RESEARCH REPORT

External Research Program

Relationship Between Moisture Content and Mechanical Properties of Gypsum Sheathing

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February 2007 Technical Series 07-100

Relationship Between Moisture Content and Mechanical Properties of Gypsum Sheathing

INTRODUCTION

CMHC sponsored a two-phased research project, the objective of which was to assess the relationship between moisture content (MC) and the mechanical properties of various gypsum-based sheathing products (for example, gypsum panel products intended for use as exterior sheathing on buildings). Specific properties to be examined include:

- water absorption
- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper)
- sheathing's ability to resist fastener pull-through
- flexural strength of the sheathing, for seismic considerations and as an index of overall mechanical integrity.

The first phase of the project involved the wetting of the gypsum products to:

- develop correlations between MC and mechanical properties
- determine maximum acceptable levels for MC of gypsum sheathing as stipulated in the National Building Code for lumber used in construction.

Phase One included also an evaluation of the accuracy of hand-held moisture meters for measuring moisture content of gypsum sheathing and determining the saturation level of moisture content for various types of gypsum sheathing. It contained also a proof-of-concept testing to investigate the performance of gypsum sheathing *in situ* under controlled environmental conditions.

The objective of Phase Two was to determine whether the mechanical properties of gypsum sheathing could be rehabilitated by drying it out once it had been wetted. Gypsum specimens were wetted to various levels of MC, dried and then tested for flexural strength and resistance to fastener pull-through. Results from the "wetted" samples were then compared to "un-wetted" specimens.

There are several reasons why it is important to understand the mechanical properties of gypsum sheathing, and how these properties vary with moisture content.

1. Although gypsum sheathing by itself is not part of the structure that holds up the building, the National Building Code grants credit for gypsum sheathing in providing shear strength. Most cladding systems are attached to the framing components of the building, and do not rely on the strength of the gypsum sheathing to support the cladding. Nevertheless, some exterior insulation finish systems (EIFS) are adhered to the sheathing, and thus, the sheathing can play a role in keeping the cladding on the building for EIFS-clad designs.

2. Many designs rely on the sheathing to support an air-barrier membrane, whether this is a self-adhered membrane (such as, in coastal climates with high exposure to wind-driven rain) or a spun-bonded polyolefin. If the gypsum sheathing loses its structural integrity, the air barrier may not perform as expected—which could lead to significant consequential damage and deterioration of building-envelope performance.

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3. There have been reports of cladding failures where building facades have fallen onto the street below, or onto a ground-floor patio. Some of these failures appear to have been related to wet gypsum sheathing: the sheathing held water in place for an extended period of time, which accelerated the corrosion of the cladding fasteners. The wet sheathing was not strong enough to resist being crushed, so the fasteners were subjected to shear and rotational forces that caused them to fail. A better understanding of the mechanical properties of gypsum sheathing—and how these properties vary with moisture content—would help avoid catastrophic failures.

4. Gypsum can hold a substantial amount of moisture: Phase One of this study determined that a sample of gypsum sheathing could hold up to 200 per cent of its weight in water. This can result in damage to water-sensitive building components adjacent to the sheathing (such as, wood or metal framing).

5. Building scientists who conduct diagnostic investigations of buildings require accurate performance criteria against which to evaluate the condition of existing assemblies. Some practitioners cannot obtain professional liability insurance in cases where mold is involved. In that case, it could be useful to have performance criteria for building materials that are not related to the formation of mold.

For new construction, designers need ways to effectively specify the expected performance of gypsum sheathing. ASTM C1396 provides a method for determining performance levels, but specifiers need to know when the material has become so wetted that it will no longer meet the criteria.

METHODOLOGY

The experimental procedure was conducted as follows.

1. Samples of gypsum sheathing were obtained from local suppliers, representing typical materials available to builders. Specimen types included:

- 12.7 mm (1/2 in.) and 15.9 mm (5/8 in.) exterior-grade gypsum sheathing (XGG)
- 12.7 mm (1/2 in.) and 15.9 mm (5/8 in.) fibre-faced gypsum sheathing (FFG).

In Phase One, standard interior gypsum wallboard was included as a control element. Wallboard was not included in Phase Two, which focused on the potential for gypsum sheathing to be rehabilitated once wetted. To acquire comparable results, samples were obtained from the same manufacturers in both phases of the study.

Figure 1A Testing Apparatus for Fastener Pull-through

2. Specimens were prepared according to the ASTM C473 testing standard. They were initially oven-dried to obtain a baseline dry weight (moisture content is expressed as a percentage of dry weight), and to provide baseline test specimens for comparison with subsequent Phase Two results. The samples were dried at 30°C to avoid dehydrating the gypsum, as it is a hydrated molecule ($CaSO_4 \cdot 2H_2O$). A low-temperature, oven-drying procedure was used to prevent excessive heat from driving off the bonded water molecule, changing the material properties. Each sample was removed from the oven and weighed every three hours: when the weight changed by less than 0.02 per cent, the specimen was considered to have reached steady-state, and the value recorded at that point was taken as the dry weight.

   Water was added to obtain specimens with predetermined moisture-content levels, nominally 1, 2, 4, 8 and 16 per cent. The actual moisture content was measured for each specimen before and after testing.

   Specimens were conditioned to promote uniform distribution of moisture, which involved sealing them in plastic wrap to minimize evaporative losses and turning them over every 24 hours to promote uniform moisture distribution. Specimens were typically conditioned for two weeks, to ensure moisture equilibrium within each one (there is no "standard" protocol for this procedure).

3. Fastener pull-through and flexural testing (shown in Figures 1A and 1B, respectively) was conducted for the oven-dried specimens and the 1 per cent specimens, and on half of the 4, 8 and 16 per cent specimens. The test apparatus is meant to replicate the condition of a fastener head penetrating the facer of the gypsum sheathing.

4. In Phase Two, some of the 4, 8 and 16 per cent specimens were oven-dried. The wetted-and-oven-dried specimens were tested for flexural strength and fastener pull-through. This was done to examine the hypothesis that gypsum sheathing that had become wetted (through exposure to weather, construction moisture, plumbing leaks, etc.) might be rehabilitated by drying it out again.

   The question that Phase Two was designed to answer was: do the mechanical properties regain their original levels (that is to say, as measured on the original oven-dry specimens) once they are re-dried to a nominal oven-dry moisture content?

Figure 1B Testing Apparatus for Flexural Strength

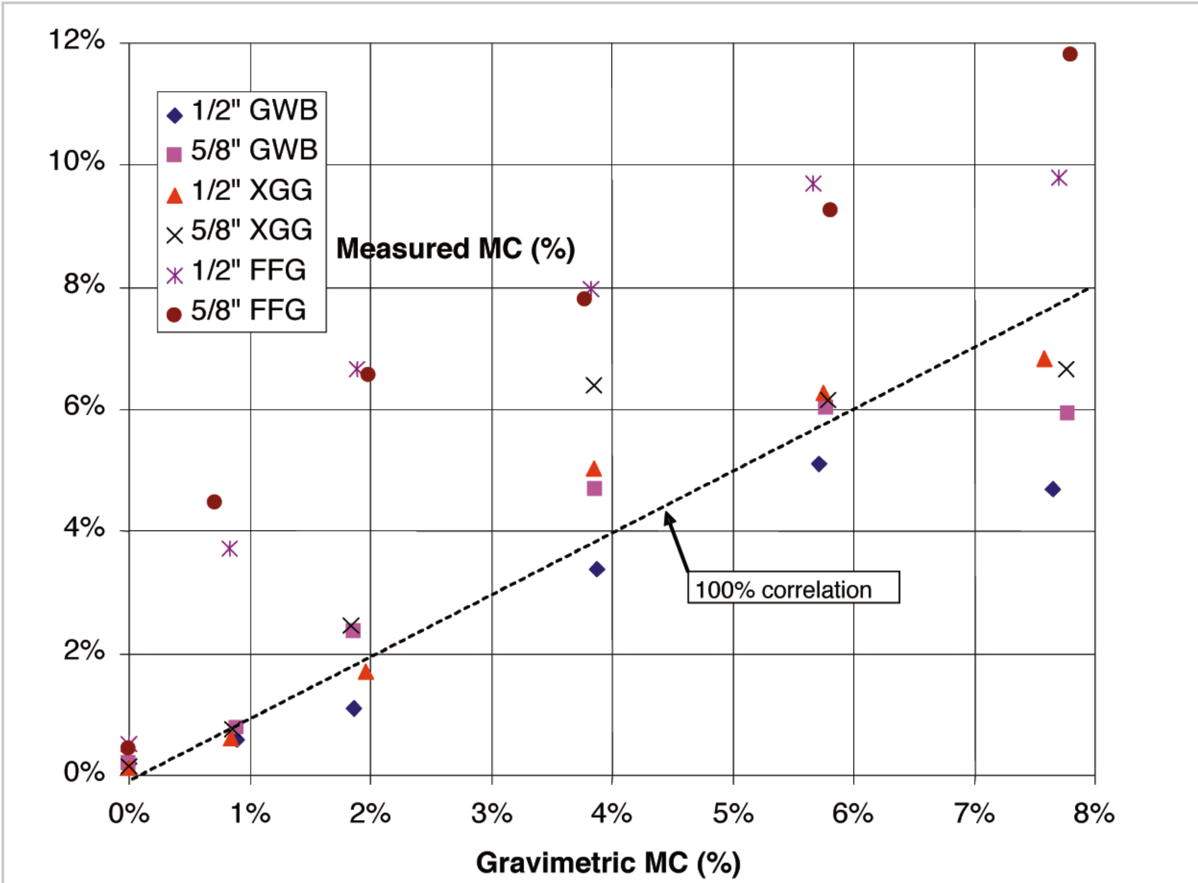

Figure 2 Moisture-meter Accuracy

DATA ANALYSIS

Figure 2, taken from the Phase One study, shows the accuracy of a hand-held moisture meter in assessing the moisture content of gypsum sheathing. Such meters are generally accurate for paper-faced gypsum sheathing up to (about) 6 per cent. Above that level, the moisture meter reads lower than the actual value. The results also show that the moisture meters read approximately 3 to 3.4 per cent higher than the gravimetric values for fibre-faced sheathing, over the range of moisture contents investigated.

NOTE: Samples labeled "GWB" are for interior gypsum wallboard, which was used in Phase One as a control specimen.

In the calibration procedure for these meters, the electrical resistivity of a standard sample of gypsum is measured at 0 and 6.4 per cent moisture content, and a linear relationship is assumed for all readings between those points. Thus, the measured electrical resistivity of a sample is compared to the endpoints using linear interpolation, to determine the assumed moisture content that is displayed on the meter (whether by a needle on a scale or by a digital readout).

The results in Figure 2 indicate that the linear assumption is reasonable between 0 and (about) 6.4 per cent for all specimens. Even for the FFG samples, which tend to read 3 to 3.4 per cent higher than the gravimetric moisture content, the relationship still appears to be linear. Above 6 per cent, however, the linear relationship does not appear to be a correct assumption.

Figure 3 shows the results of fastener pull-through tests from the Phase Two study (refer to Figure 1A for test apparatus). The specimens are characterized as "exterior-grade gypsum" (XGG)—which has a moisture-resistant paper facer on either side of a moisture-resistant treated gypsum core—or "fibre-faced gypsum" (FFG), which has glass-fibre facer material over a treated gypsum core. The numbers in the labels "XGG no. 1" and "XGG no. 2", as shown in Figure 3, refer to specimens that were tested in Phase One or Phase Two of the study (similarly for "FFG no. 1" and "FFG no. 2").

The target levels shown in Figure 3 are defined in the ASTM Standard specifications for these materials: ASTM C1177 defines test-load criteria for exterior gypsum sheathing specimens, as ASTM C1396 does for fibre-faced gypsum sheathing.

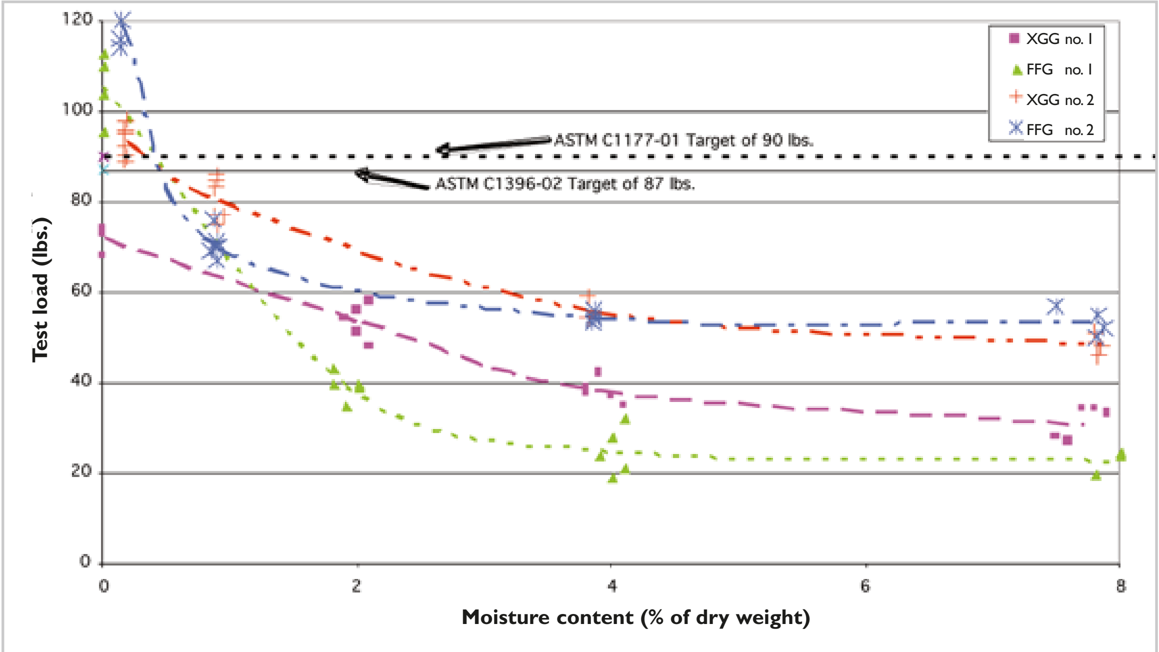

Figure 3 Fastener Pull-through Tests for 15.9 mm (5/8 in.) Gypsum Panel

There is reasonably good agreement between the Phase One and Phase Two data as the trend lines are very similar between the two groups of data. There is also very little disparities within each specimen group. The Phase Two specimens appear to have slightly higher test results than those in Phase One. The data suggests that 15.9 mm (5/8 in.) FFG and XGG specimens would meet the ASTM criteria at approximately the 0.5 per cent M.C.

CONCLUSIONS

Gypsum sheathing products can absorb almost their own weight of water, and all specimens were observed to crumble at much lower moisture contents (5 per cent). This confirms that there is a practical upper limit to the amount of water that can be added to gypsum sheathing before it loses structural integrity, and this limit occurs well below saturation.

Hand-held moisture meters are generally accurate for paper-faced gypsum sheathing up to (about) 6 per cent, but above that level the moisture meter reads lower than the actual value. The results also show that the moisture meters read approximately 3 to 3.4 per cent higher than the gravimetric values for fibre-faced (FFG) sheathing, over the range of moisture contents investigated. The moisture content varies significantly across the GWB specimens, but much less so for the XGG and FFG specimens. The speed of moisture absorption in the specimens may explain this variation, but the nature of moisture redistribution within gypsum was not within the scope of this project.

This study has determined a strong correlation between moisture content and the mechanical properties of various types of gypsum sheathing. ASTM tests for flexural strength and fastener pull-through suggest that the mechanical properties of gypsum sheathing are dramatically reduced when the moisture content is increased from 0 to 2 per cent. The mechanical properties still decrease above 2 per cent moisture content, but not as quickly. Facer delamination tests show similar degradation of performance, but it appears to be reasonable to use the fastener pull-through test to characterize facer adhesion of these products.

Exposure to high-humidity levels in typical construction can result in moisture contents of 8 to 10 per cent in gypsum sheathing. This does not include exposure to liquid water.

Taken together, these test results suggest that, as a general rule, the mechanical properties of gypsum sheathing would not meet the ASTM standards (C1177 for exterior-grade gypsum, C1396 for fibre-faced gypsum) at moisture-content levels above 1 per cent. However, whether the ASTM Standards are appropriate indicators of in-service performance (this is noted in the Standards), is questionable, as some specimens tested did not meet the criteria even when oven-dried.

When these specimens were wetted and re-dried, the resistance to flexural loading of the fibre-faced gypsum sheathing essentially recovered their original values. Exterior-grade gypsum sheathing recovered about 94 per cent of their original values, except where the facer-to-gypsum adhesion was lost (in that case, the resistance to flexural load was tested to be 66 per cent of the original value). The resistance to fastener penetration of all sheathing tested did not appear to be affected by wetting, once the specimens dried out.

It is interesting to note that the 5/8 in. exterior-grade sheathing never dried out, and only reached 1 per cent moisture content even after several days of drying in the oven. In general, the fibre-faced specimens appeared to take less time to take on water to the nominal target values and less time to dry out. Mold developed on all of the paper-faced samples, but not on the fibre-faced samples.

Housing Industry Implications

The following recommendations can be derived from the above conclusions.

- Hand-held moisture meters are appropriate for measuring the moisture content of paper-faced gypsum sheathing, within the normal range of performance for these products. These meters tend to read high values for fibre-faced gypsum sheathing.
- In general, gypsum sheathing intended for exterior use should not be exposed to sources of moisture that will result in moisture-content levels above 1 per cent (as a percentage of dry weight).
- Gypsum sheathing that experiences moisture levels above 1 per cent can be rehabilitated to some extent, if the gypsum is carefully dried in such a way that the bond between the facer and the gypsum core is not disturbed.
- The relevant ASTM Standards should be reviewed to ensure that the criteria are at appropriate levels for in-service performance.

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External Research Program: Relationship Between Moisture Content and Mechanical Properties of Gypsum Sheathing

Research Report: Relationship Between Moisture Content and Mechanical Properties of Gypsum Sheathing – Phase Two

Research Consultants: Levelton Engineering Limited

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Printed in Canada
Produced by CMHC 05-03-2007

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Février 2007 Série technique 07-100

Relation entre la teneur en eau et les propriétés mécaniques des revêtements muraux intermédiaires en plaques de plâtre

INTRODUCTION

La SCHL a commandé un projet de recherche devant être mené en deux phases, lequel avait pour objet d'examiner la relation entre la teneur en eau et les propriétés mécaniques de différents produits en plaques de plâtre servant de revêtement mural intermédiaire (par ex., les revêtements en plaques de plâtre à poser du côté extérieur des murs extérieurs des bâtiments). Au chapitre des propriétés particulières que l'on a examinées figurent :

- l'hygroscopicité
- l'adhésion ou la délamination du matériau de revêtement (treillis de fibre de verre, papier traité ou non traité)
- la capacité du revêtement intermédiaire à résister à la pénétration des fixations
- résistance en flexion du revêtement intermédiaire, pour les besoins parasismiques de même qu'à titre de mesure de l'intégrité mécanique.

Au cours de la première phase des recherches, on a mouillé les produits en plaque de plâtre afin :

- d'établir une corrélation entre la teneur en eau et les propriétés mécaniques
- de déterminer les taux maximaux de teneur en eau des revêtements intermédiaires, comme c'est le cas dans le Code national du bâtiment pour le bois utilisé en construction.

La phase 1 comprenait également une évaluation de la précision des humidimètres portatifs servant à mesurer la teneur en eau des revêtements intermédiaires en plaques de plâtre et la détermination de la teneur en eau à saturation des différents types de revêtements intermédiaires. Elle comprenait également des essais de validation visant à examiner la performance du revêtement intermédiaire en plaques de plâtre à pied d'oeuvre sous des conditions ambiantes régulées.

La phase 2 des travaux avait pour objectif de déterminer si les propriétés mécaniques des plaques de plâtres pouvaient être rétablies par assèchement. Les échantillons de plaques de plâtre ont été mouillés selon différentes teneurs en eau, asséchés, puis mis à l'essai pour en déterminer la résistance en flexion ou la résistance à la pénétration des fixations. Les résultats obtenus avec les échantillons « mouillés » ont ensuite été comparés à ceux des échantillons « non mouillés ».

Plusieurs raisons militent en faveur d'une meilleure compréhension des propriétés mécaniques des revêtements intermédiaires en plaques de plâtre, et à savoir dans quelle mesure ces propriétés varient avec la teneur en eau.

1. Bien que le revêtement intermédiaire en plaques de plâtre en soi ne fasse pas partie de la charpente du bâtiment à proprement parler, le Code national du bâtiment lui attribue des propriétés de résistance en cisaillement. La plupart des parements sont fixés aux composants structuraux du bâtiment, et ne tablent pas sur la résistance des plaques de plâtre pour soutenir le parement. Néanmoins, certains systèmes d'isolation des façades avec enduit (SIFE) adhèrent au revêtement mural intermédiaire, et ainsi, ce dernier peut jouer un rôle de maintien en place du parement dans le cas des bâtiments revêtus d'un SIFE.
2. Nombre de concepts comptent sur le revêtement intermédiaire pour soutenir une membrane pare-air, qu'elle soit autocollante (comme dans les régions climatiques littorales exposées à la pluie poussée par le vent) ou en polyoléfine filée-liée. Si le revêtement intermédiaire en plaques de plâtre perd son intégrité structurale, le pare-air ne se comportera comme prévu, ce qui pourrait engendrer d'importants dommages conséquents et une détérioration de la performance de l'enveloppe du bâtiment.

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3. On a rapporté des cas de défaillances de parement où les façades du bâtiment sont tombées dans la rue, ou sur une terrasse au rez-de-chaussée. Certaines de ces défaillances semblent être liées à des plaques de plâtre mouillées : le revêtement intermédiaire a retenu l'eau pendant une longue période, ce qui a accéléré la corrosion des fixations du parement. Le revêtement intermédiaire mouillé n'était pas suffisamment robuste pour résister à l'écrasement, ce qui fait que les fixations ont été soumises à des contraintes en cisaillement et des forces de rotation qui ont causé leur défaillance. Une meilleure compréhension des propriétés mécaniques du revêtement intermédiaire en plaques de plâtre, à savoir dans quelle mesure ces propriétés varient avec la teneur en eau, aiderait à prévenir des défaillances catastrophiques.

4. Une plaque de plâtre peut stocker une quantité considérable d'eau. La phase 1 de la présente étude a révélé qu'un échantillon de revêtement intermédiaire en plaques de plâtre, pouvait renfermer jusqu'à 200 % de son poids en eau. Cette situation peut provoquer des dommages aux composants sensibles à l'eau qui sont adjacents au revêtement intermédiaire (comme une ossature en bois ou en métal).

5. Les spécialistes en science du bâtiment qui mènent des investigations diagnostiques de bâtiments ont besoin de critères de performance précis contre lesquels évaluer l'état des assemblages existants. Certains praticiens ne réussissent pas à obtenir une assurance-responsabilité civile professionnelle s'il est question de moisissures. Dans de tels cas, il pourrait être utile de formuler des critères de performance visant les matériaux de construction, qui ne sont pas liés à la formation de moisissures.

Pour la construction nouvelle, les concepteurs requièrent des façons de spécifier efficacement la performance attendue d'un revêtement intermédiaire en plaques de plâtre. La norme ASTM C1396 fournit une méthode de déterminer les niveaux de performance, mais les concepteurs ont besoin de savoir quand le matériau est devenu si mouillé qu'il ne satisfait plus aux critères.

MÉTHODE

Les essais ont été menés comme suit :

1. Des échantillons de revêtement intermédiaire en plaques de plâtre ont été obtenus de fournisseurs locaux, ce qui représente les matériaux habituellement offerts dans le commerce aux constructeurs. Voici les types d'échantillons obtenus :

- Revêtement intermédiaire en plaques de plâtre de type extérieur de 12,7 mm (1/2 po) et de 15,9 mm (5/8 po) d'épaisseur (XGG)
- Revêtement intermédiaire en plaques de plâtre à peau en fibre, de 12,7 mm (1/2 po) et de 15,9 mm (5/8 po) d'épaisseur (FFG).

Figure 1A Appareillage d'essai de pénétration des fixations

Au cours de la phase 1, des plaques de plâtre courantes pour l'intérieur ont servi d'élément témoin. Les plaques de plâtre n'étaient pas comprises dans la phase 2, laquelle était axée sur la possibilité de rétablir les caractéristiques du revêtement intermédiaire en plaques de plâtre, une fois celles-ci mouillées. Afin d'atteindre des résultats comparables, on a obtenu les échantillons des mêmes fabricants pour les deux phases de l'étude.

