005). The FU for the earlier study was constructed on a concrete slab in the same basin as that for the current long-term flooding study and in a manner similar to the construction of the long-term flooding study. The gypsum boards used for the interior walls of the earlier study were analogous to the gypsum boards used for the long-term flooding study.

In the short-term study, the FU was exposed to water for a period of 3 days, and then the flood water was drained. The FU was then re-entered after 5 days, and drying was initiated. This is in contrast to the current effort where the FU was exposed to flood water for 3 weeks, drained, and then kept closed for another 3 weeks before re-entry. In all cases, mechanical testing was done on gypsum samples dried to a constant weight. In the case of the short-term flooding sample, the moisture content was constant after about 33 days from flooding. Mechanical test samples were taken at that time. For the long-term flooding study, after the forced drying was complete, the mechanical test samples were stored in a protected area until the mechanical testing was done. The time period for storage was approximately eight months from the time drying was complete.

Because there was significant delamination of the face paper of the gypsum board for the long-term flooding exposure (Figures 8(a) and 9), it was decided to evaluate the flexural strength of the core gypsum below and above the water line (Table 3). This delamination of the paper was not seen for the short-term FU (Figure 10). Table 3 shows the results of the flexural strength of gypsum board walls for both the long- and short-term flooding studies. The core gypsum for the long-term flooding exposure has not been affected significantly. There is a reduction of 8.5% below the water line and 5.1% above the water line with respect to the 'as received' sample.

For the short-term FU, the reduction of the flexural strength of the below-water gypsum composite (gypsum core with paper facing) is only 3.3%. This is not significant. It should also be noticed that the flexural strength of the composite (3.68 MPa) is about three times higher than that of the core gypsum (1.17 MPa). This indicates that the face paper contributes to the strength of the gypsum composite. When this paper is not adhered to the gypsum, the strength of the system is significantly reduced.

For long-term flooding of gypsum board, the damage appears to render the material useless. Previous work (Gypsum Association, 2002) has shown that water damage not only impacts the paper adhered to the gypsum, but also the nature of the gypsum. The results from the long-term and short-term flooding studies, specifically Table 3 and Figures 8–10, are consistent with these considerations.

Conclusions

The effect of long-term flood exposure (3 weeks) and delayed drying time (3 weeks) on moisture and mechanical integrity of a flooded housing unit and wall section test samples was investigated and compared with short-term exposure (3 days flooding and 5 days delayed drying). On this basis, the following conclusions can be drawn.

- Long-term (3 weeks) flood exposure and delayed (3 weeks) re-entry produced high moisture content (100%) in all walls and roof of the FU and all test samples.
- Natural drying by opening windows was not effective in reducing the moisture content of the gypsum board of the FU exposed to 3 weeks of flooding.
- A combination of dehumidification and AC has dried the FU and test samples in about 1 week. On this basis, it is recommended that forced drying using dehumidification and/or AC should be used as soon as possible to minimise the damage to flooded homes.
- The integrity of the composite gypsum wallboard was generally damaged upon long-term (3 weeks) flooding, rendering it not useable. Thus, it may be beneficial in flood-prone zones to orient gypsum board sheets (typically 4 ft × 8 ft (1.22 m × 2.44 m)) horizontally rather than vertically. For flooding height of less than 4 ft (1.22 m) from floor level, only removing the bottom sheets of the gypsum board would be needed for restoration of flooded homes.
- Severe delamination and blistering of the gypsum board occurred below water level on almost all the walls of the FU and test samples exposed to 3 weeks flooding, but the strength of the gypsum cores were not largely affected. The change was less than 10% in comparison with the strength of the as received gypsum board core.

- The integrity of the composite gypsum wallboard was not largely affected by short-term flooding exposure, up to 3 days flooding and 5 days delayed drying. Only cosmetic repairs were needed to restore the FU to its preflooding condition.

Acknowledgements

This work was funded by the Department of Homeland Security-sponsored Southeast Region Research Initiative (SERRI) at the Department of Energy's Oak Ridge National Laboratory (ORNL) and NSF grant # 0825938 through the University of Alabama Birmingham. The guidance and support of Dr Benjamin Thomas of ORNL is greatly appreciated. The laboratory assistance of Jeff Stringer (lab manager), Tuskegee University, is also acknowledged.

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