2. Les échantillons ont été préparés suivant la norme C473 de l'ASTM. Ils ont été initialement séchés au four afin d'obtenir leur poids sec normalisé (la teneur en eau est exprimée en fonction du poids sec), et de fournir des échantillons d'essai normalisés aux fins de comparaison avec la phase 2 subséquente. Les échantillons ont été asséchés à une température de 30 °C afin de prévenir la déshydratation du gypse, car il s'agit d'une molécule hydratée ($CaSO_4 \cdot 2H_2O$). Les chercheurs ont utilisé un processus de séchage au four à basse température afin d'empêcher que la chaleur excessive ne détache la molécule d'eau hydratée, ce qui aurait modifié les propriétés des échantillons. Chaque échantillon a été retiré du four et pesé toutes les trois heures : lorsque le poids changeait de moins 0,02 %, l'échantillon était considéré comme ayant atteint un état stationnaire, et la valeur enregistrée à ce moment était considéré comme poids sec.

   De l'eau a été ajoutée de manière à obtenir des échantillons présentant des teneurs en eau nominales prédéterminées de 1, 2, 4, 8 et 16 %. La teneur en eau réelle de chaque échantillon a été mesurée avant et après les essais.

   On a conditionné les échantillons de manière à promouvoir la distribution uniforme de l'eau. Pour ce faire, on les a enrobés d'une feuille de plastique afin de réduire l'évaporation au minimum, et on les a retournés toutes les 24 heures. Les échantillons ont été conditionnés pendant deux semaines, afin d'atteindre le point d'équilibre hygroscopique dans chacun (ce processus n'est pas normalisé).

3. Les essais de pénétration des fixations et les essais en flexion (montrés dans les figures 1A et 1B, respectivement) ont été menés sur les échantillons séchés au four et sur ceux à 1 % de teneur en eau, et sur la moitié des échantillons à 4, 8 et 16 % de teneur en eau. L'appareillage d'essai est censé reproduire les conditions qui mènent à la pénétration de la peau extérieure du revêtement intermédiaire en plaques de plâtre.

4. Au cours de la phase 2, certains échantillons mouillés à des teneurs en eau de 4, 8 et 16 % ont été asséchés au four, puis mis à l'essai pour déterminer leur résistance en flexion et leurs caractéristiques de pénétration des fixations. On a procédé ainsi afin de vérifier l'hypothèse selon laquelle les propriétés mécaniques d'un revêtement intermédiaire en plaques de plâtre qui a été mouillé (en raison de l'exposition aux intempéries, à l'humidité de construction, à des fuites de plomberie, etc.) puissent être rétablies en l'asséchant.

Figure 1B Appareillage d'essai de la résistance en flexion

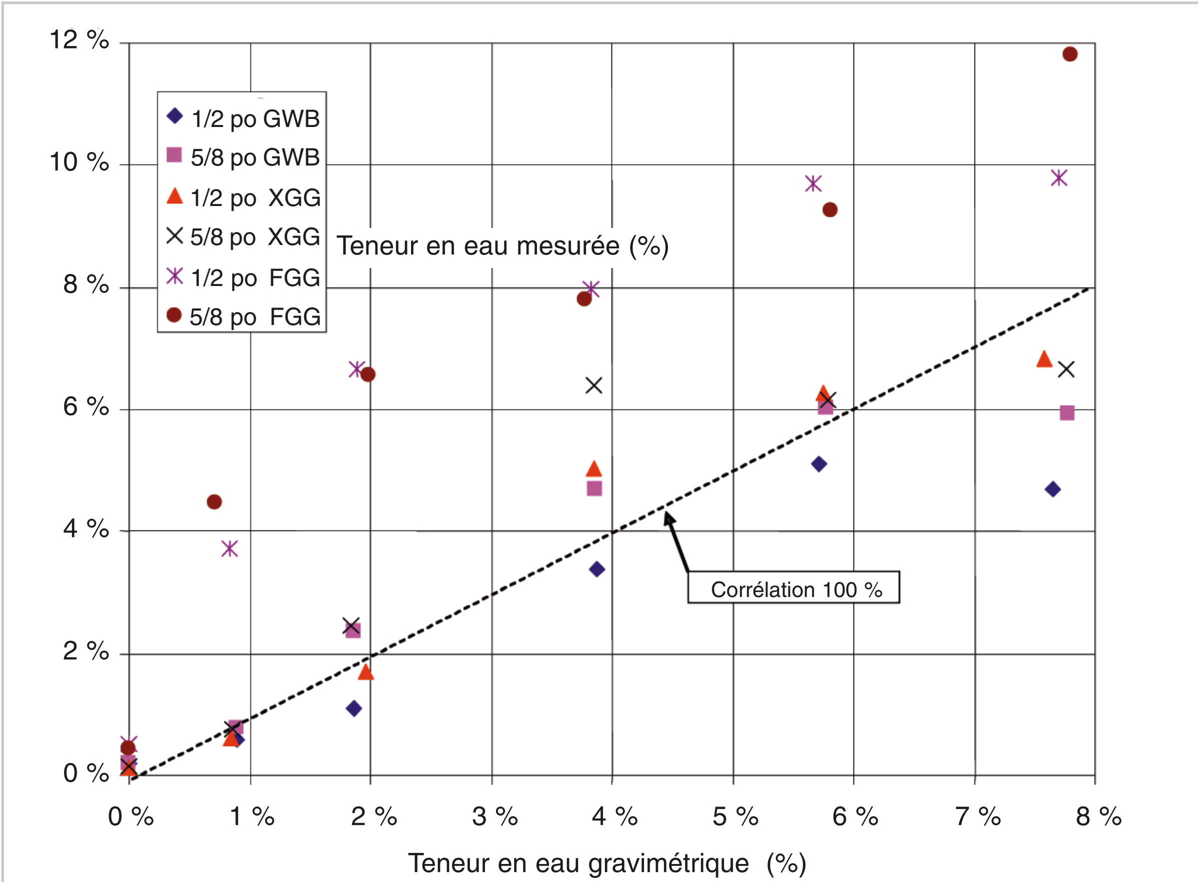

Figure 2 Précision des humidimètres

La phase 2 de l'étude a été conçue pour répondre à la question suivante : les propriétés mécaniques du revêtement intermédiaire reviennent-elles à leur ancien niveau (autrement dit, à celles mesurées sur les échantillons témoins séchés au four) une fois que l'échantillon a été ramené à la teneur en eau nominale « séchée au four »?

ANALYSE DES DONNÉES

La figure 2, tirée de la phase 1 de l'étude, montre la précision des humidimètres manuels quant à l'évaluation de la teneur en eau des revêtements intermédiaires en plaques de plâtre. En règle générale, ces humidimètres sont précis jusqu'à une teneur en eau d'environ 6 % dans le cas des revêtements intermédiaires en plaques de plâtre. Au-dessus de ce taux, les valeurs de teneurs en eau obtenues sont inférieures aux valeurs réelles. Les résultats révèlent également que les humidimètres donnent des valeurs qui sont de 3 à 3,4 % plus élevées que les valeurs gravimétriques pour les revêtements intermédiaires à peau en fibre, dans la gamme des teneurs en eau étudiées.

NOTA : Les échantillons étiquetés « GWB » s'entendent des plaques de plâtre d'intérieur, lesquelles ont été utilisées dans la phase 1 comme échantillon témoin.

En ce qui a trait au processus d'étalonnage des humidimètres, la résistivité électrique d'un échantillon normalisé de plaque de plâtre est mesurée à des teneurs en eau de 0 et de 6,4 %, et on suppose une relation linéaire pour toutes les mesures entre ces points. Ainsi, la résistivité électrique mesurée d'un échantillon est comparée aux mesures d'extrémité par interpolation linéaire, afin de déterminer la teneur en eau présumée qui est affichée sur l'humidimètre (qu'il s'agisse d'une aiguille ou d'une lecture numérique).

Les résultats montrés dans la figure 2 indiquent que l'hypothèse de relation linéaire est raisonnable de 0 % à (environ) 6,4 % pour tous les spécimens. Même dans le cas de spécimens FFG, qui ont tendance à donner des lectures qui sont de 3 à 3,4 % plus élevées que la teneur en eau gravimétrique, la relation semble néanmoins linéaire. Au-dessus du seuil de 6 %, toutefois, l'hypothèse d'une relation linéaire ne semble plus tenir la route.

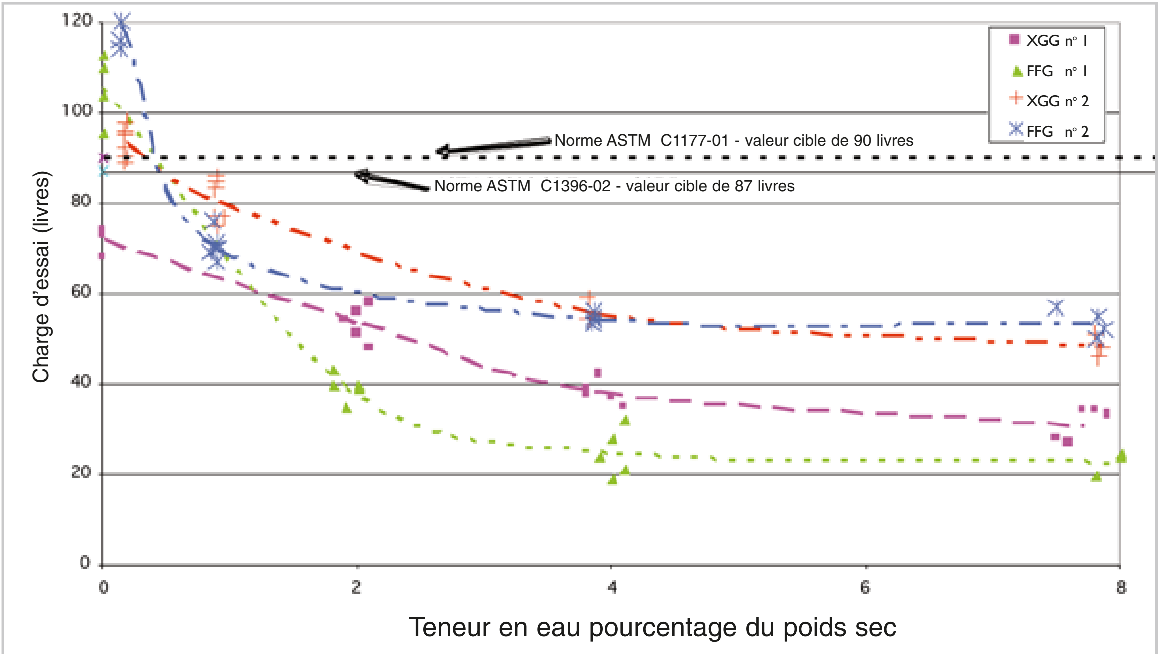

Figure 3 Essai de pénétration des fixations – plaques de plâtre de 15,9 mm (5/8 po)

La figure 3 présente les résultats des essais de pénétration des fixations menés dans l'étude de phase 2 (voir la figure 1A pour l'appareillage d'essai). Les échantillons portent la mention « plaques de plâtre pour usage extérieur (XGG), lesquelles sont revêtues d'une peau en papier résistant à l'humidité sur chacune des parois d'une âme en plâtre résistant à l'humidité, ou la mention « plaque de plâtre à peau en fibre » (FFG), lesquelles consistent en une peau en fibre posée de part et d'autre d'une âme en plâtre traité. Les chiffres qui se trouvent sur les étiquettes « XGG n° 1 » et « XGG n° 2 », comme montrée à la figure 3, renvoient aux échantillons qui ont été mis à l'essai dans la phase 1 ou 2 de l'étude (il en est de même pour les échantillons « FFG n° 1 » et « FFG n° 2 »).

Les valeurs cibles montrées dans la figure 3 sont définies dans la norme de l'ASTM à l'égard de ces matériaux : la norme C1177 énonce les critères de surcharge sur les échantillons de revêtement intermédiaire en plaques de plâtre pour usage extérieur, et il en est de même pour la norme C1396, en ce qui a trait au revêtement intermédiaire en plaques de plâtre à peau de fibre.

Les données tirées des phases 1 et 2 concordent assez bien, comme on peut le constater selon les courbes de tendance des deux groupes de données qui sont très semblables. Il y a également très peu de divergence entre chaque groupe d'échantillons. Les échantillons de la phase 2 semblent présenter des résultats d'essais légèrement supérieurs à ceux de la phase 1. Les données laissent entendre que les échantillons de 15,9 mm (5/8 po) d'épaisseur de type FFG et XGG répondraient aux critères de l'ASTM à une teneur en eau d'environ de 0,5 %.

CONCLUSIONS

Les revêtements intermédiaires en plaques de plâtre peuvent absorber presque leur propre poids en eau, et on a constaté que tous les échantillons se désagrègent à une valeur beaucoup plus faible de teneur en eau (5 %). Les résultats confirment qu'il existe une limite supérieure pratique à la quantité d'eau pouvant être absorbée par un revêtement intermédiaire en plaques de plâtre avant qu'il ne perde son intégrité structurale, et cette limite est atteinte bien avant saturation.

En règle générale, les humidimètres manuels sont suffisamment précis dans le cas des revêtements intermédiaires en plaques de plâtre à peau en papier jusqu'à une teneur en eau d'environ 6 %, mais au-dessus de ce seuil, l'humidimètre donne une lecture inférieure à la valeur réelle. Les résultats indiquent également que les humidimètres donnent une lecture qui est de 3 à 3,4 % plus élevée que les valeurs gravimétriques dans le cas des plaques à peau en fibre (FFG), dans la plage des teneurs en eau étudiées. La teneur en eau varie considérablement dans le cas des échantillons GWB, mais beaucoup moins lorsqu'il s'agit des échantillons de type XGG et FFG. La vitesse d'absorption de l'eau dans les échantillons peut expliquer cette variation, bien que la nature de la redistribution de l'eau dans le plâtre n'ait pas été comprise dans la portée de cette recherche.

L'étude révèle qu'il existe une forte corrélation entre la teneur en eau et les propriétés mécaniques de différents types de revêtement intermédiaire en plaques de plâtre. Les essais de résistance en flexion et en pénétration des fixations selon les normes de l'ASTM laissent supposer que les propriétés des revêtements intermédiaires en plaques de plâtre sont considérablement affaiblies lorsque la teneur passe de 0 à 2 %. Les propriétés mécaniques continuent de diminuer au-delà d'une teneur en eau de 2 %, mais à une vitesse moindre. Les essais de délamination de la peau révèlent qu'il se produit une semblable dégradation de performance, mais il semble raisonnable de faire appel à l'essai de pénétration des fixations pour caractériser l'adhésion de la peau sur ces produits.

L'exposition à des niveaux élevés d'humidité dans les constructions courantes engendre des teneurs en eau de l'ordre de 8 à 10 % dans les revêtements intermédiaires en plaques de plâtre, sans compter l'exposition directe à l'eau libre.

Ces résultats, mis ensemble, suggèrent qu'en règle générale, les propriétés mécaniques des revêtements intermédiaires en plaques de plâtre ne répondraient pas aux normes de l'ASTM (C1177 pour les plaques de plâtre pour usage extérieur, et C1396 pour les plaques de plâtre à peau en fibre) à des teneurs en eau supérieures à 1 %. Toutefois, on peut mettre en doute le fait que les normes de l'ASTM soient des indicateurs convenables de la performance en service (on trouve la même mention dans les normes en question), puisque certains échantillons mis à l'essai ne répondaient pas aux critères, même après avoir été séchés au four.

Lorsque ces échantillons ont été mouillés puis séchés, ceux qui étaient composés de plaques de plâtre à peau en fibre ont recouvré leur résistance en flexion initiale. Les plaques de plâtre pour usage extérieur ont recouvré environ 94 % de leurs caractéristiques mécaniques initiales, sauf dans le cas où l'adhésion de la peau en papier a été perdue (dans ce cas, la résistance en flexion a reculé à 66 % de sa valeur initiale). La résistance à la pénétration des fixations de tous les revêtements intermédiaires mis à l'essai n'a pas semblé être touchée par le mouillage une fois les échantillons séchés.

Fait intéressant, les revêtements intermédiaires en plaques de plâtre pour usage extérieur de 15,9 mm (5/8 po) ne se sont jamais asséchés complètement, et n'ont atteint qu'une teneur en eau de 1 %, même après plusieurs jours de séchage au four. En règle générale, les échantillons à peau en fibre semblent avoir pris moins de temps pour absorber l'eau jusqu'aux valeurs cibles et moins de temps pour s'assécher. Des moisissures se sont formées sur tous les échantillons recouverts de papier, mais non sur les échantillons à peau en fibre.

Conséquences pour le secteur de l'habitation

Les recommandations suivantes peuvent être formulées à partir des conclusions ci-dessus.

- Les humidimètres manuels conviennent pour mesurer la teneur en eau de revêtements intermédiaires en plaques de plâtre à peau en papier, dans la plage de performance normale de ces produits. Ces humidimètres se montrent enclins à donner des lectures élevées lorsqu'il s'agit de revêtements intermédiaires en plaques de plâtre à peau en fibre.
- En règle générale, les revêtements intermédiaires en plaques de plâtre que l'on se propose d'employer à l'extérieur, ne devraient pas être exposés à des sources d'humidité qui engendreraient une teneur en eau supérieure à 1 % dans le matériau (en pourcentage du poids sec).
- Les revêtements intermédiaires en plaques de plâtre qui affichent une teneur en eau qui excède 1 % peuvent être remis en état, dans une certaine mesure, si les plaques plâtre sont soigneusement asséchées en prenant soin de ne pas rompre le joint entre la peau extérieure et l'âme en plâtre.
- Les normes de l'ASTM pertinentes devraient être passées en revue afin de veiller à ce que les critères soient établis à des niveaux en fonction de la performance exigée à pied d'œuvre.

Directeur de projet : Silvio Plescia

Programme de subventions de recherche :
Relation entre la teneur en eau et les propriétés mécaniques des revêtements muraux en plaques de plâtre

Rapport : Relation entre la teneur en eau et les propriétés mécaniques des revêtements muraux en plaques de plâtre – phase deux

Consultants : Levelton Engineering Limited

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Imprimé au Canada
Réalisation : SCHL 05-03-07

65345

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FINAL REPORT
RELATIONSHIP BETWEEN MOISTURE CONTENT AND MECHANICAL PROPERTIES OF GYPSUM SHEATHING

Prepared for:

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January 31, 2005

File: 503-028B

This project was carried out with the assistance of Canada Mortgage and Housing Corporation (CMHC) under the terms of the External Research Program (CMHC file 6585-M178). The views expressed are the personal views of the authors and do not represent the official views of CMHC.

EXECUTIVE SUMMARY

Canada Mortgage and Housing Corporation (CMHC) retained Levelton Engineering Ltd. to investigate the performance of gypsum sheathing at various levels of moisture content, under the CMHC External Research Program.

The stated objective of this project is to examine the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum wallboard intended for use as exterior sheathing on buildings). Specific properties to be examined included:

- water absorption;
- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper, depending on the sheathing type);
- ability of the sheathing to resist fastener pull-through; and
- flexural strength of the sheathing, for seismic considerations and as a common index of overall mechanical integrity

Products tested include glass-fibre-faced sheathing (FFG); paper-faced gypsum sheathing (XGG); and standard interior drywall (GWB), which was used as a control sample.

The project was separated into distinct phases: Tasks 1 (identification saturation levels of moisture content) and 2 (evaluation of the accuracy of handheld moisture meters) addressed how moisture content is measured in gypsum sheathing products.

Task 3 (test mechanical properties of gypsum sheathing at various moisture-content levels) evaluated fastener pull-out, flexural strength and facer delamination for various types of gypsum sheathing at several different moisture-content levels. The resultant mechanical properties were compared with existing criteria defined in the relevant ASTM Standards.

Task 4 (testing of wall assemblies in a humid environment) was conducted at the test facility at Concordia University, to identify typical expected levels of moisture content in service.

The following conclusions are summarized in this report:

Moisture content expressed as a percentage of saturation is not a useful index of performance, as gypsum sheathing products can absorb almost their own weight of water, and the material was observed to crumble at a much lower moisture content

Handheld moisture meters are generally accurate for paper-faced gypsum sheathing up to approximately 6%, but above that level the moisture meter reads lower than the actual value. The moisture meters read higher than the gravimetric values for fibre-faced sheathing, over the range of moisture contents investigated. Moisture content varies significantly across the GWB specimens, but much less so for the XGG and FFG specimens. The speed of moisture absorption in the specimens may explain this variation, but this should be investigated further as the nature of moisture redistribution within gypsum was not within the scope of this project.

This study has determined that a strong correlation exists between moisture content and the mechanical properties of various types of gypsum sheathing. ASTM tests for flexural strength and fastener pull-through suggest that the mechanical properties of gypsum sheathing a dramatically reduced when the moisture content is increased from 0% to 2%. The mechanical properties still decrease above 2% moisture content, but not as quickly. Facer delamination tests show similar degradation of performance, but is appears to be reasonable to use the fastener pull-through test to characterize facer adhesion of these products.

Paper-faced gypsum sheathing (GWB and XGG) generally does not meet the performance criteria established in ASTM C1396 above a moisture content of approximately 1%, and fibre-faced sheathing (FFG) does not meet the criteria set out in ASTM C1177 above a moisture content of approximately 0.5%. These products also do not meet some of the requirements of these Standards when oven-dry, so it is not clear that the ASTM criteria are appropriate indicators of in-service performance (this is noted in the ASTM Standards).

Exposure to high-humidity levels in typical construction can result in moisture contents of 8-10% in gypsum sheathing. This does not include exposure to liquid water.

RÉSUMÉ

La Société canadienne d'hypothèques et de logement (SCHL) a retenu les services de Levelton Engineering Ltd. pour étudier, dans le cadre du Programme de subventions de recherche de la SCHL, la performance d'un revêtement intermédiaire en plaques de plâtre à des taux d'humidité variés.

L'objectif convenu de ce projet était d'examiner le rapport entre le taux d'humidité et les propriétés mécaniques du revêtement intermédiaire en plaques de plâtre (c.-à-d. les plaques de plâtre devant servir de revêtement intermédiaire extérieur pour des bâtiments). Les propriétés particulières devant faire l'objet d'un examen comprenaient :

- l'absorption d'eau;
- l'adhérence ou le décollement du matériau de surface (qu'il s'agisse d'une couche de fibre de verre, de papier traité ou non traité, selon le genre de revêtement intermédiaire);
- la résistance du revêtement au retrait des pièces de fixation;
- la résistance du revêtement à la flexion sur le plan sismique ou en guise d'indicateur courant d'intégrité mécanique.

Les produits mis à l'essai étaient un revêtement recouvert de fibre de verre (FFG), un revêtement de plaque de plâtre recouvert de papier (XGG) et des plaques de plâtre intérieures standards (GWB), qui ont servi d'échantillons de contrôle.

L'étude a été divisée en étapes distinctes : la tâche 1 (détermination des niveaux de saturation de la teneur en humidité) et la tâche 2 (évaluation de l'exactitude des humidimètres manuels) portaient sur la manière de mesurer le taux d'humidité des produits de revêtement de plâtre.

La tâche 3 (mise à l'essai des propriétés mécaniques du revêtement de plâtre à divers taux d'humidité) visait à examiner la résistance au retrait des pièces de fixation, la résistance à la flexion et le décollement du matériau de surface de divers types de revêtements de plâtre à plusieurs teneurs en humidité différentes. Les propriétés mécaniques ainsi obtenues ont été comparées aux critères existants définis dans les normes pertinentes de l'ASTM.

La tâche 4 (mise à l'essai de murs dans un milieu humide) a été exécutée à l'installation d'essai de l'Université Concordia afin de relever les taux d'humidité prévus que l'on retrouve d'habitude dans un revêtement intermédiaire en service.

Les conclusions suivantes sont résumées dans le présent rapport :

La teneur en humidité exprimée sous forme d'un pourcentage de saturation ne constitue pas un indicateur de performance utile, étant donné que les revêtements intermédiaires en plaques de plâtre peuvent absorber presque leur propre poids en eau et qu'on a constaté que le matériau se désagrégeait à une teneur en humidité nettement inférieure.

Les humidimètres manuels sont habituellement précis pour un revêtement de plâtre recouvert de papier jusqu'à environ 6 %, mais au-delà de ce taux, il donne une lecture inférieure à la valeur réelle. Les humidimètres donnent une lecture plus élevée que les valeurs gravimétriques pour le revêtement recouvert de fibre de verre, hors de la plage des teneurs en humidité étudiée. La teneur en humidité varie considérablement entre les échantillons GWB, mais tout de même moins que pour les échantillons XGG et FFG. La vitesse d'absorption de l'humidité dans les échantillons peut expliquer cette variation, mais ce phénomène devrait être étudié plus en profondeur étant donné que la nature de la redistribution de l'humidité dans les plaques de plâtre ne faisait pas partie de cette étude.

La présente étude a permis d'établir qu'il existe une forte corrélation entre la teneur en humidité et les propriétés mécaniques des divers types de revêtement de plâtre. Les essais de l'ASTM portant sur la résistance à la flexion et au retrait des pièces de fixation donnent à penser que les propriétés mécaniques du revêtement de plaques de plâtre sont énormément réduites lorsque le taux d'humidité est augmenté de 0 % à 2 %. Les propriétés mécaniques continuent à diminuer lorsque la teneur en humidité dépasse 2 %, mais pas aussi rapidement. Les essais de décollement du matériau de surface montrent que la dégradation de la performance est semblable, mais il semble raisonnable d'avoir recours à des essais de retrait des pièces de fixation afin de caractériser l'adhérence du matériau de surface sur ces produits.

Les revêtements intermédiaires constitués de plaques de plâtre recouvertes de papier (GWB et XGG) ne respectent habituellement pas les critères précisés dans la norme C1396 de l'ASTM lorsque la teneur en humidité est supérieure à environ 1 %, et le revêtement recouvert de fibre (FFG) ne respecte habituellement pas les critères établis dans la norme C1177 de l'ASTM lorsque la teneur en humidité est supérieure à environ 0,5 %. Ces produits ne satisfont également pas à certaines exigences de ces normes lorsqu'ils sont séchés au four; il n'est donc pas clair que les critères établis dans les normes de l'ASTM sont des indicateurs adéquats de la performance en service (ce fait est d'ailleurs souligné dans les normes de l'ASTM).

L'exposition d'une construction type à des taux élevés d'humidité peut faire en sorte que les teneurs en humidité du revêtement de plaque de plâtre atteignent 8 à 10 %, sans tenir compte de l'exposition à l'eau.

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APPENDICES

1. Terms of Reference/Scope of Investigation

Levelton Engineering Ltd. applied for a housing research grant under the Canada Mortgage and Housing Corporation (CMHC) External Research Program, to study the response of gypsum sheathing products to various levels of moisture content. The specific scope of work and terms of reference for the project are outlined in the announcement of award from CMHC (CMHC reference C.R. 6585-M178 dated June 10, 2003).

The stated objective of this project is to examine the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum wallboard intended for use as exterior sheathing on buildings). Specific properties to be examined included:

- water absorption;
- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper, depending on the sheathing type);
- ability of the sheathing to resist fastener pull-through; and
- flexural strength of the sheathing, as a common index of overall mechanical integrity

Gypsum sheathing is often specified in construction or remediation projects in accordance with the ASTM C1177 (Reference 14) or C1396 (Reference 15) Standards, which define the performance of gypsum sheathing in terms of the above characteristics. In a sense, then, the objectives of this project could be expressed as determining the moisture content at which gypsum sheathing can no longer be defined as gypsum sheathing, because it no longer meets one or more of the above criteria, as defined in ASTM C1177 or C1396. Ideally, one would determine a threshold for “acceptable” or “unacceptable” levels of moisture content (whether the concern is facer delamination, which leads to failure of insulated sheathing systems bonded to the facer; or fastener pull-out, which leads to sheathing detachment; or loss of mechanical integrity, which leads to several modes of failure in the wall assembly). Note that this approach implicitly assumes that the performance criteria defined in those Standards are based on optimum performance of the product, and are representative of expected field performance. The scope of this project was not intended to determine whether the levels of performance defined in the ASTM Standards are appropriate.

It was also proposed to determine whether hand-held electric-resistance meters, typically used for measuring moisture content of gypsum sheathing, are reasonably accurate for that purpose, or if some new apparatus or protocol is required. Building-envelope consultants are often called upon to diagnose problems in buildings with gypsum sheathing, and a moisture-content survey is one of the tools used to assist in such diagnoses.

Previous CMHC-supported research on gypsum sheathing (e.g., References 1 and 2) provided results on, among other things, the performance of gypsum sheathing under induced-moisture conditions (i.e., condensation, or adsorption of moisture from moist air in contact with the sheathing). The observed phenomena to indicate performance of the material, as that performance varies with moisture content, were more focussed on the presence or absence of mould (Reference 1) or condensed water (Reference 2) on the surface of the sheathing.

This project considers higher moisture loads, as would be experienced in sheathing exposed to weather over a period of time (or in the event of a plumbing leak, or redistribution of construction moisture, or other situation related to the presence of liquid water rather than water vapour). The observed performance parameters include actual measured mechanical properties of the sheathing, rather than subjective observations, and these results can be used to define limit states in the design process.

Expected results of the proposed project include:

- recommendations for a method of measuring moisture content of gypsum-based sheathing *in situ*
- defining a relationship between moisture content and mechanical properties of gypsum sheathing
- definitions for "dry", "wet", and "saturated" gypsum sheathing, to assist Code development and enforcement agencies in defining appropriate levels of moisture content in these products, as is now done for wood components.
- a preliminary "proof-of-concept" evaluation of the performance of gypsum sheathing products in a controlled high-humidity environment is intended to provide an indication of the relationship between field conditions and expected moisture-content levels (and material property behaviour) for gypsum-based sheathing products.

2. BACKGROUND

Gypsum sheathing is widely used in multi-residential buildings, often in concrete structures with steel studs. Such designs are found throughout Canada in rental and condominium apartments. This study is not intended to call that practice into question (indeed, the authors of the report use gypsum sheathing in their designs as well), but rather to provide some guidance to building designers and building scientists when designing or assessing gypsum-sheathed buildings.

Many manufacturers of gypsum wallboard provide a type of board intended for use as exterior wall sheathing. There are two main types: one has a silicone-treated gypsum core and water-resistant paper facers. In other products, the treated gypsum core is faced with glass-fibre random-woven mats. A third product, which is being phased out but was used until quite recently in some areas, has an untreated core but water-resistant paper facers. Although these products are not intended for direct exposure to weather during its intended service life, they are expected to be moisture-resistant during construction, and reasonably resistant to incidental moisture ingress. The largest manufacturer of fiberglass-faced gypsum advertises "…superb protection from the elements with unsurpassed water resistance. These panels will not delaminate or deteriorate due to weather – even during construction delays that last as long as six months after installation" (see Reference 3). In describing the application of this product, however, the manufacturer notes that the product "…is exceptionally resistant to weather, but it is not intended for immersion in water or sustained exposure to water and moisture".

As for paper-faced XGG, this manufacturer notes (Reference 4):

- Improved nail holding characteristics.
- Stronger core-to-paper bond for improved flexibility and durability.
- Harder edges that result in fewer handling issues.
- Offers performance characteristics and strength comparable to gypsum board produced by the industry before efforts were made to lighten panels.

The manufacturer of this product responds to a question about whether the product can be wet with the comment (Reference 5): "Gypsum board should not be allowed to get wet…[h]owever, there are situations where the board could get wet in transportation/storage or installed in-place. If the board gets wet in an installed in-place situation, first remove the sources of moisture. Then, allow the board to dry out thoroughly. Once the board is dry, examine it for paper-to-core bond failure, mold and mildew growth, nail pops and sag (in case of ceilings). Paper-to-core bond failure and board sag are irreversible damages and the board should be replaced."

Other manufacturers make similar advertising claims – but at the same time, the gypsum industry has sponsored a seminar entitled “The call it DRYwall for a reason”, with the message of the seminar being that every effort should be made to keep gypsum-based products dry.

Exterior sheathing should be able to handle large moisture loads during construction, and incidental moisture thereafter, but no guidance is provided to the designer or contractor as to how much moisture is “too much”. In the absence of such guidance, it might be prudent to use these products sparingly in high-exposure locations (e.g., regions with high wind-driven rains or near large bodies of water), or not at all in the case of wet climates (e.g., Atlantic Canada or coastal British Columbia). Indeed, there are known instances of large-scale building envelope failures in coastal climates, where the primary mode of failure was related to the use of gypsum-based products as exterior sheathing. Many cases of building-envelope failure have been documented in North Carolina, yet the Web page of Guilford County, NC recommends exterior gypsum sheathing (in compliance with ASTM C79, which has since been superseded by C1396) as a satisfactory substrate for stucco (Reference 6). One can infer from this that there must be some acceptable level of moisture content for gypsum sheathing, but no such levels are defined.

The Pacific northwestern states are also known to have experienced failures related to the use of “exterior-grade sheathing”, yet the Northwest Wall and Ceiling Bureau (Reference 7) recommends “treated-core gypsum” for exterior walls in that region. “Treated-core gypsum” could be defined to include paper-faced XGWB as well as glass-fibre-faced product, and the former may not be appropriate in some applications, but not enough is known about the mechanical properties of this material to provide information to the design or builder – or to Code development and enforcement agencies – in this regard.

Also, developing a reliable (and portable) way of making such measurements would be useful to building-science practitioners and researchers investigating buildings with gypsum sheathing (or with interior gypsum finish). Moisture-content measurements are routinely undertaken for wood-based building products, with various correction factors related to grain direction and size, temperature and species. At the outset of this project it was felt that, if such measurements are acceptable in a variable, non-homogeneous organic material such as wood (with its inherent variability in density, grain spacing and direction, species, etc.), then it should be possible to define a relationship between moisture content and (for example) electrical resistance in a somewhat more homogeneous product such as gypsum sheathing. There are, however, no readily available data to support this hypothesis, other than the specious observation that hand-held meters are routinely being used for that purpose.

Even if such a relationship is defined, some guidance as to the interpretation of field measurement of moisture content is required. Building Scientists are familiar with the acceptable ranges for moisture content in wood-framed buildings. Indeed, this information is now available to the general public, in large part due to the publication of CMHC’s Best Practice Guides (e.g., Reference 8). Thus, we know that moisture content of less than 19% in wood is considered “dry”, and this is used in Building Codes throughout the country as a requirement for limiting moisture in new wood-framed construction. A measured moisture content of 25-28% in wood (which is the fibre-saturation point, and varies depending on the species) is also considered a significant threshold, as it defines the level above which mould colonization is likely.

Such limits are not known for gypsum-based products, leaving design consultants to develop their own (differing, and usually inconsistent) rules of thumb for “safe” or “unsafe” moisture-content levels in those products. As a result, misconceptions about the capacity of gypsum sheathing to sustain moisture may lead to prolonged exposure of the sheathing before closing up the wall assembly.

3. METHODOLOGY

The research method was conducted in three parts:

1. Determine the accuracy of hand-held meters for measuring moisture content of gypsum sheathing, and determination of “saturation” level of moisture content for various types of gypsum sheathing. Readings of hand-held moisture meters will be compared against gravimetric analysis for a wide range of specimens to which a measured quantity of water has been added. The effect of time required to redistribute moisture through the specimens will also be investigated, as this relates to redistribution of moisture within a wall assembly.
2. Assess the desired mechanical properties of various types of gypsum sheathing at various moisture contents, using standard ASTM materials testing procedures. The intent is to develop correlations between moisture content and mechanical properties (flexural strength, fastener pull-out and delamination of facer material), and to determine maximum acceptable levels for moisture content of gypsum sheathing, as is done in the National Building Code for lumber used in construction.
3. Perform proof-of-concept testing for gypsum sheathing in wall assemblies, to be tested in a large-scale climate simulation chamber. This will investigate the performance of gypsum sheathing in situ under controlled conditions, and will provide an indication of the effect of wet gypsum sheathing on adjacent building components (steel studs, fasteners, etc.) under controlled conditions.

3.1 TEST SPECIMENS

There are several different types of gypsum sheathing. Given the budgetary restrictions of this project (and the fact that this is a proof-of-concept exercise), we chose to focus our investigation on two types of gypsum sheathing, with standard gypsum wallboard as a control specimen. All of the following specimens were tested at 1/2” and 5/8” thickness:

1. Standard gypsum, with untreated core and untreated paper facers on both sides. This product is normally used for interior finish, and is only included as a control specimen to provide comparative data. **Throughout this report, the standard gypsum wallboard specimens will be designated “GWB”.**
2. Exterior gypsum sheathing, with moisture-resistant core and moisture resistant paper facers. **Throughout this report, the moisture-resistant paper-faced gypsum sheathing specimens will be designated “XGG”.**
3. A product is also available with a moisture-resistant gypsum core and glass-fibre facers. This product is becoming the standard for use in wet climates, although paper-faced products are still used in some cases due to their lower cost. **Throughout this report, the fibre-faced gypsum specimens will be designated “FFG”.**

3.2 TEST PROTOCOL

This section of the report describes the test procedures used, with the results of the experimentation described in Section 4. The testing in Tasks 1 (Moisture Meter Accuracy) and 2 (Mechanical Properties of Moist Sheathing) were all conducted on samples obtained from local building supply centres, to reflect the quality of product used on construction sites (except for the

XGG product, as suppliers in the Vancouver area did not provide gypsum sheathing with a treated core when this study was done. In that case, treated-core product was imported from Washington State for use in this project). Sample material was purchased from the distributor, not donated from any manufacturer.

Specimens were cut from standard 1220 x 2440 mm (4' x 8') gypsum sheathing panels, at least 100 mm away from ends and edges of the sheet stock, as specified in ASTM C473 (Reference 9). Specimens were cut from the same job lot (to reduce variability from the manufacturing process), and were cut to a standard size of 300 x 300 mm (12" x 12"). After cutting, all specimens were conditioned to 20°C and 50% RH.

3.2.1 Preliminary investigation - Water adsorption

The first Task defined in this project was an assessment of the accuracy of hand-held meters, which are used to measure the moisture content of gypsum sheathing (typically expressed as a percentage of its dry weight). Before this task could be undertaken, however, it was necessary to determine whether there were any practical limits of the amounts of water to be added, which required a determination of the saturation level for various gypsum-based products. We used a procedure similar to the test for "water resistance of core-treated water-repellent gypsum boards" in the ASTM C473 Standard (Reference 9). Instead of submerging the samples for only 2 hours (as the C473 test requires), however, they were submerged until they reached a constant weight (i.e., they had absorbed as much water as they could, and were by definition "saturated").

Samples of the specimens were oven-dried to a constant weight (i.e., their mass changed by less than 0.02% in successive measurements). ASTM C472 (Reference 13) requires that the drying occurs at 45°C. Gypsum is a hydrated molecule ($CaSO_4 \cdot 2H_2O$), however, so we felt that it was important to keep the oven temperature low enough to avoid dehydration. We wanted to keep this project simple, and phase change due to dehydration would unnecessarily complicate our study. As we were concerned that some partial dehydration may still occur at 45°C, a drying temperature of 30°C was used instead. Although the time to oven-dry took longer at the lower temperature, we felt that the increased level of confidence in the accuracy of the dry weight was worth the time.

The C472 procedure does not specify the frequency of successive measurements used to determine constant weight, so the criterion for wood-based products, defined in the ASTM D4442 procedure (Reference 10), was used to determine dry weight. The D4442 procedure defines procedures for gravimetric measurement to determine moisture content in wood samples, and was modified for this project. D4442 requires that the samples are to be removed from the drying oven and weighed every three hours: when the weight changes by less than 0.02%, the specimen was considered to have reached steady-state, and the value recorded at that point was considered to be the dry weight.

The specimens were conditioned to promote uniform distribution of moisture, which involved sealing the specimens in plastic wrap to minimize evaporative losses and turning the specimens over every 24 hours to promote moisture distribution. Specimens were typically stored for two weeks in this manner, to ensure moisture equilibrium within each specimen (there is no "Standard" protocol for this procedure).

Once the "saturation" moisture content was defined for each specimen type, the desired levels of moisture contents were determined for Task 1. This important step also provided oven-dry density and weight of all three types of specimens, used throughout the project as a datum (i.e., all moisture contents are given as a percentage of dry weight for each of the specimen types).

3.2.2 Moisture Meter Accuracy

The objective of this Task was to apply an existing ASTM method (used to measure moisture content in wood) to gypsum-based products, and to assess the accuracy of that method or suggest necessary modifications to the procedure. This procedure could then be used in diagnostic analyses of buildings, or in verification of appropriate moisture-content levels for gypsum sheathing in the context of Building Code development and application.

Known quantities of water were added to a matrix of gypsum-based sheathing specimens. The resulting moisture contents were measured using ASTM procedures for hand-held moisture meters and direct gravimetric analysis. A procedure for measuring moisture content in gypsum products by gravimetry is described in ASTM C472 (Reference 13), but other procedures (ASTM D4444 and D4442, References 11 and 10, respectively) intended for use with wood and wood-based materials, were also investigated for possible application to gypsum-based materials.

After a measured amount of water was added to each sample, all samples were wrapped in foil to minimize evaporative losses, and stored flat in a controlled environment for two weeks to promote uniform distribution of the moisture. The samples were turned over every 24 hours to ensure even distribution of moisture throughout the specimen (although it could be an interesting subject of future investigation, localized moisture concentration was not part of this project).

Electrical-resistance readings were then taken using a commercially available pin-type moisture meter (commonly used to evaluate moisture content in wood). Measurements were taken at three locations on each sample (at the centre and at opposing corners), and each sample was weighed to determine its moisture content (expressed as a percentage of oven-dry weight, which was determined in the preliminary set-up).

A separate sample was provided for each intended level of moisture content. This task involved three samples of three different types of sheathing at two different thicknesses, each of which was evaluated at six different moisture-content levels, for a total of 108 data points.

The resulting data (108 gravimetric measurements and 324 readings from a calibrated hand-held meter) were analyzed to determine whether correlations exist for the various products, and to assess the accuracy of the readings from the hand-held meters. Gravimetry was used to measure moisture contents for the remaining Tasks, in case the pin probes affected facer delamination and flexural strength (see the description for Task 2).

3.2.3 Mechanical properties

The objective of this Task was to assess the mechanical properties of various gypsum-based sheathing products at varying levels of moisture content. Specific properties to be examined include:

- delamination of facer material (glass-fibre mats, treated paper or untreated paper)
- ability of the sheathing to resist fastener pull-out; and
- flexural strength of the sheathing, for seismic considerations and as an index of overall mechanical integrity

A matrix of specimens was developed, and a measured amount of water added to each specimen. The specimens were conditioned to promote uniform distribution of moisture, which involved sealing the specimens in plastic wrap to minimize evaporative losses and turning the specimens over every 24 hours to promote moisture distribution. Specimens were typically stored for two weeks in this manner, to ensure moisture equilibrium within each specimen (there is no protocol for this procedure). Each specimen was then tested for fastener pullout and flexural strength, as described in ASTM C473 (Reference 9).

The test for facer delamination was a modified version of CSA A23.2-6B (Reference 12), which is normally used to test adhesion of tiles to concrete substrates. To our knowledge, there are no Standard Specifications for gypsum facer delamination, and one of the objectives for this project was to provide an indication of moisture levels at which this property becomes a concern. Prior to testing, the moisture content of all specimens was verified using gravimetry.

In Section 4 of this report, the resulting performance measured for each specimen as it varies with moisture content is presented and compared to the Standard Specification requirements for gypsum sheathing materials (defined in the ASTM C1177 and C1396 Standards). Again, the objective is to identify threshold moisture-content levels for each property of interest.

3.3 Environmental Chamber Testing

The intent of the last phase of the project was to perform a proof-of-concept test to determine typical moisture-content levels for gypsum-based sheathing products in wall assemblies exposed to high humidity levels for extended periods. This was intended to provide a preliminary correlation of weather exposure to in-service moisture content (and therefore, mechanical properties) of gypsum-based sheathing products.

As a simple proof-of-concept evaluation of gypsum-based sheathing in a wall assembly, test panels were constructed and installed in an environmental chamber. The panels comprised each type of gypsum sheathing evaluated in the materials-testing phases of the project, attached to steel studs with glass-fibre batt insulation, polyethylene vapour retarder and interior gypsum finish. The sheathing was be covered with typical sheathing membrane and held in a high-humidity environment for an extended period.

This work was being conducted in the Environmental Chamber and with the research staff of the Building Envelope Performance Laboratory at Concordia University in Montreal. Three specimens of 0.8m wide (one stud cavity with half a cavity on each side) by 1.2m high (with the possibility of 2.4m) were mounted in a test hut within the Environmental Chamber. The inside of the hut was at normal interior conditions. The exterior of the hut (i.e. the inside of the Environmental Chamber) was controlled to reproduce the desired exterior conditions. The resulting moisture content was monitored through a phase of high relative humidity to study moisture redistribution and drying of the sheathing panels for 3-4 weeks. Each specimen was instrumented with thermocouples and relative humidity sensors on both side of the sheathing, and with moisture probe and gravimetric samples for moisture content monitoring.

4. RESEARCH RESULTS

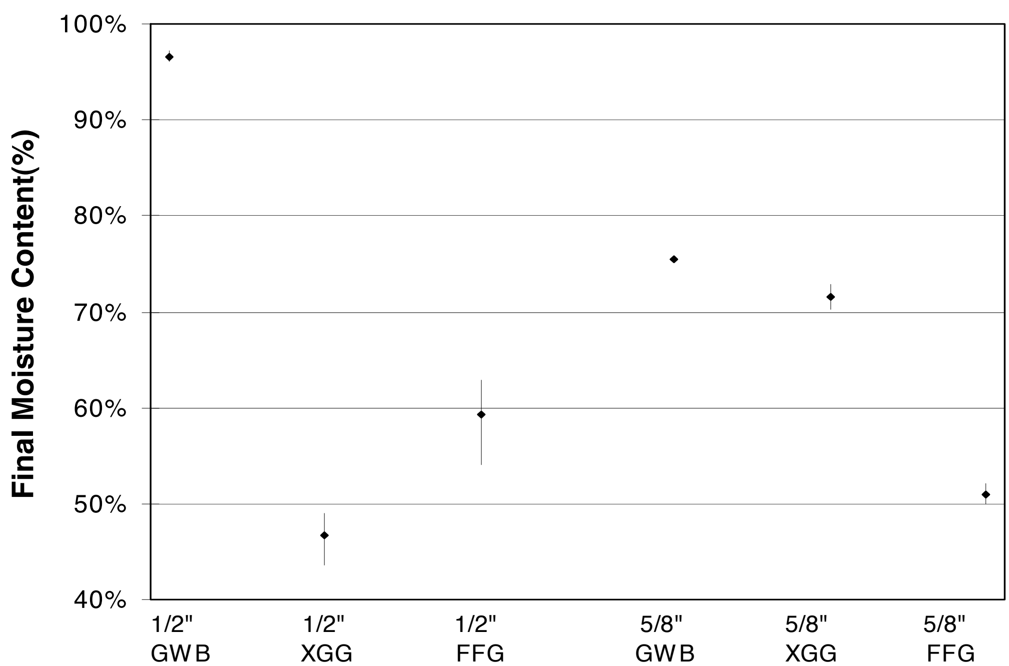
4.1 PRELIMINARY INVESTIGATION - WATER ADSORPTION

As described in Section 3.2.1, several samples of gypsum sheathing were brought to equilibrium with air at 20°C and 50% RH. Water was added to saturation, and the specimens were weighed, oven-dried, and measured again. The maximum moisture content attained during this procedure is called the "final moisture content" of the specimen, expressed as a percentage of its dry weight. The mean saturation values (see Appendix A) for each specimen type were:

Specimen Type	Saturation ("Final") Moisture Content
1/2" Standard Gypsum Wall board (GWB)	96.5%
1/2" Paper-faced Gypsum Sheathing (XGG)	46.7
1/2" Glass-fibre-faced Gypsum Sheathing (FFG)	59.2
5/8" Standard Gypsum Wall board (GWB)	75.5
5/8" Paper-faced Gypsum Sheathing (XGG)	72.5
5/8" Glass-fibre-faced Gypsum Sheathing (FFG)	52.0

Thus, there is a large variation in the saturation level of each specimen, but the 1/2" GWB samples appear to be able to absorb almost their own weight in water. No other identifiable trends are apparent from these test results. Figure 1 summarizes the results of this analysis, showing the measurement range and mean value for each specimen type.

Figure 1. Saturation of Gypsum Sheathing



During this measurement procedure, the edges of the specimens began to crumble long before saturation was reached. As this could have introduced a catastrophic error in the results (because the final mass of the specimens would be difficult to determine), a bead of wax was applied to the perimeter of each specimen to seal the edges from absorbing excess moisture, and to prevent the edges from crumbling. The dry weight was measured again, including the weight of the added wax seal.

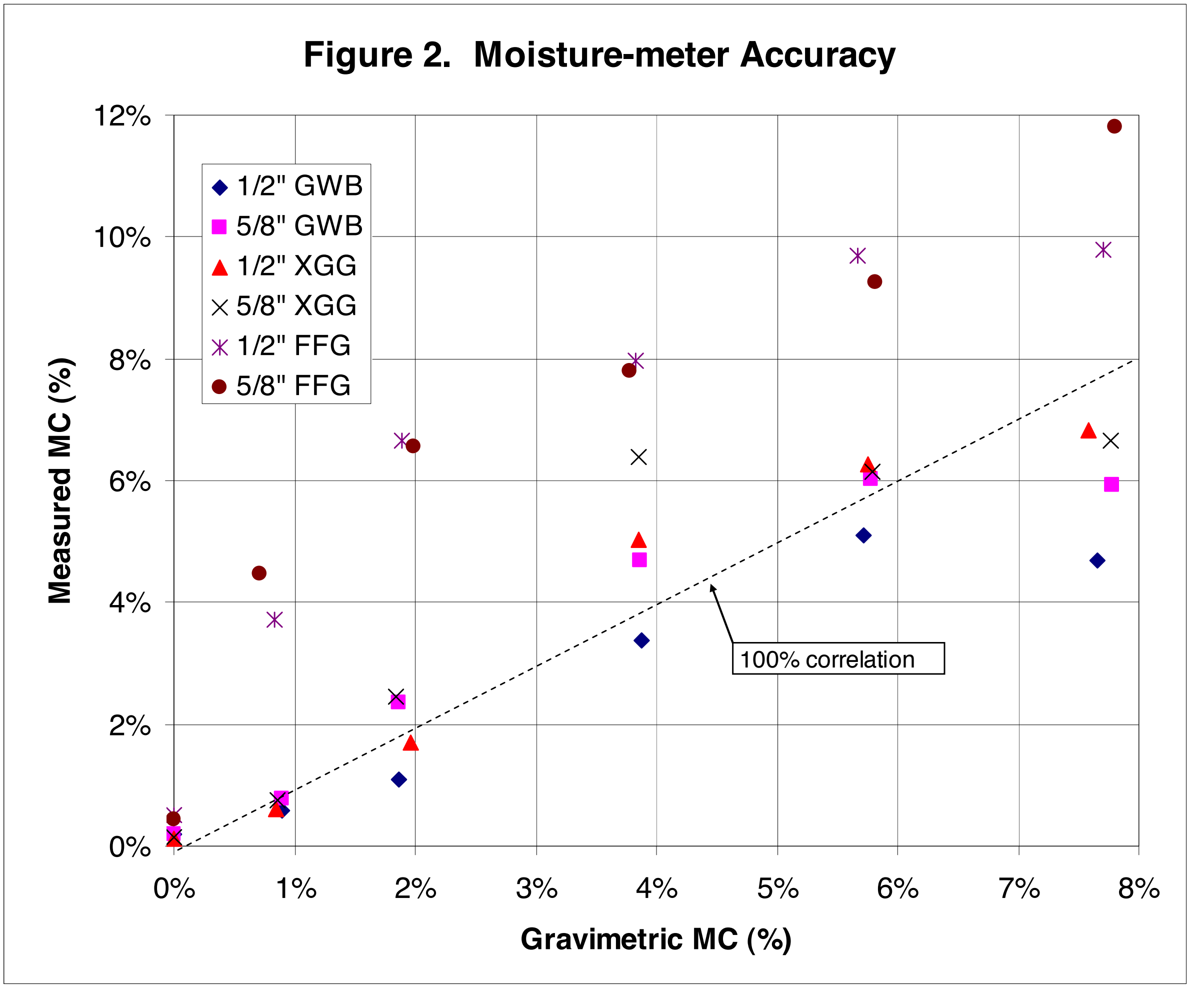
The fact that the specimens were crumbling confirms that there is a practical upper limit to the amount of water that can be added to gypsum sheathing before it loses structural integrity. It is also apparent that this limit occurs well below saturation. This necessitated a change in the research plan. It was originally intended to set the moisture-content levels used in Task 1 as percentages of the saturation level for each specimen type. The results of this preliminary investigation showed that this approach would not be practical, so the moisture-content levels for Task 2 were arbitrarily set at 0%, 1%, 2%, 4%, 6% and 8% (as a percentage of dry weight).

4.2 MOISTURE METER ACCURACY

As described in the previous section, the results of the preliminary investigation defined the appropriate moisture-content levels for this Task. Therefore, a measured quantity of water was added to several pre-conditioned specimens with the intent of producing moisture contents of 0%, 1%, 2%, 4%, 6%, and 8%. The wetted specimens were stored for two weeks, and were turned over every 24 hours, to ensure an even moisture distribution (the specimens were stored horizontally, wrapped in polyethylene and foil to minimize evaporative losses).

At the end of the conditioning period, the samples were weighed, and a new (factory-calibrated) hand-held moisture-content meter was used to measure the moisture content at the centre and two diagonally opposite corners of each panel. The moisture-probe pins penetrate the sample to a fixed depth of approximately 1/8 – 3/16”, and are thus measuring the moisture content of the gypsum core. The meter measures the electrical resistance between two metal pins separated by a known fixed distance. A calibration exercise is performed periodically on these meters to equate the measured resistance to a known moisture content. The meter used has three separate scales: one for wood-based products, one for gypsum, and one relative scale to be used for concrete-based products. Readings on the gypsum scale (to be read directly as moisture content as a percentage of dry weight) were compared with the moisture content determined by gravimetric analysis (following the ASTM D4442 procedure described in Reference 10).

As noted previously, the C472 and D4442 procedures were modified to prevent dehydration of the gypsum specimens. The D4442 Standard as written requires specimens to be oven dried at 103°F ($\pm$2°C) to obtain its dry weight, but this could alter the chemical structure of the gypsum, which comprises a calcium sulfate molecule bonded to two water molecules (chemical formula for gypsum is $CaSO_4 \cdot 2H_2O$). The C472 procedure specifies oven drying at 45 °C to reduce the potential for over-drying, but we wanted to make sure that the product was completely dry without becoming dehydrated, and the D4442 procedure for determining dryness (weigh the sample every 3 hours until the measurement changes by less than 0.02%) is more rigorous than the procedure defined in C472 (dry the sample for 2 hours, then weigh it). Therefore, we used the D4442 criterion, with a reduced temperature to ensure that drying was thorough. The oven temperature was set at 30°C, and the moisture content was measured periodically until successive measurements changed by less than 0.02%. The resulting measurement was then recorded as dry weight, and this value was used to compute the gravimetric moisture content from the weight measurements for each of the wetted specimens.



The comparisons for each specimen type are provided in Appendix B of this report, and are summarized for all specimens in Figure 2. The dashed line in Figure 2 indicates the ideal case, where the moisture content determined via the handheld meter is equal to the gravimetric value.

This shows that the meters are generally accurate for paper-faced gypsum sheathing up to (approximately) 6%, but above that level the moisture meter reads lower than the actual value. The results also show that the moisture meters read approximately 3 - 3.4% higher than the gravimetric values for fibre-faced sheathing, over the range of moisture contents investigated.

What Figure 2 does not show is that the moisture content varies significantly across the GWB specimens, but much less so for the XGG and FFG specimens. The speed of moisture absorption in the specimens may explain this variation, but this should be investigated further as the nature of moisture redistribution within gypsum was not within the scope of this project.

To better understand the results shown in Figure 2, it is useful to consider the operation of the handheld meters. The calibration procedure for handheld moisture meters is typically done at the manufacturer's facility, and establishes the relationship between the measured electrical resistivity of the material and the moisture-content reading displayed on the meter. Calibration is usually done for materials (wood, gypsum or other samples, depending on the type of meter) at oven-dry conditions and at "saturation". By way of example, "saturation" for wood products is often taken to be 40% (as a percentage of dry weight), and readings above this moisture content may be displayed as "40+" or "99.9", depending on the make and model of the meter.

As the results of Task 1 show, "saturation" for gypsum products – defined as the maximum possible moisture content – could be defined as some value between 47% and 97%, depending on the product. For the purpose of calibrating moisture meters, however, "saturation" is typically defined as 6.4%, and higher readings are displayed as "6.4" or "99.9" on some meters (the meter used in this project displays extrapolated results: readings of up to 15.8% were recorded).

In the calibration procedure, the electrical resistivity of a standard sample of gypsum is measured at 0% and 6.4% moisture content, and a linear relationship is assumed for all readings between those points. Thus, the measured electrical resistivity of a sample is compared to the endpoints using linear interpolation, to determine the assumed moisture content that is displayed on the meter (whether by a needle on a scale or by a digital readout).

The results in Figure 2 indicate that the linear assumption is reasonable between 0% and (approximately) 6.4% for all specimens. Even for the FFG samples, which tend to read 3 - 3.4% lower than the gravimetric moisture content, the relationship still appears to be linear. Above 6%, however, the linear relationship does not appear to be a correct assumption, especially for the GWB and XGG specimens. For those cases (GWB and XGG), a large variability in the three readings taken for each specimen is observed at high moisture contents.

4.3 MECHANICAL PROPERTIES

As noted in Section 1, each material was tested to evaluate the following mechanical properties:

- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper, depending on the sheathing type);
- ability of the sheathing to resist fastener pull-through; and
- flexural strength of the sheathing, for seismic considerations and as a common index of overall mechanical integrity

4.3.1 Fastener Pull-through

Each specimen was tested for fastener pull-through, as described in ASTM C473. As that Standard explains, "The ability of gypsum panel products to resist nail pull-through is evaluated by determining the load required to push a standard nail head through the product." The "standard nail head" is represented by a steel shaft with a step change in the diameter of the shaft (see Figure 3). The diameter of the "nail shank" and "nail head" are defined to precise tolerances in C473. This study uses the C473 "Method B" of applying the test load, which moves the head of the test apparatus at a constant speed. While this does not provide a true constant rate of strain (the strain on the specimen actually increases up to the point of failure), it is easier to control and measure the load applied on the specimen.

The "test nail" is pushed through the specimen up to the "nail head", and the maximum applied load is recorded: this represents the amount of force that the specimen can resist just before the "nail head" breaks through the facer. This test was repeated on five separate specimens, for each type of sheathing material. The results of the testing are provided in Appendix C, and summarized graphically in Figures 4 and 5.

FIGURE 3. TESTING APPARATUS FOR FASTENER PULL-THROUGH

Figures 4 and 5 display the results of testing for 60 specimens: five of each type of sheathing, tested at four different moisture contents. The test results for the 1/2" specimens and the 5/8" specimens both show a pattern of decrease in resistance to fastener pull-through as moisture content increases. The Figures also include threshold values of applied force described in ASTM C1177 and C1396. Thus, a technical specification for gypsum that reads "shall conform to ASTM C1396" can be considered to read "shall have a fastener pull-through strength of at least 77 pounds of applied force…" (for 1/2" sheathing, or 87 pounds for 5/8" sheathing).

Figures 4 and 5 indicate good repeatability of the results, with very little scatter shown for each specimen group. Trendlines are added to indicate a pattern of behaviour for all three types of sheathing. We observe that the only products that consistently met their ASTM Standards were the 5/8" FFG specimens, when tested at 0% moisture content. Four of the five 5/8" XGG specimens, and one of the 5/8" GWB specimens, also met the ASTM 1396 target when tested at 0% moisture content. The other materials (i.e., 1/2" XGG and FFG, and almost all of the GWB products) did not meet the ASTM criteria at 0% moisture content, and all of the products failed to meet the criteria when tested at greater than 0% moisture content. This appears to be an unusual result, especially where the materials are tested "dry". It is possible that our specimen selection process accidentally chose a poor sample of materials (although the selection was random); or material quality is generally not what it should be, or the ASTM criteria are not representative of the required product performance.

It might be interesting to evaluate the ASTM criteria, and to relate those performance levels (in this case, for pull-through loads on various types of gypsum sheathing fasteners) to expected forces encountered in actual service, but such an evaluation is beyond the scope of this study. At present, many building designers use the current ASTM criteria to specify gypsum sheathing products (which is the stated intent of the Standards), and it appears that, for whatever reason, most of the products chosen for this study do not meet those criteria.

We note that the ASTM C473 test method for nail pull resistance (i.e., fastener pull-through) contains the following statement: “The degree of correlation between this test method and service performance has not been fully determined”.

FIGURE 4. FASTENER PULL-THROUGH TESTS FOR 1/2" GYPSUM PANEL

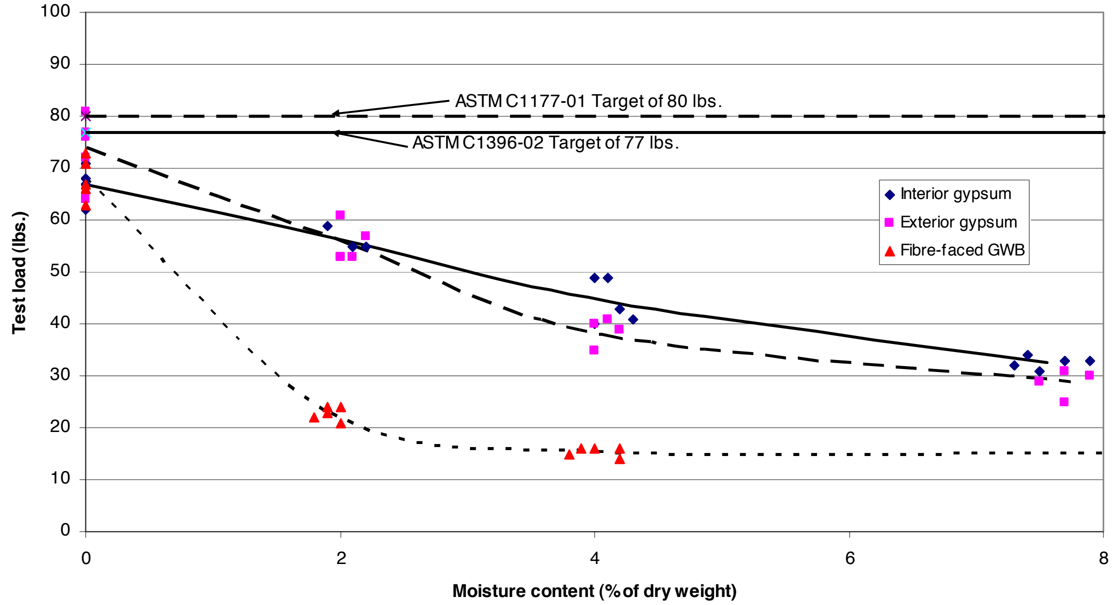
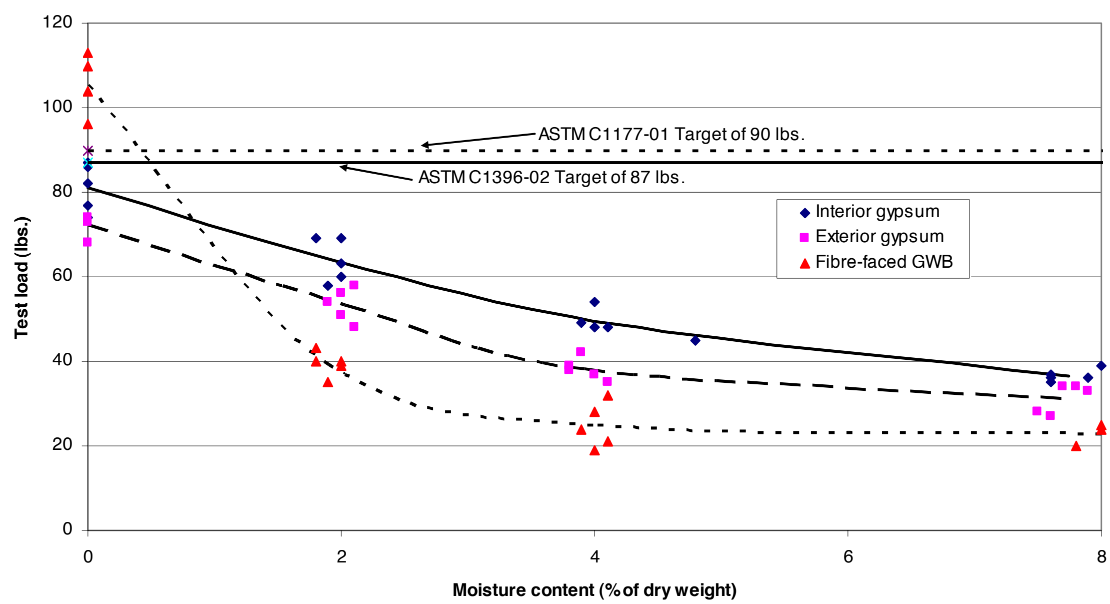


FIGURE 5. FASTENER PULL-THROUGH TESTS FOR 5/8" GYPSUM PANEL



The trendline for FFG in Figure 5 to estimate the moisture content at which the FFG sheathing meets the ASTM C1177 criteria: in this case, it appears that FFG sheathing with less than 0.3% moisture content will have sufficient fastener-holding capacity, but that any other gypsum sheathing would not meet the ASTM C1396 criterion. These results should not be considered conclusive, however, as testing with different job-lots of sheathing may provide different results.

Typical test samples from the fastener pull-through trials are shown in Figure 6. These photographs show the base-case interior-grade gypsum sheathing, to provide an interesting (and somewhat typical) illustration of the different behaviour of the specimens at varying moisture contents.

The “dry” specimen (0% m.c., Figure 6a) shows a classic failure pattern. Once the nail head breaches the facer – because the applied load exceeds the shear strength of the paper – the nail head quickly moves through the gypsum core in a sudden and brittle shear (note the clean edges created by the nail head above the cone fracture). Once the nail head has penetrated a sufficient depth of the sample, the remaining thickness of gypsum cannot resist the applied force. The result is the classic cone-shaped ductile failure pattern shown in Figure 6a.

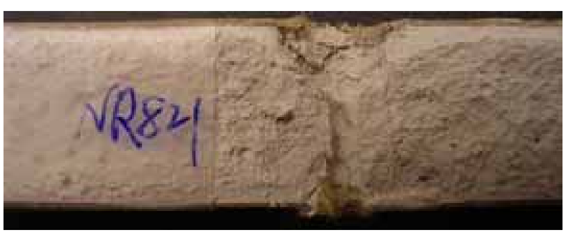
Figure 6b shows a similar cone-shaped failure pattern, but the energy absorbed in the initial breach is also ductile, as the damp gypsum absorbs more energy by crushing rather than in a clear, brittle shear failure. Figures 6c and 6d show similar patterns, but more of the energy is abosrbed in crushing the damper specimens, and the failure cone occurs closer to the bottom of the specimen. At higher moisture contents, the lower facer is seen to deform, as it begins to absorb some of the applied load (Figure 6d).

FIGURE 6. SECTIONAL VIEW OF SAMPLES FROM FASTENER PULL-OUT TESTS

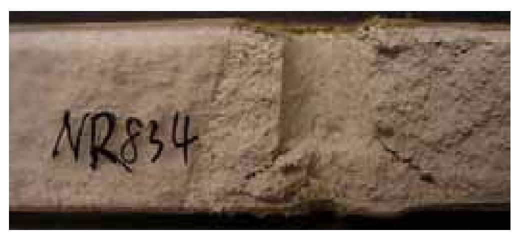
a) GWB AT 0% MOISTURE CONTENT

b) GWB AT 2% MOISTURE CONTENT

c) GWB AT 4% MOISTURE CONTENT



d) GWB AT 8% MOISTURE CONTENT



4.3.2 Flexural Strength

The flexural-strength test is also described in the C473 Standard (see Figure 7). The specimen is simply supported at each end, and a load is applied at the centre of the specimen. The specific dimensions of the supports, the test specimens, and the load applicator are described in the C473 Standard, as is the method and rate of load application. The test apparatus shown in Figure 7 was constructed specifically for this project, to meet the exact specifications of ASTM C473. Again, the maximum recorded load represents the applied force just prior to failure of the specimen in flexure.

As noted in Section 4.3.1, the C473 Standard describes two methods of applying flexural loads. This study also uses "Method B" for flexural testing, which uses a Universal Tester to apply a load at a constant cross-head speed (the cross-head is just visible at the top of Figure 7).

Each type of specimen was tested for flexural strength in four different configurations: face-up with the grain of the facer parallel to the supports, face-up with the grain of the facer perpendicular to the supports, and face-down in both directions.

FIGURE 7. TESTING APPARATUS FOR FLEXURAL STRENGTH

Figure 8 shows photographs of some FFG test specimens after flexural testing to failure. As with the fastener-penetration tests shown in Figure 6, the "dry" specimens showed evidence of brittle fracture (see Figure 8a). Damper specimens exhibited more ductile fracture, as the specimen was able to distribute some of the applied load before it ruptured (Figure 8b). An interesting behaviour is exhibited in the FFG specimens at high moisture content: the glass-fibre facer is strong enough to maintain its integrity in tensions while the gypsum core crushes under the applied load. Thus, the specimen actually fails in compression (Figure 8c).

FIGURE 8. SECTIONAL VIEW OF SAMPLES FROM FLEXURAL TESTS

a)FFG AT 0% MOISTURE CONTENT

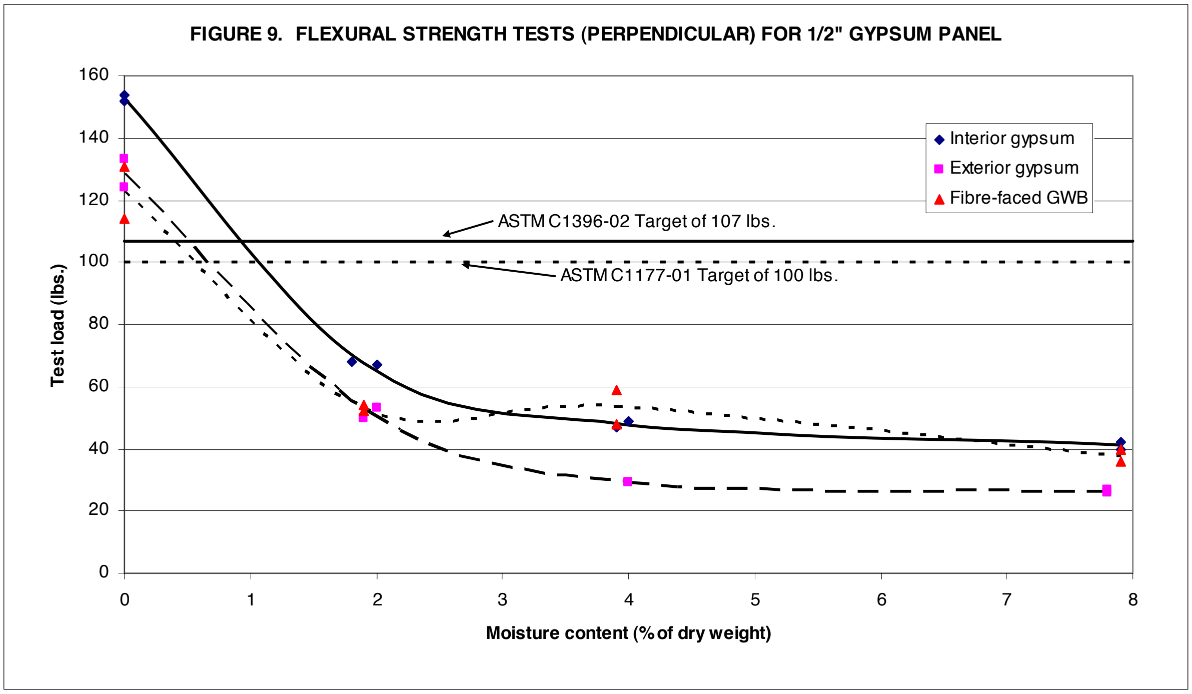
b)FFG AT 2% MOISTURE CONTENT

c)FFG AT 8% MOISTURE CONTENT

The results of flexural testing are tabulated in Appendix C. Figures 9 and 10 present the results for flexural tests with the load applied perpendicular to the grain of the paper facers (not applicable to FFG, but those specimens were tested in a similar orientation). The curves represent two data points for each product type at each moisture-content level: one test with specimens "face up", and one "face down", per the ASTM C473 protocol. As with all materials testing results in this project, the data show very good repeatability, with data points from each product type clustered in reasonably tight groupings (except for the results for FFG in Figure 10).

The results show a substantial decrease in breaking strength for all specimens when moisture content is increased from 0% to 2%, but a much smaller decrease in strength as moisture content increases above 2%. It is interesting to note that the GWB specimens generally yielded the highest test results. The ASTM C1177 and C1396 criteria targets are included in the graphs: Figure 9 suggests that GWB specimens meet the ASTM criterion at a moisture content of 1% or less: XGG and FFG specimens meet the criteria at a moisture content less than approximately 0.6%. Figure 10 suggests threshold moisture-content levels of approximately 0.8% for 5/8" GWB and XGG, and 0.3% for 5/8" FFG.

Test results for sheathing tested parallel to the facer grain are shown in Figures 11 and 12. These results show values much lower than the results represented in Figures 9 and 10, but the ASTM criteria for perpendicular tests is also lower (36 lbs. rather than 107 lbs. for 1/2" sheathing; 46 lbs. instead of 147 lbs. for 5/8" sheathing). Figure 11 suggests that GWB and XGG sheathing meets the C1396 criterion at: approximately 1.2% moisture content, and FFG specimens meet the C1177 criterion at approximately 0.5% moisture content.



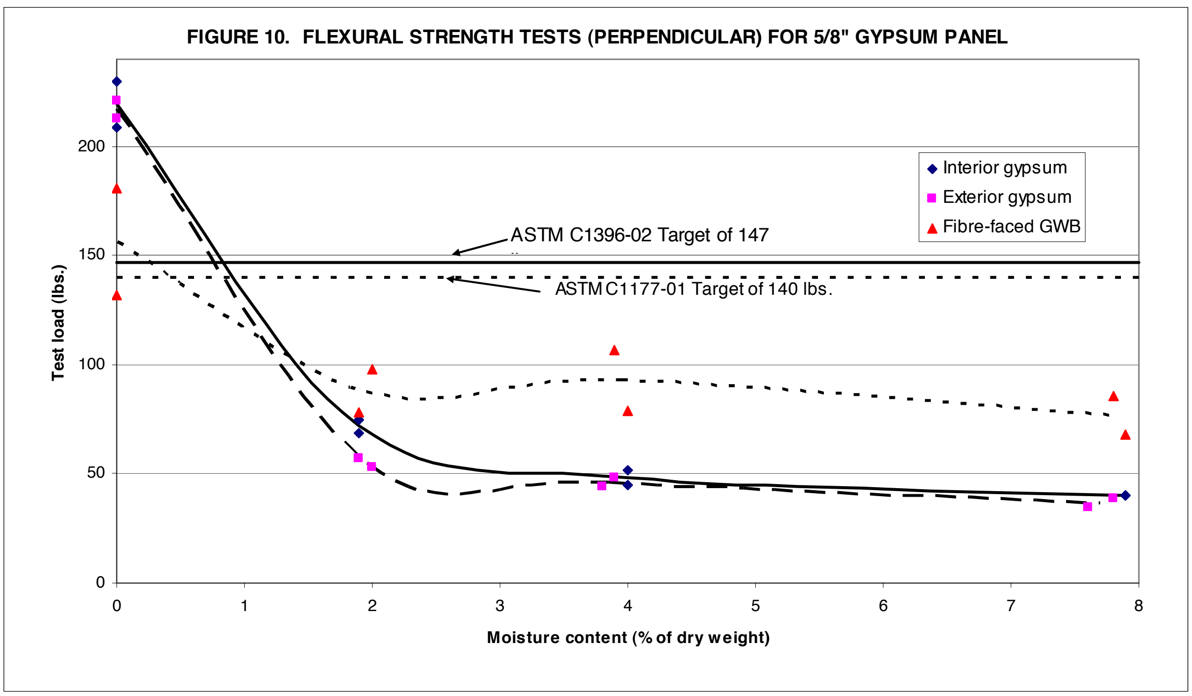


Figure 12 suggests that the 5/8" GWB and XGG specimens would comply with the C1396 requirements at moisture contents less than approximately 2%, and the 5/8" FFG products would meet the C1177 criterion at 0.4 – 0.5% moisture content, when a load is applied parallel to the long direction of the sheathing.

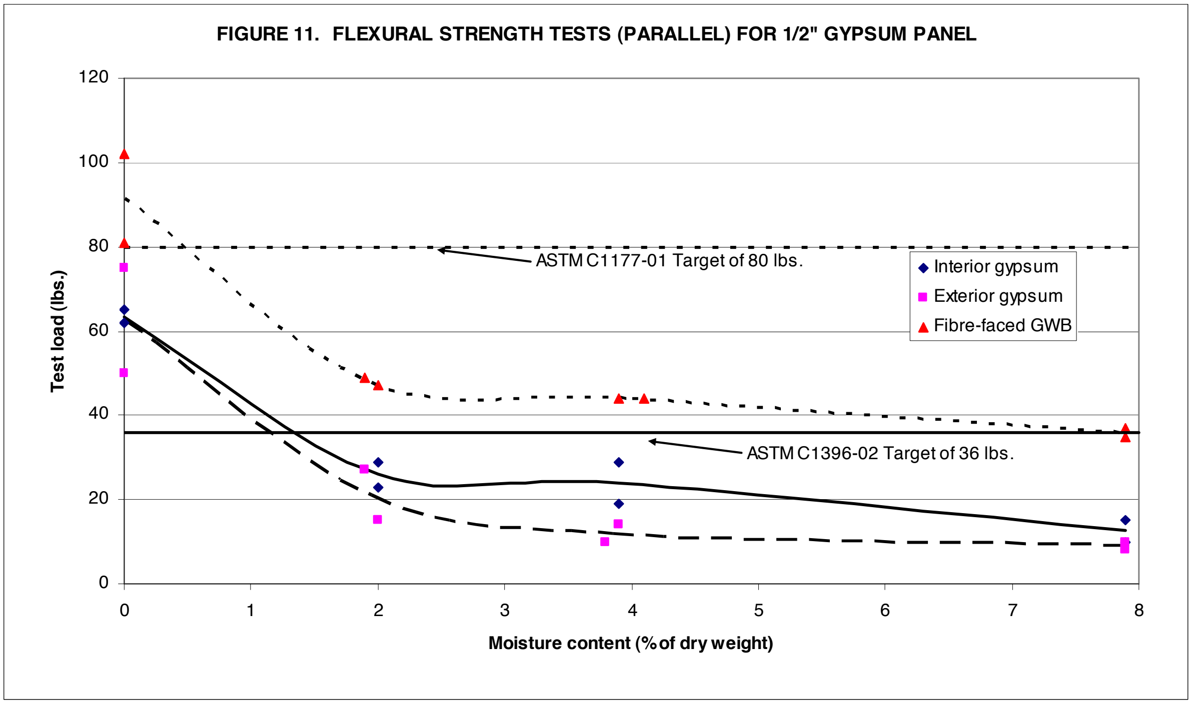


FIGURE 11. FLEXURAL STRENGTH TESTS (PARALLEL) FOR 1/2" GYPSUM PANEL
Test load (lbs.)
Moisture content (% of dry weight)
ASTM C1177-01 Target of 80 lbs.
ASTM C1396-02 Target of 36 lbs.
Interior gypsum
Exterior gypsum
Fibre-faced GWB
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8

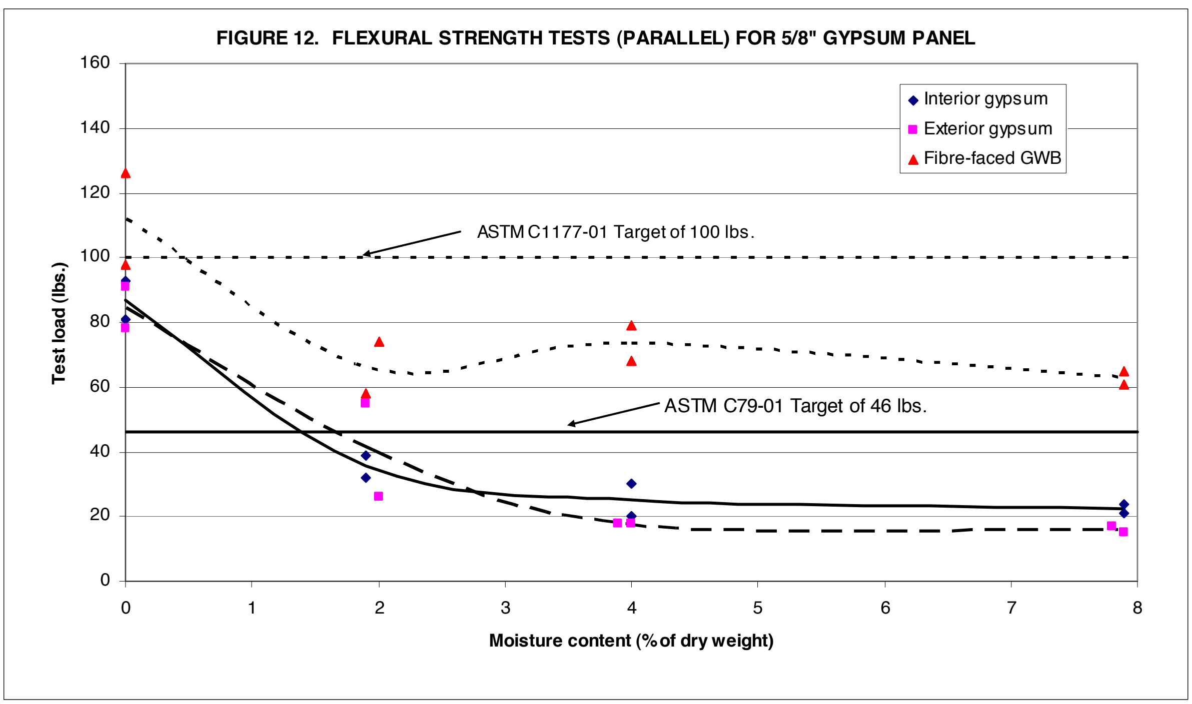


FIGURE 12. FLEXURAL STRENGTH TESTS (PARALLEL) FOR 5/8" GYPSUM PANEL
Test load (lbs.)
Moisture content (% of dry weight)
ASTM C1177-01 Target of 100 lbs.
ASTM C79-01 Target of 46 lbs.
Interior gypsum
Exterior gypsum
Fibre-faced GWB
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8

4.3.3 Facer Delamination

The test for facer delamination was a modified version of CSA A23.2-6B (Reference 12), which is normally used to test adhesion of tiles to concrete substrates. To our knowledge, there are no Standard Specifications for gypsum facer delamination, and one of the objectives for this project was to provide an indication of moisture levels at which this property becomes a concern. In this procedure, a test plate is firmly adhered to the facer, and the amount of tensile force required to separate the facer from the gypsum substrate is measured (Figure 13).

FIGURE 13. TESTING APPARATUS FOR FACER DELAMINATION

Facer-delamination test results are tabulated in Appendix C, and shown graphically in Figures 14 and 15. These show that the applied forces for facer delamination are of similar magnitude as the fastener pull-through tests (compare Figures 4 and 5 with Figures 14 and 15). Both procedures test the integrity of the facer, and it appears to be reasonable to use the fastener pull-through test to characterize facer adhesion of these products.

FIGURE 14. FACER ADHESION TESTS FOR 1/2" GYPSUM PANEL

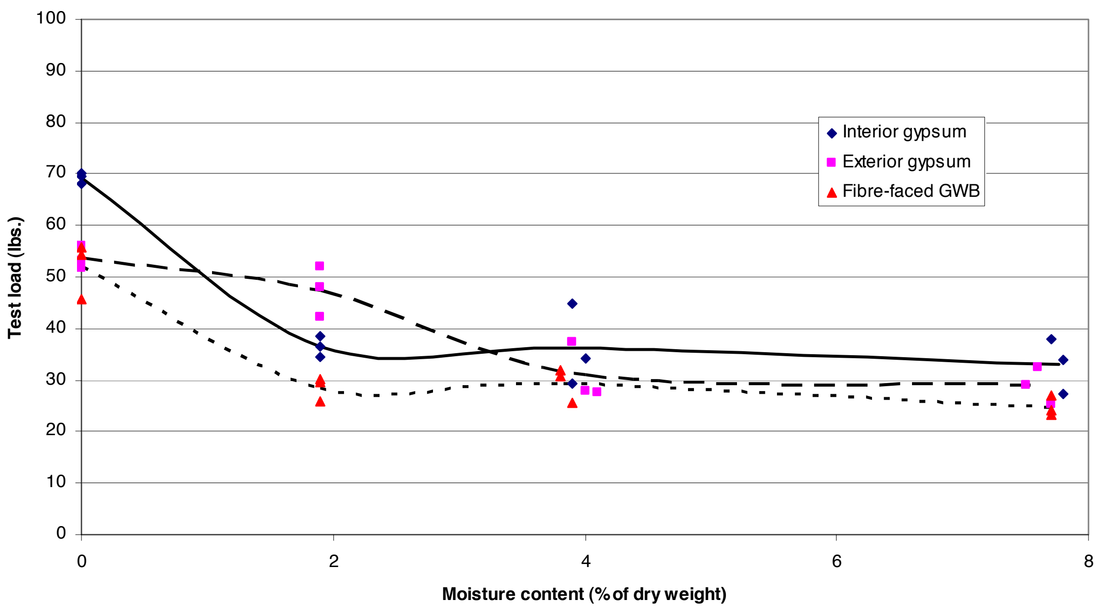
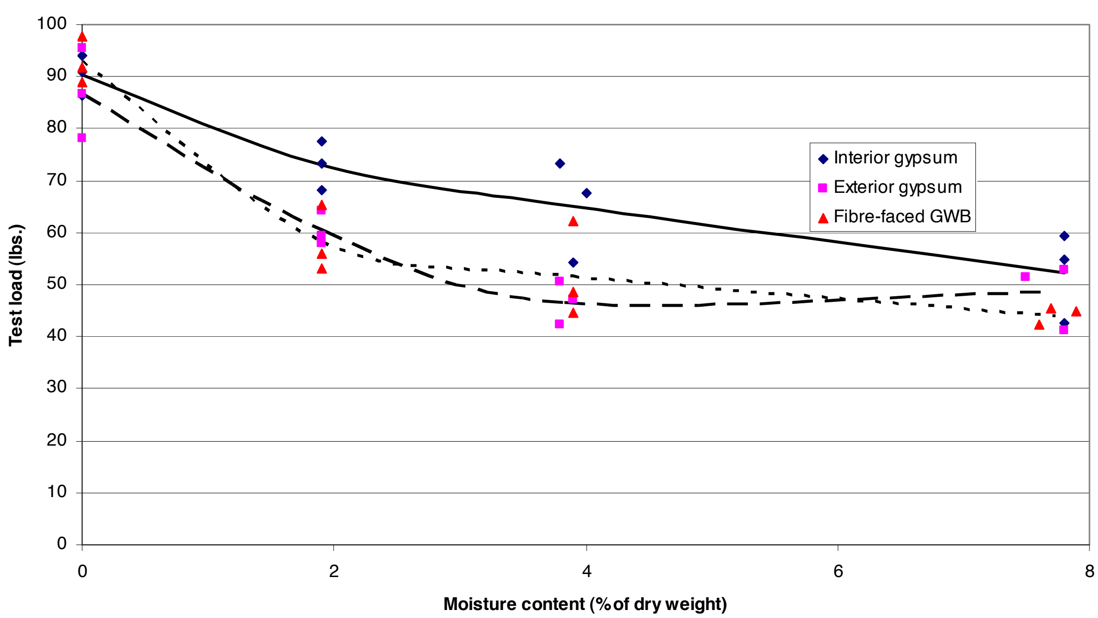


FIGURE 15. FACER ADHESION TESTS FOR 5/8" GYPSUM PANEL



4.4 ENVIRONMENTAL CHAMBER TESTING

As noted in Section 3.3, test panels were constructed and installed in the Environmental Chamber of the Building Envelope Performance Laboratory at Concordia University in Montreal. The results of those tests are presented in the Concordia report attached as Appendix D.

Apart from the conclusions reported for the ability of the test apparatus to record moisture contents (using pin probes and gravimetry), the overall conclusion is that gypsum sheathing exposed to exterior relative humidity levels of 60 – 75% can attain moisture contents of 8 – 10% (as a percentage of dry weight). This does not even consider the moisture-content levels that one might expect in the presence of liquid water (due to wind-driven rain, plumbing leak, or accumulation of condensation in the wall assembly).

5. CONCLUSIONS AND RECOMMENDATIONS

Moisture content expressed as a percentage of saturation is not a useful index of performance, as gypsum sheathing products can absorb almost their own weight of water, and the material was observed to crumble at a much lower moisture content. The fact that the specimens were crumbling confirms that there is a practical upper limit to the amount of water that can be added to gypsum sheathing before it loses structural integrity, and this limit occurs well below saturation.

Handheld moisture meters are generally accurate for paper-faced (GWB and XGG) gypsum sheathing up to (approximately) 6%, but above that level the moisture meter reads lower than the actual value. The results also show that the moisture meters read approximately 3 - 3.4% higher than the gravimetric values for fibre-faced (FFG) sheathing, over the range of moisture contents investigated. The moisture content varies significantly across the GWB specimens, but much less so for the XGG and FFG specimens. The speed of moisture absorption in the specimens may explain this variation, but this should be investigated further as the nature of moisture redistribution within gypsum was not within the scope of this project.

This study has determined a strong correlation between moisture content and the mechanical properties of various types of gypsum sheathing. ASTM tests for flexural strength and fastener pull-through suggest that the mechanical properties of gypsum sheathing are dramatically reduced when the moisture content is increased from 0% to 2%. The mechanical properties still decrease above 2% moisture content, but not as quickly. Facer delamination tests show similar degradation of performance, but is appears to be reasonable to use the fastener pull-through test to characterize facer adhesion of these products.

Paper-faced gypsum sheathing (GWB and XGG) generally does not meet the performance criteria established in ASTM C1396 above a moisture content of approximately 1%, and fibre-faced sheathing (FFG) does not meet the criteria set out in ASTM C1177 above a moisture content of approximately 0.5%. These products do not meet some of the requirements of these Standards even when oven-dry (0% moisture content), so it is not clear that the ASTM criteria are appropriate indicators of in-service performance (this is noted in the ASTM Standards).

Exposure to high-humidity levels in typical construction can result in moisture contents of 8-10% in gypsum sheathing. This does not include exposure to liquid water.

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APPENDIX A

MEASUREMENTS OF

SATURATED MOISTURE CONTENT

OF GYPSUM SHEATHING SPECIMENS

<u>CMHC GWB Test Program</u>

Levelton Engineering Ltd.

Saturation Moisture Content

12" x 12" sample size

		Sample 1	Sample 2	Sample 3	Average	Max	Min	Mean
Regular	Saturated (g)	1456.8	1455.3	1450.1	1454.07			
1/2"	Dry (g)	743.1	738.2	738.6	739.967			
	M.C.	96.0%	97.1%	96.3%	96.5%	97.1%	96.0%	96.5%
Ext. Gr.	Saturated (g)	1053.6	1040.5	1026	1040.03			
1/2"	Dry (g)	707.5	704.7	714.3	708.833			
	M.C.	48.9%	47.7%	43.6%	46.7%	48.9%	43.6%	46.7%
Faced	Saturated (g)	1279.9	1289.3	1312.4	1293.87			
1/2"	Dry (g)	830.4	802.1	805.5	812.667			
	M.C.	54.1%	60.7%	62.9%	59.2%	62.9%	54.1%	59.2%
Regular	Saturated (g)	1876.1	1860.9	1880.3	1872.43			
5/8"	Dry (g)	1069.1	1059.6	1071.9	1066.87			
	M.C.	75.5%	75.6%	75.4%	75.5%	75.6%	75.4%	75.5%
Ext. Gr.	Saturated (g)	1627.3	1627.8	1649.1	1634.73			
5/8"	Dry (g)	941.2	949.6	968.9	953.233			
	M.C.	72.9%	71.4%	70.2%	71.5%	72.9%	70.2%	71.5%
Faced	Saturated (g)	1672.2	1688.3	1648.2	1669.57			
5/8"	Dry (g)	1107.9	1109.6	1099.4	1105.63			
	M.C.	50.9%	52.2%	49.9%	51.0%	52.2%	49.9%	51.0%

APPENDIX B

MEASURED MOISTURE CONTENT OF

GYPSUM SHEATHING SPECIMENS

CMHC GWB Test Program

Levelton Engineering Ltd.

File: 503-028B

Moisture Content

12" x 12" sample size

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
	Average Actual M.C.	0.0%	0.9%	1.9%	3.9%	5.7%	7.7%
	Average Meter M.C.	0.2%	0.6%	1.1%	3.4%	5.1%	4.7%
Regular	Dry (g)	730	730	727.2	731.9	727.1	736.7
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	7.3	14.5	29.3	43.6	58.9
	Test Mass (g)	730.0	736.8	739.8	760.3	769.1	792.9
	Actual M.C.	0.0%	0.9%	1.7%	3.9%	5.8%	7.6%
	Top Right	0.2%	0.6%	0.8%	6.6%	7.7%	7.0%
	Centre	0.2%	0.6%	1.0%	2.0%	1.4%	7.1%
	Bottom Left	0.2%	0.6%	1.6%	1.8%	1.7%	2.8%
	Average M.C.	0.2%	0.6%	1.1%	3.5%	3.6%	5.6%
Regular	Dry (g)	726	726	726.4	731.7	721.7	727.8
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	7.3	14.5	29.3	43.3	58.2
(Same M.C.)	Test Mass (g)	726.0	731.9	740.2	760.3	761.8	783.2
	Actual M.C.	0.0%	0.8%	1.9%	3.9%	5.6%	7.6%
	Top Right	0.2%	0.5%	1.1%	2.4%	5.1%	1.2%
	Centre	0.2%	0.5%	0.9%	2.1%	6.2%	4.5%
	Bottom Left	0.2%	0.6%	1.0%	5.1%	6.1%	7.8%
	Average M.C.	0.2%	0.5%	1.0%	3.2%	5.8%	4.5%
Regular	Dry (g)	721.1	721.1	717.7	724.6	711.2	715.1
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	7.2	14.4	29.0	42.7	57.2
(Same M.C.)	Test Mass (g)	721.0	727.8	731.7	752.4	752.5	770.3
	Actual M.C.	0.0%	0.9%	2.0%	3.8%	5.8%	7.7%
	Top Right	0.2%	0.6%	0.9%	1.3%	6.3%	1.4%
	Centre	0.2%	0.6%	1.1%	1.7%	4.3%	3.3%
	Bottom Left	0.2%	0.6%	1.4%	7.3%	7.1%	7.1%
	Average M.C.	0.2%	0.6%	1.1%	3.4%	5.9%	3.9%

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Average Actual M.C.		0.0%	0.9%	1.9%	3.9%	5.8%	7.8%
Average Meter M.C.		0.2%	0.8%	2.3%	4.7%	6.0%	5.9%
Regular	Dry (g)	1070.1	1070.1	1054.7	1055.4	1053.6	1067.1
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	10.7	21.1	42.2	63.2	85.4
	Test Mass (g)	1070.1	1078.8	1074.0	1096.2	1114.8	1149.9
	Actual M.C.	0.0%	0.8%	1.8%	3.9%	5.8%	7.8%
	Top Right	0.2%	0.7%	2.2%	6.0%	6.2%	2.1%
	Centre	0.2%	0.7%	2.4%	4.0%	6.6%	8.2%
	Bottom Left	0.2%	0.7%	1.7%	5.3%	4.1%	8.0%
	Average M.C.	0.2%	0.7%	2.1%	5.1%	5.6%	6.1%
Regular	Dry (g)	1043	1043	1043.6	1047	1028.9	1042.3
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	10.4	20.9	41.9	61.7	83.4
(Same M.C.)	Test Mass (g)	1043.0	1052.1	1063.2	1087.5	1089.0	1123.0
	Actual M.C.	0.0%	0.9%	1.9%	3.9%	5.8%	7.7%
	Top Right	0.2%	0.7%	3.2%	3.1%	8.0%	3.5%
	Centre	0.2%	0.7%	2.4%	2.9%	6.2%	6.5%
	Bottom Left	0.2%	0.8%	2.2%	7.9%	5.4%	9.1%
	Average M.C.	0.2%	0.7%	2.6%	4.6%	6.5%	6.4%
Regular	Dry (g)	1050	1050	1031.8	1067.6	1038.5	1047.9
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	10.5	20.6	42.7	62.3	83.8
(Same M.C.)	Test Mass (g)	1050.0	1060.4	1051.3	1108.9	1097.7	1130.0
	Actual M.C.	0.0%	1.0%	1.9%	3.9%	5.7%	7.8%
	Top Right	0.2%	0.8%	2.3%	6.3%	7.2%	7.0%
	Centre	0.2%	0.9%	2.4%	2.3%	6.8%	1.2%
	Bottom Left	0.2%	0.9%	2.3%	4.4%	3.7%	7.8%
	Average M.C.	0.2%	0.9%	2.3%	4.3%	5.9%	5.3%

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Average Actual M.C.		0.0%	0.8%	2.0%	3.8%	5.8%	7.6%
Average Meter M.C.		0.1%	0.6%	1.7%	5.0%	6.3%	6.8%
Ext. Gr.	Dry (g)	721.7	721.7	716	725.7	712.9	716.2
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	7.2	14.3	29.0	42.8	57.3
	Test Mass (g)	721.7	727.4	729.9	754.0	754.2	769.9
	Actual M.C.	0.0%	0.8%	1.9%	3.9%	5.8%	7.5%
	Top Right	0.1%	0.5%	1.3%	6.3%	7.1%	6.7%
	Centre	0.1%	0.6%	1.4%	4.5%	7.0%	6.8%
	Bottom Left	0.2%	0.7%	1.8%	2.4%	6.5%	7.2%
	Average M.C.	0.1%	0.6%	1.5%	4.4%	6.9%	6.9%
Ext. Gr.	Dry (g)	726.1	726.1	723.3	734.7	722	711.8
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	7.3	14.5	29.4	43.3	56.9
(Same M.C.)	Test Mass (g)	726.1	732.6	738.3	762.8	763.5	766.1
	Actual M.C.	0.0%	0.9%	2.1%	3.8%	5.7%	7.6%
	Top Right	0.1%	0.6%	2.3%	4.0%	7.3%	6.4%
	Centre	0.1%	0.6%	1.6%	4.2%	4.0%	7.0%
	Bottom Left	0.2%	0.6%	2.0%	6.1%	4.2%	6.6%
	Average M.C.	0.1%	0.6%	2.0%	4.8%	5.2%	6.7%
Ext. Gr.	Dry (g)	727	727	721	729.7	722.6	711.5
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	7.3	14.4	29.2	43.4	56.9
(Same M.C.)	Test Mass (g)	727.0	733.2	734.6	757.6	763.9	765.8
	Actual M.C.	0.0%	0.9%	1.9%	3.8%	5.7%	7.6%
	Top Right	0.1%	0.6%	0.9%	6.6%	7.0%	6.7%
	Centre	0.1%	0.6%	1.7%	6.3%	6.3%	7.1%
	Bottom Left	0.1%	0.6%	2.4%	4.8%	7.1%	7.0%
	Average M.C.	0.1%	0.6%	1.7%	5.9%	6.8%	6.9%

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Average Actual M.C.		0.0%	0.9%	1.8%	3.9%	5.8%	7.8%
Average Meter M.C.		0.2%	0.8%	2.4%	6.4%	6.2%	6.6%
Ext. Gr.	Dry (g)	964.5	964.5	961.6	955	957.5	932.5
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	9.6	19.2	38.2	57.5	74.6
	Test Mass (g)	964.5	972.9	978.1	992.3	1013.0	1004.6
	Actual M.C.	0.0%	0.9%	1.7%	3.9%	5.8%	7.7%
	Top Right	0.2%	0.7%	1.9%	6.8%	6.2%	6.7%
	Centre	0.1%	0.8%	2.7%	6.5%	6.2%	6.0%
	Bottom Left	0.2%	0.7%	2.9%	6.7%	7.1%	6.8%
	Average M.C.	0.2%	0.7%	2.5%	6.7%	6.5%	6.5%
Ext. Gr.	Dry (g)	942.9	942.9	944.1	956.2	951.8	920.8
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	9.4	18.9	38.2	57.1	73.7
(Same M.C.)	Test Mass (g)	942.9	951.4	961.7	993.3	1007.1	992.1
	Actual M.C.	0.0%	0.9%	1.9%	3.9%	5.8%	7.7%
	Top Right	0.2%	0.8%	1.9%	6.2%	6.9%	6.4%
	Centre	0.1%	0.8%	2.6%	6.4%	6.3%	7.0%
	Bottom Left	0.2%	0.8%	2.8%	6.5%	6.3%	7.5%
	Average M.C.	0.2%	0.8%	2.4%	6.4%	6.5%	7.0%
Ext. Gr.	Dry (g)	961.5	961.5	963.3	973.8	981.7	940.7
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	9.6	19.3	39.0	58.9	75.3
(Same M.C.)	Test Mass (g)	961.5	969.4	982.1	1010.6	1038.2	1014.2
	Actual M.C.	0.0%	0.8%	2.0%	3.8%	5.8%	7.8%
	Top Right	0.1%	0.7%	2.4%	6.3%	4.7%	5.1%
	Centre	0.1%	0.8%	2.7%	6.0%	4.5%	6.9%
	Bottom Left	0.2%	0.7%	2.1%	6.1%	7.2%	7.4%
	Average M.C.	0.1%	0.7%	2.4%	6.1%	5.5%	6.5%

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Average Actual M.C.		0.0%	0.8%	1.9%	3.8%	5.7%	7.7%
Average Meter M.C.		0.5%	3.7%	6.7%	8.0%	9.7%	9.8%
Faced	Dry (g)	819.7	819.7	793.1	820.8	792.5	788.9
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	8.2	15.9	32.8	47.6	63.1
	Test Mass (g)	819.7	827.1	808.1	852.6	838.5	850.0
	Actual M.C.	0.0%	0.9%	1.9%	3.9%	5.8%	7.7%
	Top Right	0.5%	2.5%	6.6%	8.4%	15.2%	11.2%
	Centre	0.5%	4.0%	6.8%	8.1%	7.2%	10.7%
	Bottom Left	0.5%	6.0%	6.5%	7.2%	7.2%	9.6%
	Average M.C.	0.5%	4.2%	6.6%	7.9%	9.9%	10.5%
Faced	Dry (g)	817.3	817.3	806.9	818	796.5	773.5
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	8.2	16.1	32.7	47.8	61.9
(Same M.C.)	Test Mass (g)	817.3	823.6	822.3	848.8	840.1	832.6
	Actual M.C.	0.0%	0.8%	1.9%	3.8%	5.5%	7.6%
	Top Right	0.5%	3.2%	6.8%	7.6%	9.8%	11.8%
	Centre	0.5%	3.5%	7.4%	7.7%	10.2%	7.9%
	Bottom Left	0.5%	3.8%	7.1%	8.4%	11.4%	9.8%
	Average M.C.	0.5%	3.5%	7.1%	7.9%	10.5%	9.8%
Faced	Dry (g)	825.4	825.4	815.1	806.2	805.1	803.9
1/2"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	8.3	16.3	32.2	48.3	64.3
(Same M.C.)	Test Mass (g)	825.4	832.1	830.3	837.2	851.3	866.0
	Actual M.C.	0.0%	0.8%	1.9%	3.8%	5.7%	7.7%
	Top Right	0.5%	2.7%	6.0%	10.0%	8.1%	11.9%
	Centre	0.5%	3.4%	6.4%	7.5%	8.3%	7.3%
	Bottom Left	0.5%	4.3%	6.4%	6.7%	9.9%	7.9%
	Average M.C.	0.5%	3.5%	6.3%	8.1%	8.8%	9.0%

	(Different M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Average Actual M.C.		0.0%	0.7%	2.0%	3.8%	5.8%	7.8%
Average Meter M.C.		0.4%	4.5%	6.6%	7.8%	9.3%	11.8%
Faced	Dry (g)	1089.5	1095.9	1100.1	1098.4	1101.8	1093.1
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 1	Added Water (g)	0.0	11.0	22.0	43.9	66.1	87.4
	Test Mass (g)	1089.5	1099.9	1122.0	1139.9	1166.1	1177.6
	Actual M.C.	0.0%	0.4%	2.0%	3.8%	5.8%	7.7%
	Top Right	0.4%	4.3%	6.8%	7.8%	9.4%	11.2%
	Centre	0.4%	4.5%	5.1%	7.6%	7.9%	9.4%
	Bottom Left	0.5%	5.3%	6.9%	7.6%	8.1%	13.5%
	Average M.C.	0.4%	4.7%	6.3%	7.7%	8.5%	11.4%
Faced	Dry (g)	1084.7	1084.7	1104.2	1096.1	1103.5	1100.9
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 2	Added Water (g)	0.0	10.8	22.1	43.8	66.2	88.1
(Same M.C.)	Test Mass (g)	1084.7	1094.6	1127.1	1138.2	1167.7	1187.5
	Actual M.C.	0.0%	0.9%	2.1%	3.8%	5.8%	7.9%
	Top Right	0.5%	4.9%	6.5%	9.6%	8.7%	8.9%
	Centre	0.4%	4.7%	6.8%	7.3%	9.9%	9.1%
	Bottom Left	0.5%	4.8%	7.2%	7.4%	9.3%	15.8%
	Average M.C.	0.5%	4.8%	6.8%	8.1%	9.3%	11.3%
Faced	Dry (g)	1086.2	1086.2	1090.6	1096.9	1108.9	1103.6
5/8"	Target M.C.	0.0%	1.0%	2.0%	4.0%	6.0%	8.0%
Test 3	Added Water (g)	0.0	10.9	21.8	43.9	66.5	88.3
(Same M.C.)	Test Mass (g)	1086.2	1095.7	1111.3	1137.8	1173.3	1190.0
	Actual M.C.	0.0%	0.9%	1.9%	3.7%	5.8%	7.8%
	Top Right	0.4%	3.8%	6.3%	7.7%	10.9%	10.4%
	Centre	0.5%	4.0%	6.6%	7.6%	10.6%	12.5%
	Bottom Left	0.4%	4.0%	6.9%	7.5%	8.6%	15.4%
	Average M.C.	0.4%	3.9%	6.6%	7.6%	10.0%	12.8%

APPENDIX C

MEASURED MECHANICAL PROPERTIES OF GYPSUM SHEATHING SPECIMENS

CMHC GWB Test Program					
Levelton Engineering Ltd.					
File:	503-028B				
Adhesion					
12" x 12" sample size					
	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Regular	Dry (g)	735.3	736	734	
1/2"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)	735.3	736.0	734.0	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	69.67	70	68.23	69.30
	Stress (MPa)	0.07	0.07	0.07	0.07
Regular	Dry (g)	745	742.7	735.6	
1/2"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	29.8	29.7	29.4	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	773.9	772.5	764.6	
	Actual M.C.	3.9%	4.0%	3.9%	3.9%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Regular	Dry (g)	739.3	738.2	733.4	
1/2"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	59.1	59.1	58.7	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	796.9	795.6	789.9	
	Actual M.C.	7.8%	7.8%	7.7%	7.8%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	27.34	33.84	37.92	33.03
	Stress (MPa)	0.03	0.03	0.04	0.03

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Regular	Dry (g)	1059	1031.1	1051.3	
5/8"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)				
	Actual M.C.	-100.0%	-100.0%	-100.0%	-100.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	91.05	93.92	86.42	90.46
	Stress (MPa)	0.09	0.09	0.09	0.09
Regular	Dry (g)	1066.1	1051.8	1054.5	
5/8"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	42.6	42.1	42.2	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	1106.9	1093.4	1095.7	
	Actual M.C.	3.8%	4.0%	3.9%	3.9%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Regular	Dry (g)	1069.1	1053.5	1060	
5/8"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	85.5	84.3	84.8	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	1152.4	1136.1	1143.2	
	Actual M.C.	7.8%	7.8%	7.8%	7.8%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	**42.66**	54.78	59.30	52.25
	Stress (MPa)	0.04	0.06	0.06	0.05

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Ext. Gr.	Dry (g)	703.8	708.1	710.5	
1/2"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)	703.8	708.1	710.5	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	53.02	51.81	56.11	53.65
	Stress (MPa)	0.05	0.05	0.06	0.05
Ext. Gr.	Dry (g)	707.5	709.3	709.3	
1/2"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	28.3	28.4	28.4	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	736.3	737.0	738.0	
	Actual M.C.	4.1%	3.9%	4.0%	4.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Ext. Gr.	Dry (g)	705.7	709.8	719.9	
1/2"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	56.5	56.8	57.6	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	759.9	763.6	773.7	
	Actual M.C.	7.7%	7.6%	7.5%	7.6%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	25.24	32.52	28.99	28.92
	Stress (MPa)	0.03	0.03	0.03	0.03

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Ext. Gr.	Dry (g)	945.1	952.3	988.1	
5/8"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)	945.1	952.3	988.1	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	78.04	86.53	95.46	86.68
	Stress (MPa)	0.08	0.09	0.10	0.09
Ext. Gr.	Dry (g)	940.5	948.2	986.8	
5/8"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	37.6	37.9	39.5	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	976.3	984.9	1024.7	
	Actual M.C.	3.8%	3.9%	3.8%	3.8%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Ext. Gr.	Dry (g)	941.5	942.1	958.3	
5/8"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	75.3	75.4	76.7	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	1015.1	1015.3	1030.0	
	Actual M.C.	7.8%	7.8%	7.5%	7.7%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	52.80	41.23	51.37	48.47
	Stress (MPa)	0.05	0.04	0.05	0.05

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Faced	Dry (g)	803.2	797.9	803.3	
1/2"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)	803.2	797.9	803.3	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	45.75	54.34	55.78	51.96
	Stress (MPa)	0.05	0.05	0.06	0.05
Faced	Dry (g)	802.7	801.5	808.9	
1/2"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	32.1	32.1	32.4	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	833.7	832.3	839.9	
	Actual M.C.	3.9%	3.8%	3.8%	3.8%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Faced	Dry (g)	784.3	788.5	799.4	
1/2"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	62.7	63.1	64.0	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	844.8	849.3	861.1	
	Actual M.C.	7.7%	7.7%	7.7%	7.7%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	26.90	23.37	24.25	24.84
	Stress (MPa)	0.03	0.02	0.02	0.03

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Average
Faced	Dry (g)	1100.5	1112.5	1106.3	
5/8"	Target M.C.	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	
	Plate Mass (g)				
	Test Mass (g)	1100.5	1112.5	1106.3	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	97.60	91.71	88.96	92.76
	Stress (MPa)	0.10	0.09	0.09	0.09
Faced	Dry (g)	1098.7	1105.9	1090.1	
5/8"	Target M.C.	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	43.9	44.2	43.6	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	1141.6	1148.5	1132.6	
	Actual M.C.	3.9%	3.9%	3.9%	3.9%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)				0.00
	Stress (MPa)	0.00	0.00	0.00	0.00
Faced	Dry (g)	1100.9	1111.2	1108.9	
5/8"	Target M.C.	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	88.1	88.9	88.7	
(Diff. M.C.)	Plate Mass (g)				
	Test Mass (g)	1188.0	1195.4	1194.0	
	Actual M.C.	7.9%	7.6%	7.7%	7.7%
	Plate Dia. (mm)	75.0	75.0	75.0	
	Test Load (lbs.)	44.75	42.33	45.42	44.17
	Stress (MPa)	0.05	0.04	0.05	0.04

CMHC GWB Test Program

Levelton Engineering Ltd.

File: 503-028B

Nail Pull

6" x 6" sample size

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Regular	Dry (g)	185.3	181.7	181	179.9	184.1	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	185.3	181.7	181.0	179.9	184.1	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	67	67	68	71	62	67
Regular	Dry (g)	188.5	181.8	183.2	180.7	184.8	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	7.5	7.3	7.3	7.2	7.4	
(Diff. M.C.)	Test Mass (g)	196.5	189.0	190.8	188.5	192.2	
	Actual M.C.	4.2%	4.0%	4.1%	4.3%	4.0%	4.1%
	Test Load (lbs.)	43	40	49	41	49	44
Regular	Dry (g)	183.5	184.7	182	182.7	186.7	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	14.7	14.8	14.6	14.6	14.9	
(Diff. M.C.)	Test Mass (g)	197.7	198.3	195.7	196.0	201.5	
	Actual M.C.	7.7%	7.4%	7.5%	7.3%	7.9%	7.6%
	Test Load (lbs.)	33	34	31	32	33	33

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Regular	Dry (g)	247.6	254.3	252.5	247	255.7	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	247.6	254.3	252.5	247.0	255.7	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	77	87	86	74	82	81
Regular	Dry (g)	255.1	258.5	253.1	248.4	260	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	10.2	10.3	10.1	9.9	10.4	
(Diff. M.C.)	Test Mass (g)	265.3	268.6	263.4	260.2	270.5	
	Actual M.C.	4.0%	3.9%	4.1%	4.8%	4.0%	4.2%
	Test Load (lbs.)	48	49	48	45	54	49
Regular	Dry (g)	258.5	259	249.4	249.5	257.7	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	20.7	20.7	20.0	20.0	20.6	
(Diff. M.C.)	Test Mass (g)	278.2	278.7	269.3	269.1	277.2	
	Actual M.C.	7.6%	7.6%	8.0%	7.9%	7.6%	7.7%
	Test Load (lbs.)	37	35	39	36	36	37

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Ext. Gr.	Dry (g)	176.5	176.8	176	178.4	179.6	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	176.5	176.8	176.0	178.4	179.6	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	81	76	64	77	72	74
Ext. Gr.	Dry (g)	179.3	178.9	179.5	178.3	181.1	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	7.2	7.2	7.2	7.1	7.2	
(Diff. M.C.)	Test Mass (g)	186.4	186.0	186.9	185.4	188.7	
	Actual M.C.	4.0%	4.0%	4.1%	4.0%	4.2%	4.0%
	Test Load (lbs.)	40	35	41	35	39	38
Ext. Gr.	Dry (g)	184.5	182.4	180.1	181.8	183.3	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	14.8	14.6	14.4	14.5	14.7	
(Diff. M.C.)	Test Mass (g)	198.7	196.9	193.9	195.5	197.7	
	Actual M.C.	7.7%	7.9%	7.7%	7.5%	7.9%	7.7%
	Test Load (lbs.)	25	30	31	29		23

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Ext. Gr.	Dry (g)	231.7	236	239	246.6	241.6	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	231.7	236.0	239.0	246.6	241.6	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	74	73	73	68	73	72
Ext. Gr.	Dry (g)	238.6	236.3	239.6	244.5	242.7	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	9.5	9.5	9.6	9.8	9.7	
(Diff. M.C.)	Test Mass (g)	247.8	245.7	248.8	253.8	252.6	
	Actual M.C.	3.9%	4.0%	3.8%	3.8%	4.1%	3.9%
	Test Load (lbs.)	42	37	39	38	35	38
Ext. Gr.	Dry (g)	245.7	242	250.4	244.4	248.5	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	19.7	19.4	20.0	19.6	19.9	
(Diff. M.C.)	Test Mass (g)	264.9	261.1	269.3	262.9	267.7	
	Actual M.C.	7.8%	7.9%	7.5%	7.6%	7.7%	7.7%
	Test Load (lbs.)	34	33	28	27	34	31

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Faced	Dry (g)	208	199.5	198	196.8	194.4	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	208.0	199.5	198.0	196.8	194.4	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	63	71	73	67	66	68
Faced	Dry (g)	194.6	206.3	196.8	193.3	194.2	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	7.8	8.3	7.9	7.7	7.8	
(Diff. M.C.)	Test Mass (g)	202.2	215.0	204.3	201.0	202.3	
	Actual M.C.	3.9%	4.2%	3.8%	4.0%	4.2%	4.0%
	Test Load (lbs.)	16	14	15	16	16	15
Faced	Dry (g)	193.8	195.3	200.7	195	200.7	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	15.5	15.6	16.1	15.6	16.1	
(Diff. M.C.)	Test Mass (g)	209.7	211.3	216.9	210.9	217.2	
	Actual M.C.	8.2%	8.2%	8.1%	8.2%	8.2%	8.2%
	Test Load (lbs.)	14	17	12	14	19	15

	(Same M.C.)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Faced	Dry (g)	265.3	262.7	267.7	260.9	267	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	0.0	
	Test Mass (g)	265.3	262.7	267.7	260.9	267.0	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	113	96	104	110	104	105
Faced	Dry (g)	264.3	267.3	263.7	264.3	263.1	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	10.6	10.7	10.5	10.6	10.5	
(Diff. M.C.)	Test Mass (g)	275.0	278.2	274.0	275.1	273.6	
	Actual M.C.	4.0%	4.1%	3.9%	4.1%	4.0%	4.0%
	Test Load (lbs.)	19	32	24	21	28	25
Faced	Dry (g)	260.8	262.9	267.1	264.2	262.1	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	20.9	21.0	21.4	21.1	21.0	
(Diff. M.C.)	Test Mass (g)	281.7	284.0	288.7	284.9	283.4	
	Actual M.C.	8.0%	8.0%	8.1%	7.8%	8.1%	8.0%
	Test Load (lbs.)	24	25	26	20	19	23

CMHC GWB Test Program

Levelton Engineering Ltd.

File: 503-028B

Flexure

12" x 16" sample size

	(Same M.C.)	Parallel Up	Parallel Down	Perpendicular Up	Perpendicular Down	Average
Regular	Dry (g)	985.1	986.1	984.5	986.8	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	985.1	986.1	984.5	986.8	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	154	152	62	65	108
Regular	Dry (g)	975.2	974	986.6	986.8	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	39.0	39.0	39.5	39.5	
(Diff. M.C.)	Test Mass (g)	1013.4	1012.7	1025.1	1025.7	
	Actual M.C.	3.9%	4.0%	3.9%	3.9%	3.9%
	Test Load (lbs.)	47	49	19	29	36
Regular	Dry (g)	975.6	981.9	986.4	982.3	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	78.0	78.6	78.9	78.6	
(Diff. M.C.)	Test Mass (g)	1052.7	1059.4	1064.7	1059.9	
	Actual M.C.	7.9%	7.9%	7.9%	7.9%	7.9%
	Test Load (lbs.)	42	40	15	**10**	27

	(Same M.C.)	Parallel	Parallel	Perpendicular	Perpendicular	Average
		Up	Down	Up	Down	
Regular	Dry (g)	1377.1	1377.8	1371	1366.1	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	1377.1	1377.8	1371.0	1366.1	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	230	209	81	93	153
Regular	Dry (g)	1371.2	1378.6	1370	1365.7	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	54.8	55.1	54.8	54.6	
(Diff. M.C.)	Test Mass (g)	1425.7	1433.3	1424.7	1419.7	
	Actual M.C.	4.0%	4.0%	4.0%	4.0%	4.0%
	Test Load (lbs.)	52	45	20	30	37
Regular	Dry (g)	1378.2	1387.4	1356.5	1350.4	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	110.3	111.0	108.5	108.0	
(Diff. M.C.)	Test Mass (g)	1486.9	1497.6	1463.2	1456.2	
	Actual M.C.	7.9%	7.9%	7.9%	7.8%	7.9%
	Test Load (lbs.)	40	40	24	**21**	31

	(Same M.C.)	Parallel	Parallel	Perpendicular	Perpendicular	Average
		Up	Down	Up	Down	
Ext. Gr.	Dry (g)	928.2	933.5	920.9	947.4	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	928.2	933.5	920.9	947.4	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	124	133	75	50	96
Ext. Gr.	Dry (g)	931.4	945.6	935.9	945.3	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	37.3	37.8	37.4	37.8	
(Diff. M.C.)	Test Mass (g)	968.6	983.6	972.8	981.6	
	Actual M.C.	4.0%	4.0%	3.9%	3.8%	3.9%
	Test Load (lbs.)	29	29	14	10	21
Ext. Gr.	Dry (g)	942.4	943	939.5	952.1	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	75.4	75.4	75.2	76.2	
(Diff. M.C.)	Test Mass (g)	1015.5	1016.9	1013.8	1027.0	
	Actual M.C.	7.8%	7.8%	7.9%	7.9%	7.8%
	Test Load (lbs.)	27	26	10	8	18

	(Same M.C.)	Parallel	Parallel	Perpendicular	Perpendicular	Average
		Up	Down	Up	Down	
Ext. Gr.	Dry (g)	1241	1257.7	1243.3	1277.2	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	1241.0	1257.7	1243.3	1277.2	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	221	213	91	78	151
Ext. Gr.	Dry (g)	1264.1	1275.3	1257.7	1286.3	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	50.6	51.0	50.3	51.5	
(Diff. M.C.)	Test Mass (g)	1311.8	1325.5	1306.4	1337.4	
	Actual M.C.	3.8%	3.9%	3.9%	4.0%	3.9%
	Test Load (lbs.)	44	48	18	18	32
Ext. Gr.	Dry (g)	1283.7	1290.2	1246.4	1282.1	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	102.7	103.2	99.7	102.6	
(Diff. M.C.)	Test Mass (g)	1381.8	1391.2	1345.1	1382.3	
	Actual M.C.	7.6%	7.8%	7.9%	7.8%	7.8%
	Test Load (lbs.)	35	39	15	17	27

	(Same M.C.)	Parallel	Parallel	Perpendicular	Perpendicular	Average
		Up	Down	Up	Down	
Faced	Dry (g)	1113.5	1073.2	1107.4	1059.4	
1/2"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	1113.5	1073.2	1107.4	1059.4	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	131	114	102	81	107
Faced	Dry (g)	1058.2	1116.4	1100.6	1070.8	
1/2"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	42.3	44.7	44.0	42.8	
(Diff. M.C.)	Test Mass (g)	1099.5	1160.1	1145.3	1112.8	
	Actual M.C.	3.9%	3.9%	4.1%	3.9%	4.0%
	Test Load (lbs.)	48	59	44	44	49
Faced	Dry (g)	1069.4	1057.8	1119.5	1082.3	
1/2"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	85.6	84.6	89.6	86.6	
(Diff. M.C.)	Test Mass (g)	1153.5	1141.5	1207.6	1167.5	
	Actual M.C.	7.9%	7.9%	7.9%	7.9%	7.9%
	Test Load (lbs.)	40	36	35	37	37

	(Same M.C.)	Parallel	Parallel	Perpendicular	Perpendicular	Average
		Up	Down	Up	Down	
Faced	Dry (g)	1460.5	1484.6	1467.1	1465.7	
5/8"	Target M.C.	0.0%	0.0%	0.0%	0.0%	
Test 1	Added Water (g)	0.0	0.0	0.0	0.0	
	Test Mass (g)	1460.5	1484.6	1467.1	1465.7	
	Actual M.C.	0.0%	0.0%	0.0%	0.0%	0.0%
	Test Load (lbs.)	181	132	126	98	134
Faced	Dry (g)	1485.8	1471.6	1458.2	1448.3	
5/8"	Target M.C.	4.0%	4.0%	4.0%	4.0%	
Test 2	Added Water (g)	59.4	58.9	58.3	57.9	
(Diff. M.C.)	Test Mass (g)	1543.7	1530.4	1516.5	1505.6	
	Actual M.C.	3.9%	4.0%	4.0%	4.0%	4.0%
	Test Load (lbs.)	107	79	79	68	83
Faced	Dry (g)	1458	1471.5	1458.6	1462.6	
5/8"	Target M.C.	8.0%	8.0%	8.0%	8.0%	
Test 3	Added Water (g)	116.6	117.7	116.7	117.0	
(Diff. M.C.)	Test Mass (g)	1571.4	1587.6	1574.3	1578.2	
	Actual M.C.	7.8%	7.9%	7.9%	7.9%	7.9%
	Test Load (lbs.)	86	68	61	65	70

APPENDIX D

ENVIRONMENTAL TESTING OF GYPSUM SHEATHING PANELS AT CONCORDIA UNIVERSITY

Concordia University
Faculty of Engineering and Computer Science
Department of Building, Civil and Environmental Engineering

Relationship between moisture content and mechanical properties of gypsum sheathing

Task 3: Proof-of-concept test on moisture content level of gypsum board in walls exposed to simulated conditions

Final Report

December 2nd, 2004

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Proof-of-concept test on moisture content level of gypsum board in walls exposed to simulated conditions

Objective: To test and monitor the moisture content changes in gypsum sheathing panels built on steel stud frames in a large scale environmental chamber under variable indoor and outdoor conditions.

Introduction:

Gypsum paneling is often used as an architectural finishing element for interior surfaces of residential structural walls and indoor partitions. It is relatively cheap to produce, easy to install and somewhat fire resistant. Interior gypsum board is generally exposed to constant environmental conditions with only minor fluctuations. In non-combustible construction, as steel stud construction replaced concrete masonry units, the choice of exterior sheathing is gypsum board or cement board (OSB and plywood are combustible therefore not eligible). Exterior materials are exposed to far greater environmental fluctuations and may be subject to prolonged exposure to water and moisture.

Sheathing manufacturers state that exterior gypsum sheathing is designed to withstand the elements, including moisture and water infiltration. In order to test the performance of gypsum panels on steel studs, a testing procedure was developed to measure moisture content changes within the gypsum under two different conditions. Within Concordia's Environmental Chamber, a series of panels were tested under specified indoor and outdoor conditions. During the test, the interior and exterior environmental conditions were monitored with a data acquisition system and the moisture content within the gypsum panels measured periodically. The feasibility of measuring moisture content in gypsum through gravimetry was studied.

Apparatus:

The experiment involved the construction of four separate test panels that were installed in the environmental chamber of Concordia's Building Envelope Laboratory. The chamber can reproduce the indoor and outdoor conditions as determined for the test. The panels were constructed with a height of 1080 mm and width of 835 mm. A typical envelope detail is shown in Figure 1, and the details for all four panels can be found in Appendix D1.

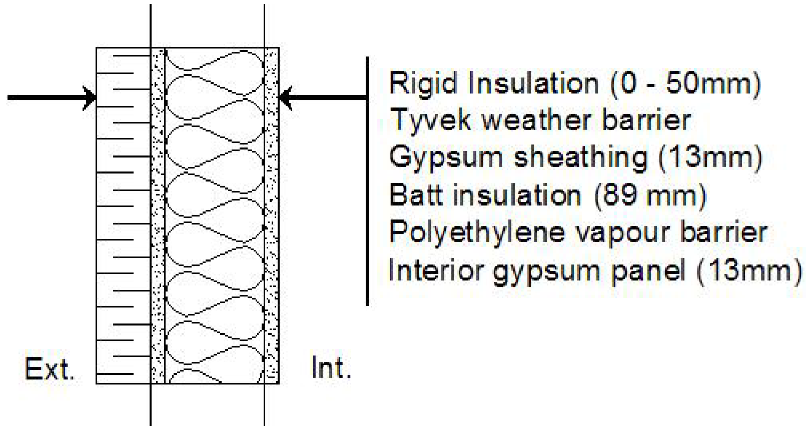


Figure 1. Typical envelope detail

The four panels used in the experiment were constructed using different combinations of rigid and batt insulation thicknesses to reproduce a variety of construction assemblies that may exist in the field. The configuration of the insulation used in each panel is presented in Table 1 below.

Table 1. Insulation

	Rigid Insulation	Batt Insulation
Panel A	None	89 mm
Panel B	50 mm	89 mm
Panel C	25 mm	89 mm
Panel D	50 mm	None

Each panel was equipped with 8 thermocouples (Type T), 1 relative humidity sensor, 5 moisture content sensors and three gravimetric samples. Two thermocouples were placed on the interior gypsum surface exposed to the indoor environment. Another thermocouple was paired with a relative humidity sensor that was placed at the center of the inter-stud space inside the batt insulation (where applicable). Finally, the moisture content sensors were all placed on the exterior gypsum panels and paired with thermocouples. The configuration of the sensors on the exterior gypsum sheathing is shown below in Figure 2.

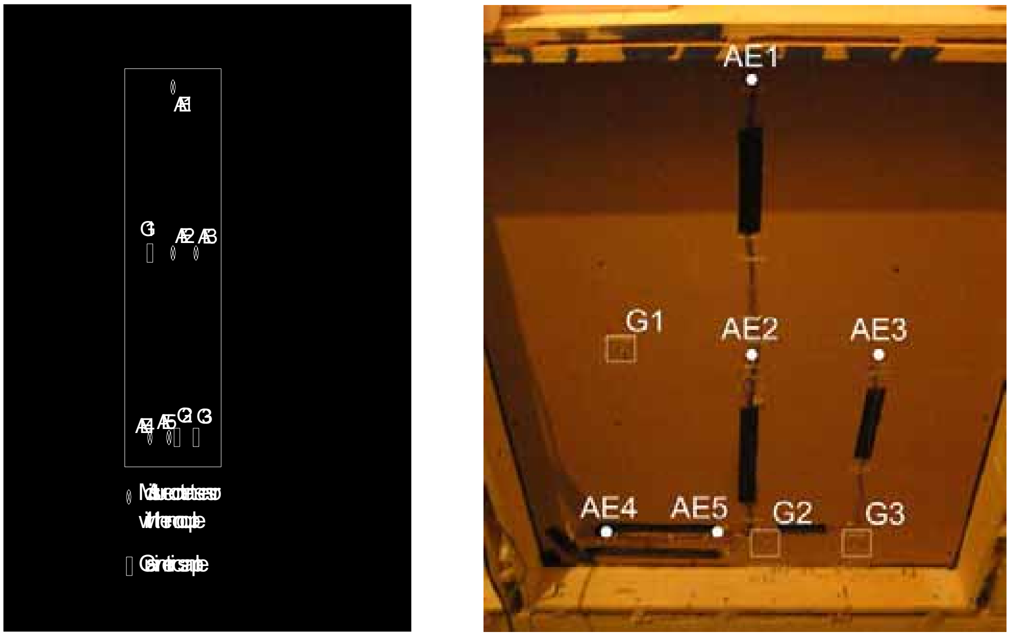


Figure 2. Exterior sheathing sensor and gravimetric sample locations

Procedure

Once the panels were built and installed in the environmental chamber, the pre-testing phase of the experiment began. Every sensor was tested with hand held measurement devices prior to the start of the experiment to ensure the validity of the data. The sensors were then connected to the data acquisition system and verified again. Any erroneous readings were investigated and corrected.

The conditions of the environmental chamber were brought to steady state and changed at the midpoint of the experiment. The interior/exterior conditions are shown below in Table 2. Note that temperatures are dry bulb temperatures.

Table 2. Environmental chamber conditions

	May 1st to July 12th	**July 12th to Sept. 10th**
Interior Conditions	21 °C, 60% RH	21 °C, 30% RH
Exterior Conditions	13.5 °C, 60% RH	5 °C, 60% RH*

* The setpoint was 60% RH, but in reality it hovered around 75% due to the low temperature.

The testing procedure was straightforward in execution. The data acquisition system automatically recorded the temperature and relative humidity data for the test assembly. The manual measurements consisted of daily recording of the moisture content pins and weekly gravimetric sample weighing.

Data

The moisture content data can be found in Figures 3 through 6, and in table form in Appendix D2. The moisture content is expressed in percent of dry weight, as measured with the Delmhorst moisture content meter. No calibration curve was used.

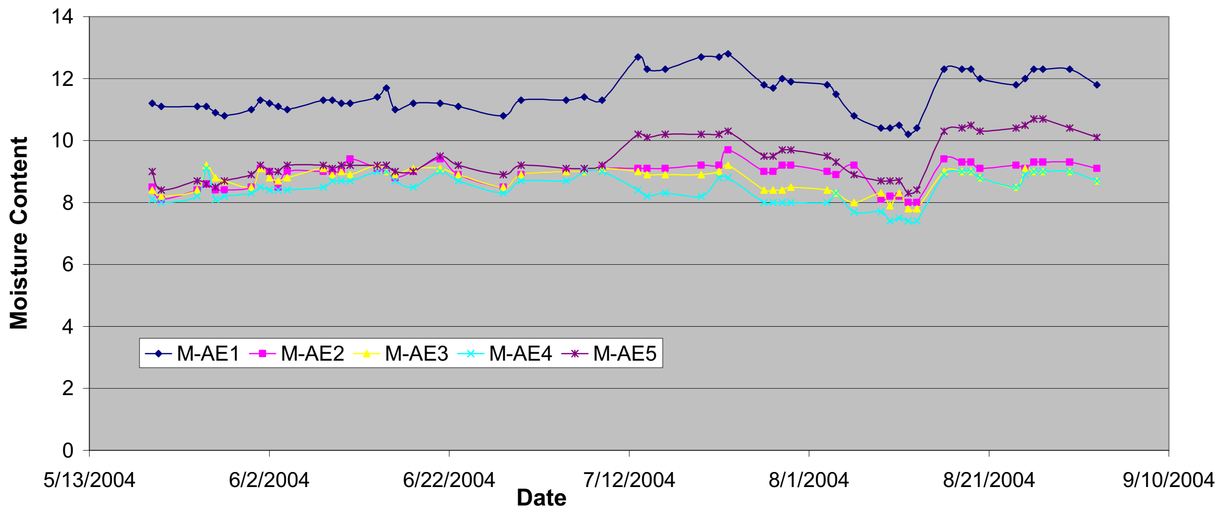


Figure 3. Moisture Content Sensor Results - Panel A

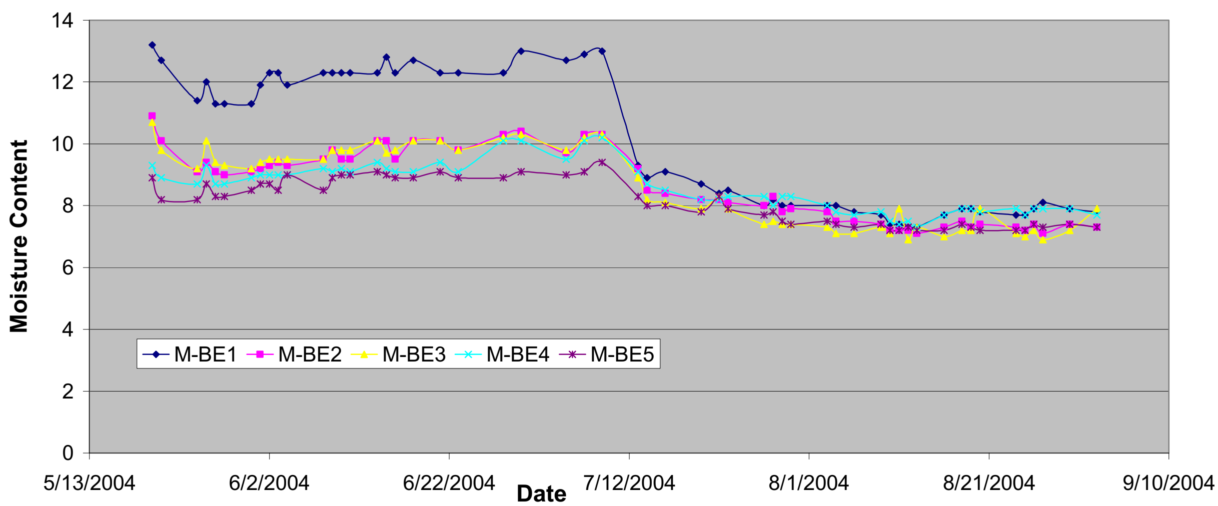


Figure 4. Moisture Content Sensor Results - Panel B

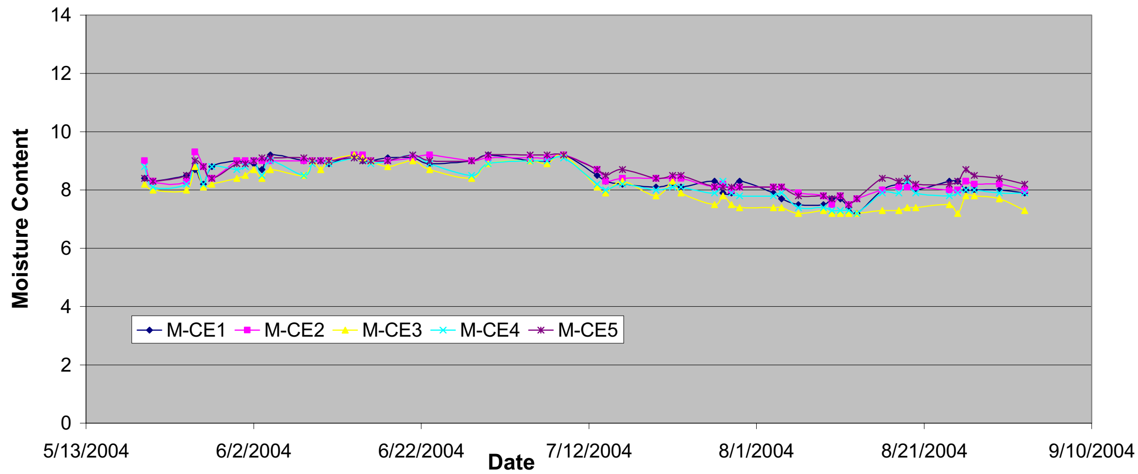


Figure 5. Moisture Content Sensor Results - Panel C

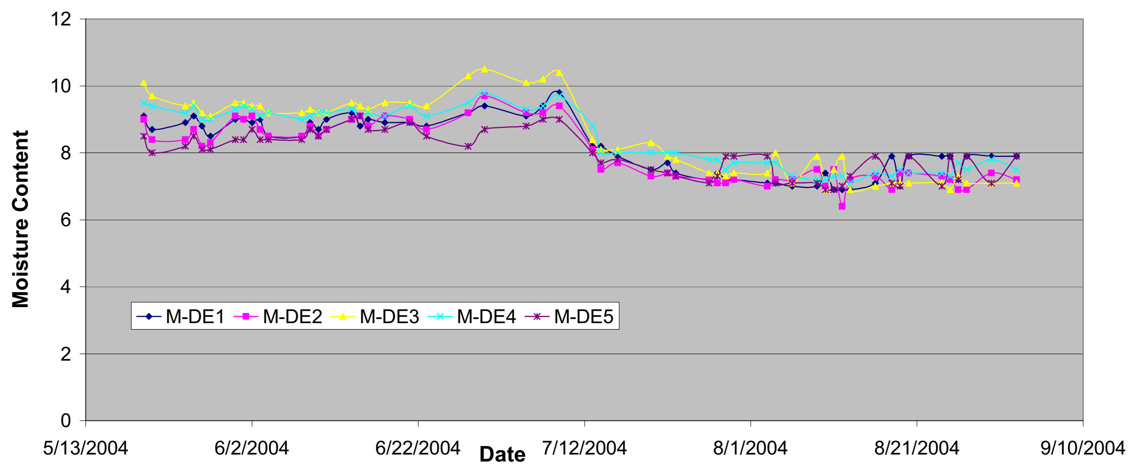


Figure 6. Moisture Content Sensor Results - Panel D

As the graphs above show a change of moisture content when the temperature was decreased and that the gravimetric samples do not have any change of mass, the changes in Figures 3-6 result from the dependency on temperature of the moisture content readings.

The gravimetric samples proved to be ineffective at measuring changes in moisture content changes in gypsum. The brittle nature of gypsum board proved to be problematic in the periodic weighing of the samples because of the loss in mass during the weighing process. Every time the samples were removed and replaced into the gypsum sheathing a minute amount of the gypsum powder would fall from the sample. Over time the loss in mass was enough to obscure the change in mass due to moisture. Sealing the edges of the samples can reduce the loss in mass from the weighing process, but has the side effect of introducing a capillary break between the sample and the adjacent gypsum. The gravimetric samples are shown in Figure 7 below.

Figure 7. Gravimetric samples

The gravimetric data is tabulated in Appendix D3, and is shown below in Figure 8.

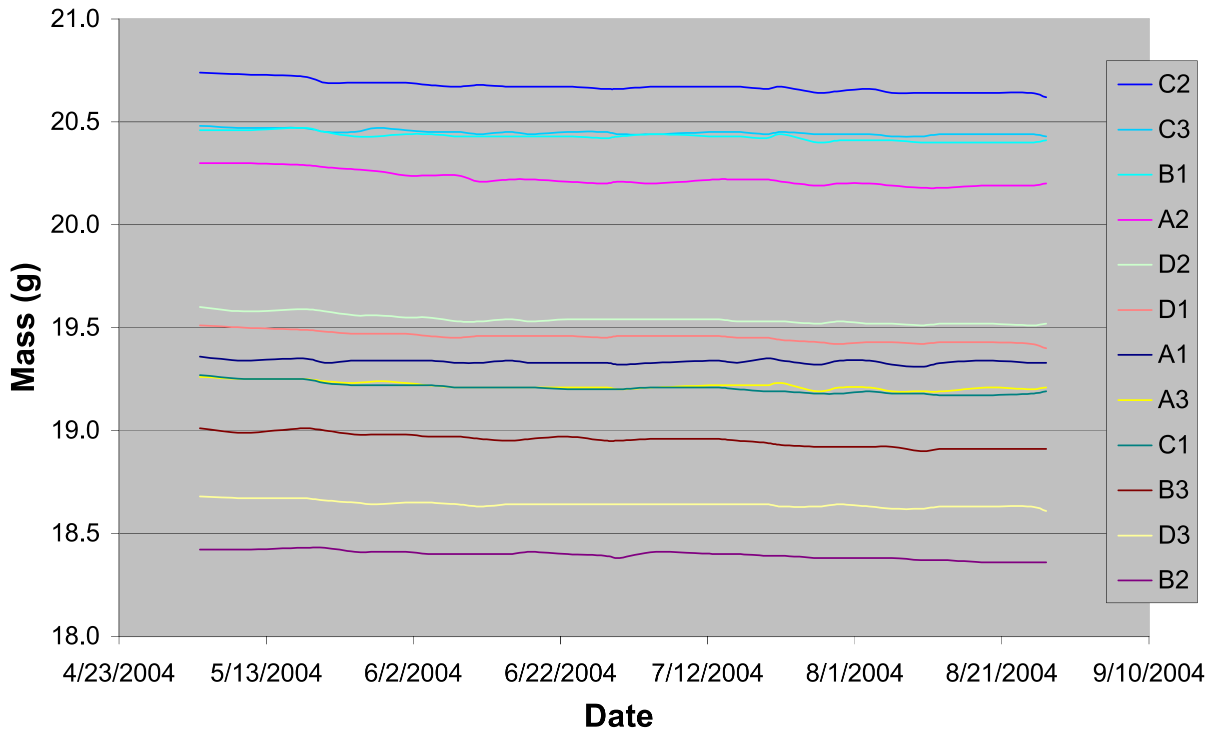


Figure 8. Gravimetric sample data

The temperature of the surface of the gypsum was measured using the data acquisition system. Data was recorded every five minutes from 11:30 AM on June 2nd, 2004, until 11:55 PM September 2nd, 2004. The result was over 26000 data points for 32 thermocouples and 4 RH sensors. To summarize this data, the outdoor surface temperature results were averaged and compared with the indoor surface temperatures and the outdoor temperature values. The results for each panel are shown below in Figures 9 through 12.

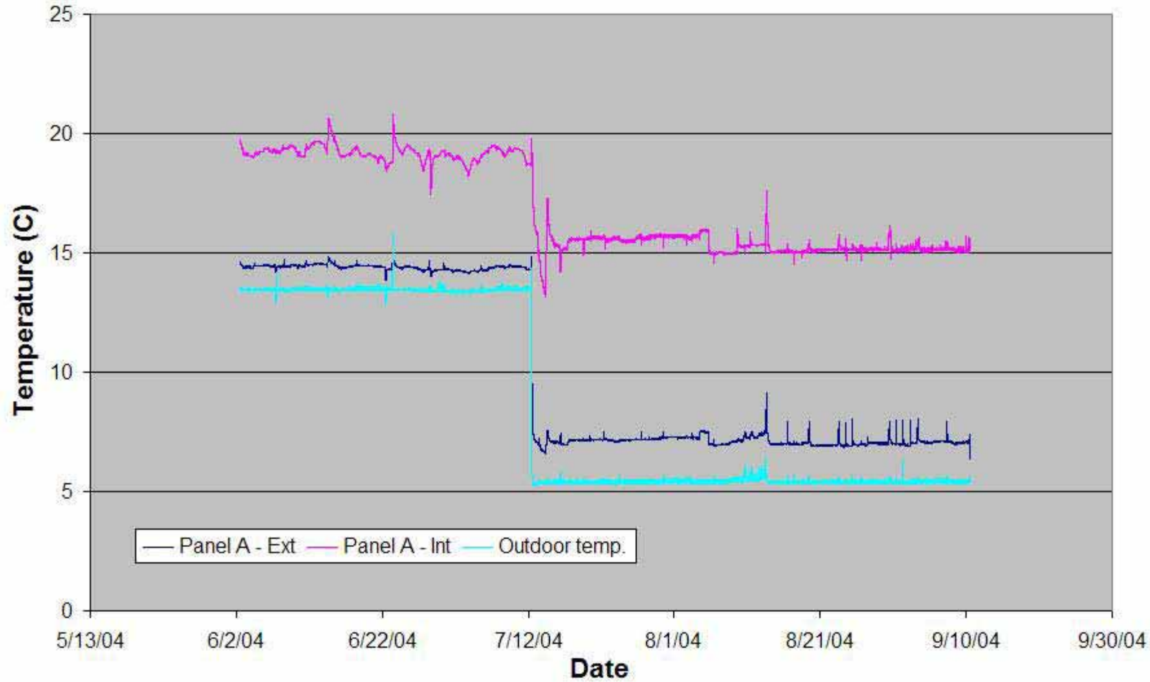


Figure 9. Panel A Surface Temperatures

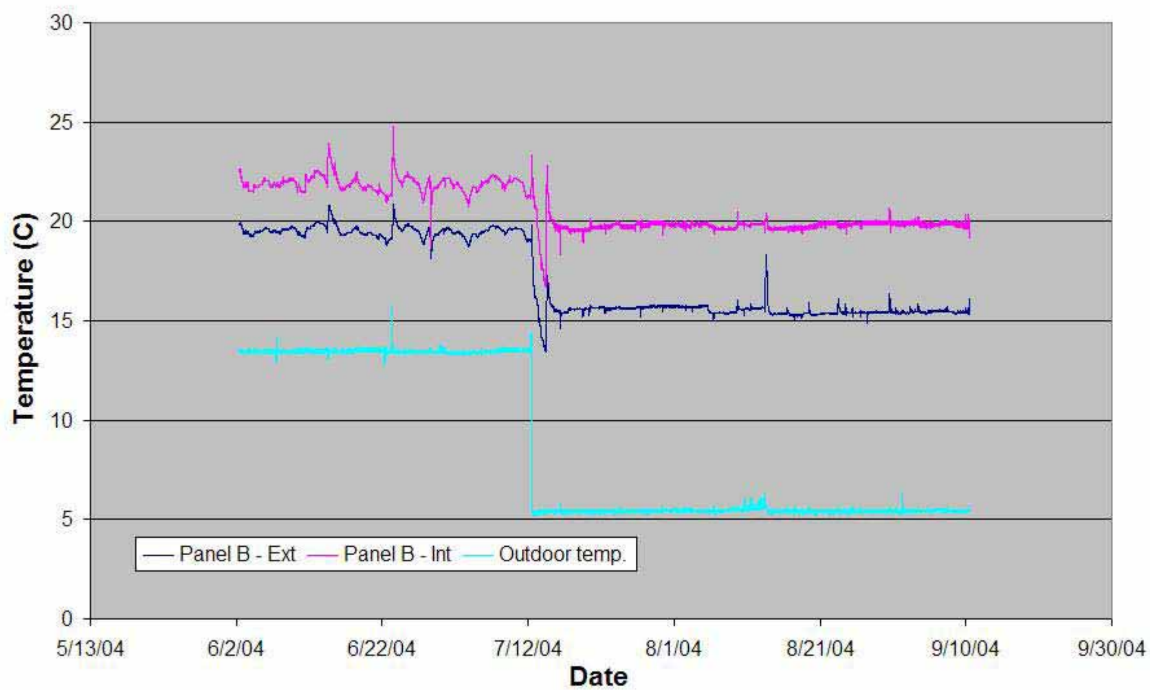


Figure 10. Panel B Surface Temperatures

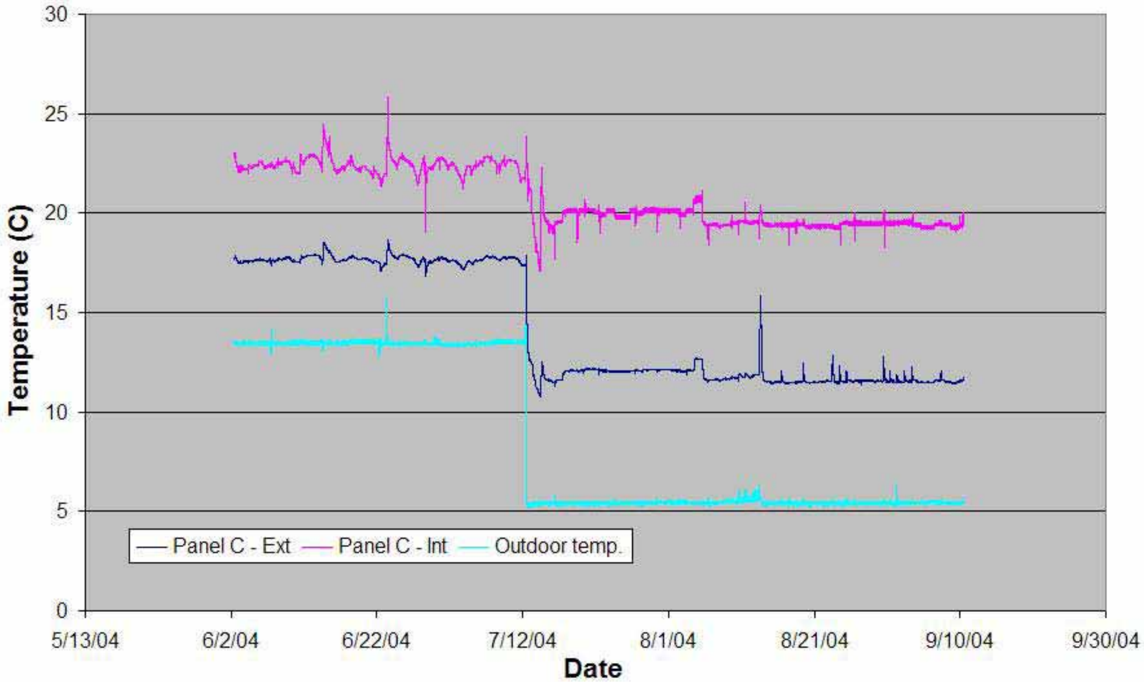


Figure 11. Panel C Surface Temperatures

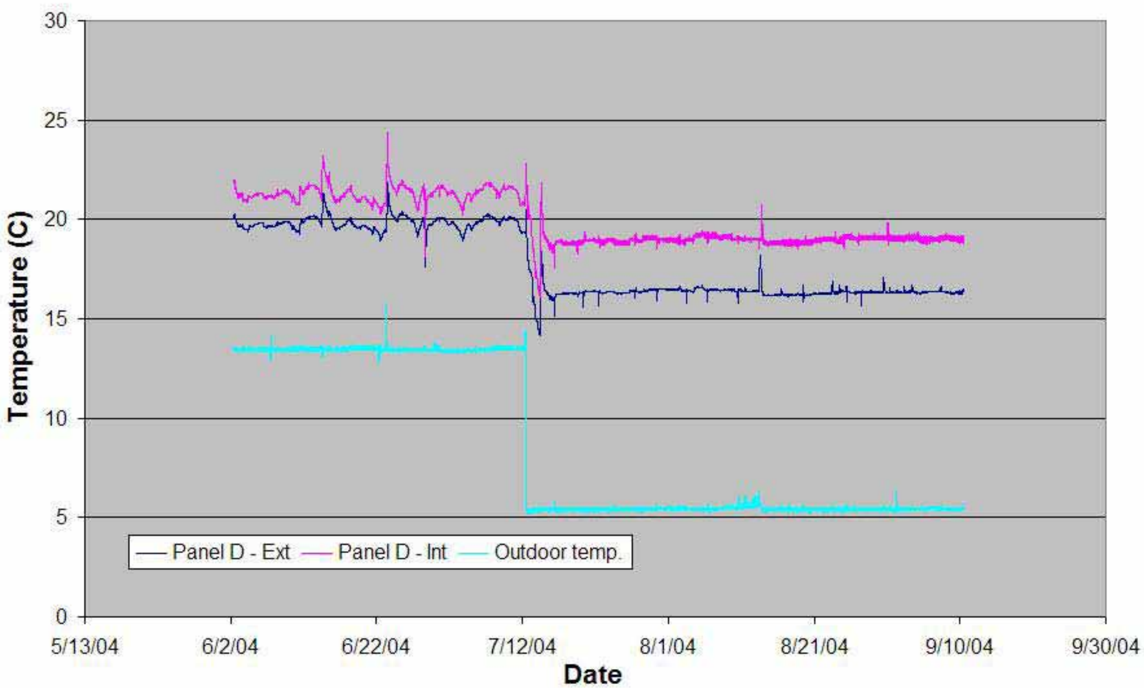


Figure 12. Panel D Surface Temperatures

The dewpoint temperature of the indoor air for 21 °C dry bulb and 60% RH is approximately 13 °C. For the second portion of the experiment the dewpoint temperature dropped to around 3 °C. As can be seen from the surface temperature graphs above, for the conditions used in the experiment the indoor surface temperature never approaches the dewpoint temperature to indicate a risk of condensation on the interior surface of the gypsum.

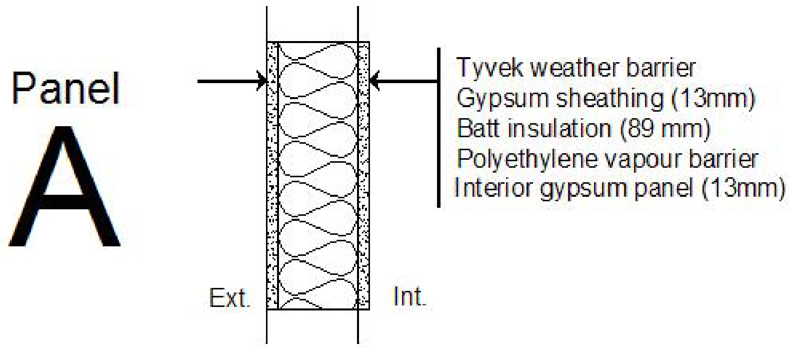
However, if interior air were to penetrate into the assembly in the form of air exfiltration, there is a possibility of condensation on the exterior gypsum, particularly in the case of Panel A where the surface temperature of the gypsum hovered around 14 °C. With proper air- and vapour-barrier systems in place in the assembly, inside vapour will play a negligible role in wetting of exterior gypsum board. Possible sources of wetting of the exterior gypsum sheathing could include humid indoor air exfiltration, water infiltration and outdoor conditions with very high relative humidity.

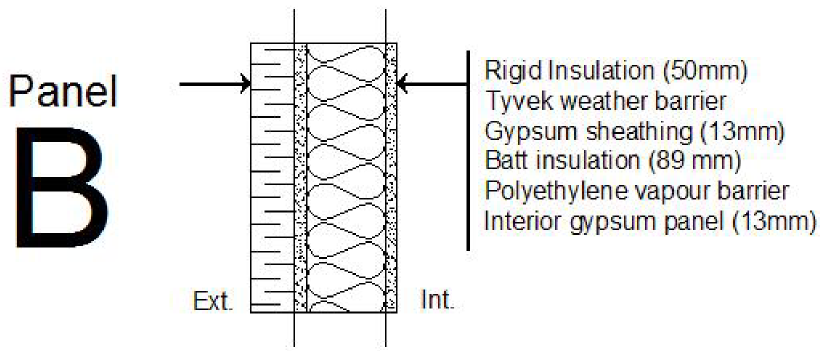
Conclusions

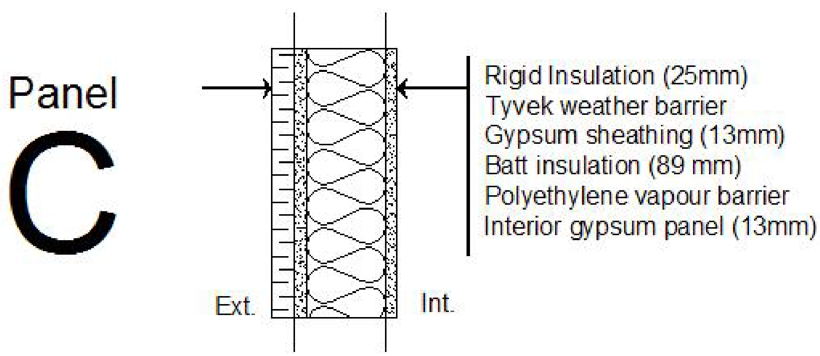
Moisture content values in gypsum can be measured using a variety of techniques with varying accuracy. Two methods were studied in this experiment: moisture pins connected to a Delmhorst Moisture Content Meter, and moisture content through gravimetry. The former method requires conversion of the results since the instrument itself is calibrated to measure moisture content in wood and not in gypsum. The gravimetric samples proved to be ineffective due to a gradual loss in mass attributed to the brittle nature of the gypsum. A possible solution would be to seal the edges of the samples, though this may introduce another source of error due to the capillary break of the sealing material.

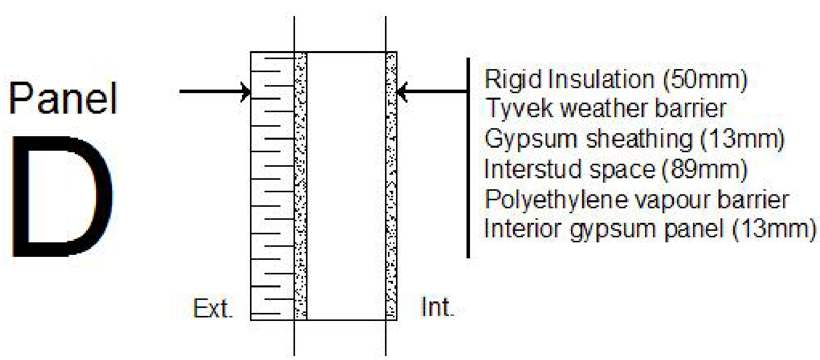
The results of the experiment did not indicate any significant change in the gypsum panels for cold conditions with average relative humidity. Further work could include exposing the panels to high relative humidity conditions using a smaller environmental chamber for a more controlled environment. In addition, the impact of direct exposure to liquid water on exterior grade gypsum panels should be studied.

<u>**Appendix D1: Test panel envelope details**</u>









Appendix D2: Moisture Content Data by using Delmhorst handheld meter connected to the wires of the pins

Panel A Moisture Content Results

Date	Panel A					Date	Panel A				
	M-AE1	M-AE2	M-AE3	M-AE4	M-AE5		M-AE1	M-AE2	M-AE3	M-AE4	M-AE5
5/20/2004	11.2	8.5	8.4	8.1	9.0	7/14/2004	12.3	9.1	8.9	8.2	10.1
5/21/2004	11.1	8.1	8.2	8.0	8.4	7/16/2004	12.3	9.1	8.9	8.3	10.2
5/25/2004	11.1	8.4	8.4	8.2	8.7	7/20/2004	12.7	9.2	8.9	8.2	10.2
5/26/2004	11.1	8.6	9.2	9.1	8.6	7/22/2004	12.7	9.2	9.0	8.8	10.2
5/27/2004	10.9	8.4	8.8	8.1	8.5	7/23/2004	12.8	9.7	9.2	8.8	10.3
5/28/2004	10.8	8.4	8.7	8.2	8.7	7/27/2004	11.8	9.0	8.4	8.0	9.5
5/31/2004	11.0	8.5	8.5	8.3	8.9	7/28/2004	11.7	9.0	8.4	8.0	9.5
6/1/2004	11.3	9.1	9.1	8.5	9.2	7/29/2004	12.0	9.2	8.4	8.0	9.7
6/2/2004	11.2	9.0	8.8	8.4	9.0	7/30/2004	11.9	9.2	8.5	8.0	9.7
6/3/2004	11.1	8.5	8.7	8.4	9.0	8/3/2004	11.8	9.0	8.4	8.0	9.5
6/4/2004	11.0	9.0	8.8	8.4	9.2	8/4/2004	11.5	8.9	8.3	8.3	9.3
6/8/2004	11.3	9.0	9.1	8.5	9.2	8/6/2004	10.8	9.2	8.0	7.7	8.9
6/9/2004	11.3	9.0	8.9	8.7	9.1	8/9/2004	10.4	8.1	8.3	7.7	8.7
6/10/2004	11.2	9.0	9.0	8.7	9.2	8/10/2004	10.4	8.2	7.9	7.4	8.7
6/11/2004	11.2	9.4	8.9	8.7	9.2	8/11/2004	10.5	8.2	8.3	7.5	8.7
6/14/2004	11.4	9.1	9.2	9.0	9.2	8/12/2004	10.2	8.0	7.8	7.4	8.3
6/15/2004	11.7	9.0	9.0	9.0	9.2	8/13/2004	10.4	8.0	7.8	7.4	8.4
6/16/2004	11.0	8.8	8.9	8.7	9.0	8/16/2004	12.3	9.4	9.0	8.9	10.3
6/18/2004	11.2	9.0	9.1	8.5	9.0	8/18/2004	12.3	9.3	9.0	9.0	10.4
6/21/2004	11.2	9.4	9.1	9.0	9.5	8/19/2004	12.3	9.3	9.0	9.0	10.5
6/23/2004	11.1	8.9	8.9	8.7	9.2	8/20/2004	12.0	9.1	8.8	8.8	10.3
6/28/2004	10.8	8.5	8.5	8.3	8.9	8/24/2004	11.8	9.2	8.5	8.5	10.4
6/30/2004	11.3	8.9	8.9	8.7	9.2	8/25/2004	12.0	9.1	9.1	8.9	10.5
7/5/2004	11.3	9.0	9.0	8.7	9.1	8/26/2004	12.3	9.3	9.0	9.0	10.7
7/7/2004	11.4	9.0	9.0	9.0	9.1	8/27/2004	12.3	9.3	9.0	9.0	10.7
7/9/2004	11.3	9.1	9.1	9.0	9.2	8/30/2004	12.3	9.3	9.0	9.0	10.4
7/13/2004	12.7	9.1	9.0	8.4	10.2	9/2/2004	11.8	9.1	8.7	8.7	10.1

Panel B Moisture Content Results

Date	Panel B					Date	Panel B				
	M-AE1	M-AE2	M-AE3	M-AE4	M-AE5		M-AE1	M-AE2	M-AE3	M-AE4	M-AE5
5/20/2004	13.2	10.9	10.7	9.3	8.9	7/14/2004	8.9	8.5	8.2	8.7	8.0
5/21/2004	12.7	10.1	9.8	8.9	8.2	7/16/2004	9.1	8.4	8.1	8.5	8.0
5/25/2004	11.4	9.1	9.2	8.7	8.2	7/20/2004	8.7	8.2	7.9	8.2	7.8
5/26/2004	12.0	9.4	10.1	9.3	8.7	7/22/2004	8.4	8.2	8.3	8.2	8.3
5/27/2004	11.3	9.1	9.4	8.7	8.3	7/23/2004	8.5	8.1	7.9	8.3	7.9
5/28/2004	11.3	9.0	9.3	8.7	8.3	7/27/2004	8.0	8.0	7.4	8.3	7.7
5/31/2004	11.3	9.1	9.2	8.9	8.5	7/28/2004	8.2	8.3	7.5	8.0	7.8
6/1/2004	11.9	9.2	9.4	9.0	8.7	7/29/2004	8.0	7.8	7.4	8.3	7.5
6/2/2004	12.3	9.3	9.5	9.0	8.7	7/30/2004	8.0	7.9	7.4	8.3	7.4
6/3/2004	12.3	9.4	9.5	9.0	8.5	8/3/2004	8.0	7.8	7.3	8.0	7.5
6/4/2004	11.9	9.3	9.5	9.0	9.0	8/4/2004	8.0	7.5	7.1	7.8	7.4
6/8/2004	12.3	9.5	9.5	9.2	8.5	8/6/2004	7.8	7.5	7.1	7.7	7.3
6/9/2004	12.3	9.8	9.8	9.1	8.9	8/9/2004	7.7	7.4	7.3	7.8	7.4
6/10/2004	12.3	9.5	9.8	9.2	9.0	8/10/2004	7.4	7.2	7.1	7.5	7.2
6/11/2004	12.3	9.5	9.8	9.1	9.0	8/11/2004	7.4	7.2	7.9	7.4	7.2
6/14/2004	12.3	10.1	10.1	9.4	9.1	8/12/2004	7.3	7.2	6.9	7.5	7.3
6/15/2004	12.8	10.1	9.7	9.2	9.0	8/13/2004	7.3	7.1	7.3	7.3	7.2
6/16/2004	12.3	9.5	9.8	9.1	8.9	8/16/2004	7.7	7.3	7.0	7.7	7.2
6/18/2004	12.7	10.1	10.1	9.1	8.9	8/18/2004	7.9	7.5	7.2	7.9	7.4
6/21/2004	12.3	10.1	10.1	9.4	9.1	8/19/2004	7.9	7.3	7.2	7.9	7.3
6/23/2004	12.3	9.8	9.8	9.1	8.9	8/20/2004	7.8	7.4	7.9	7.8	7.2
6/28/2004	12.3	10.3	10.2	10.1	8.9	8/24/2004	7.7	7.3	7.1	7.9	7.2
6/30/2004	13.0	10.4	10.3	10.1	9.1	8/25/2004	7.7	7.2	7.0	7.7	7.2
7/5/2004	12.7	9.7	9.8	9.5	9.0	8/26/2004	7.9	7.4	7.2	7.9	7.4
7/7/2004	12.9	10.3	10.2	10.1	9.1	8/27/2004	8.1	7.1	6.9	7.9	7.3
7/9/2004	13.0	10.3	10.3	10.2	9.4	8/30/2004	7.9	7.4	7.2	7.9	7.4
7/13/2004	9.3	9.2	8.9	9.1	8.3	9/2/2004	7.8	7.3	7.9	7.7	7.3

Panel C Moisture Content Results

Date	Panel C					Date	Panel C				
	M-AE1	M-AE2	M-AE3	M-AE4	M-AE5		M-AE1	M-AE2	M-AE3	M-AE4	M-AE5
5/20/2004	8.4	9.0	8.2	8.8	8.4	7/14/2004	8.3	8.3	7.9	8.0	8.5
5/21/2004	8.3	8.3	8.0	8.1	8.3	7/16/2004	8.2	8.4	8.3	8.2	8.7
5/25/2004	8.5	8.3	8.0	8.2	8.5	7/20/2004	8.1	8.4	7.8	8.0	8.4
5/26/2004	8.7	9.3	8.8	9.0	9.0	7/22/2004	8.2	8.4	8.3	8.1	8.5
5/27/2004	8.2	8.8	8.1	8.2	8.8	7/23/2004	8.1	8.4	7.9	8.1	8.5
5/28/2004	8.8	8.4	8.2	8.8	8.4	7/27/2004	8.3	8.1	7.5	7.9	8.1
5/31/2004	9.0	9.0	8.4	8.7	8.9	7/28/2004	7.9	8.2	7.8	8.3	8.1
6/1/2004	8.9	9.0	8.5	8.8	8.9	7/29/2004	7.9	8.0	7.5	7.9	8.1
6/2/2004	8.9	9.0	8.7	9.0	9.0	7/30/2004	8.3	8.1	7.4	7.8	8.1
6/3/2004	8.7	9.0	8.4	8.5	9.1	8/3/2004	7.9	8.1	7.4	7.8	8.1
6/4/2004	9.2	9.0	8.7	9.0	9.1	8/4/2004	7.7	8.1	7.4	7.9	8.1
6/8/2004	9.0	9.0	8.5	8.5	9.1	8/6/2004	7.5	7.9	7.2	7.4	7.8
6/9/2004	9.0	9.0	9.0	8.9	9.0	8/9/2004	7.5	7.8	7.3	7.4	7.8
6/10/2004	9.0	9.0	8.7	9.0	9.0	8/10/2004	7.7	7.5	7.2	7.3	7.7
6/11/2004	8.9	9.0	9.0	8.9	9.0	8/11/2004	7.7	7.8	7.2	7.3	7.8
6/14/2004	9.2	9.2	9.2	9.1	9.1	8/12/2004	7.4	7.5	7.2	7.3	7.5
6/15/2004	9.0	9.2	9.1	9.0	9.0	8/13/2004	7.2	7.7	7.2	7.2	7.7
6/16/2004	9.0	9.0	9.0	8.9	9.0	8/16/2004	8.0	8.0	7.3	7.9	8.4
6/18/2004	9.1	9.0	8.8	9.0	9.0	8/18/2004	8.2	8.1	7.3	7.9	8.3
6/21/2004	9.1	9.1	9.0	9.2	9.2	8/19/2004	8.2	8.1	7.4	8.3	8.4
6/23/2004	8.9	9.2	8.7	8.9	9.0	8/20/2004	8.0	8.1	7.4	7.9	8.2
6/28/2004	9.0	9.0	8.4	8.5	9.0	8/24/2004	8.3	8.0	7.5	7.8	8.2
6/30/2004	9.2	9.1	8.9	8.9	9.2	8/25/2004	8.3	8.0	7.2	7.9	8.3
7/5/2004	9.0	9.1	9.0	9.0	9.2	8/26/2004	8.0	8.3	7.8	8.0	8.7
7/7/2004	9.0	9.1	8.9	9.0	9.2	8/27/2004	8.0	8.2	7.8	8.0	8.5
7/9/2004	9.2	9.2	9.2	9.1	9.2	8/30/2004	8.0	8.2	7.7	7.9	8.4
7/13/2004	8.5	8.7	8.1	8.2	8.7	9/2/2004	7.9	8.0	7.3	7.9	8.2

Panel D Moisture Content Results

Date	Panel D					Date	Panel D				
	M-AE1	M-AE2	M-AE3	M-AE4	M-AE5		M-AE1	M-AE2	M-AE3	M-AE4	M-AE5
5/20/2004	9.1	9.0	10.1	9.5	8.5	7/14/2004	8.2	7.5	8.1	8.0	7.7
5/21/2004	8.7	8.4	9.7	9.4	8.0	7/16/2004	7.9	7.7	8.1	8.0	7.8
5/25/2004	8.9	8.4	9.4	9.2	8.2	7/20/2004	7.5	7.3	8.3	8.0	7.5
5/26/2004	9.1	8.7	9.5	9.4	8.5	7/22/2004	7.7	7.4	7.9	8.0	7.4
5/27/2004	8.8	8.2	9.2	9.0	8.1	7/23/2004	7.4	7.3	7.8	8.0	7.3
5/28/2004	8.5	8.3	9.1	9.0	8.1	7/27/2004	7.2	7.2	7.4	7.8	7.1
5/31/2004	9.0	9.1	9.5	9.3	8.4	7/28/2004	7.4	7.1	7.4	7.8	7.3
6/1/2004	9.0	9.0	9.5	9.4	8.4	7/29/2004	7.2	7.1	7.3	7.5	7.9
6/2/2004	8.9	9.1	9.4	9.3	8.7	7/30/2004	7.2	7.2	7.4	7.7	7.9
6/3/2004	9.0	8.7	9.4	9.1	8.4	8/3/2004	7.1	7.0	7.4	7.7	7.9
6/4/2004	8.5	8.5	9.2	9.2	8.4	8/4/2004	7.1	7.2	8.0	7.7	7.1
6/8/2004	8.5	8.5	9.2	9.0	8.4	8/6/2004	7.0	7.2	7.1	7.3	7.1
6/9/2004	8.9	8.8	9.3	9.1	8.7	8/9/2004	7.0	7.5	7.9	7.2	7.1
6/10/2004	8.7	8.5	9.2	9.2	8.5	8/10/2004	7.4	7.0	6.9	7.2	6.9
6/11/2004	9.0	8.7	9.2	9.2	8.7	8/11/2004	6.9	7.5	7.5	7.3	6.9
6/14/2004	9.2	9.0	9.5	9.3	9.0	8/12/2004	6.9	6.4	7.9	7.3	7.0
6/15/2004	8.8	9.1	9.4	9.1	9.1	8/13/2004	6.9	7.2	6.9	7.1	7.3
6/16/2004	9.0	8.8	9.3	9.2	8.7	8/16/2004	7.1	7.3	7.0	7.4	7.9
6/18/2004	8.9	9.1	9.5	9.1	8.7	8/18/2004	7.9	6.9	7.1	7.3	7.1
6/21/2004	8.9	9.0	9.5	9.4	8.9	8/19/2004	7.0	7.4	7.1	7.5	7.0
6/23/2004	8.8	8.7	9.4	9.1	8.5	8/20/2004	7.9	7.4	7.1	7.4	7.9
6/28/2004	9.2	9.2	10.3	9.5	8.2	8/24/2004	7.9	7.3	7.1	7.4	7.0
6/30/2004	9.4	9.7	10.5	9.8	8.7	8/25/2004	7.9	7.2	6.9	7.3	7.9
7/5/2004	9.1	9.2	10.1	9.3	8.8	8/26/2004	7.2	6.9	7.3	7.7	7.2
7/7/2004	9.4	9.2	10.2	9.4	9.0	8/27/2004	7.9	6.9	7.1	7.5	7.9
7/9/2004	9.8	9.4	10.4	9.7	9.0	8/30/2004	7.9	7.4	7.1	7.8	7.1
7/13/2004	8.2	8.1	8.4	8.8	8.0	9/2/2004	7.9	7.2	7.1	7.5	7.9

Appendix D3: Gravimetric data

Mass in grams

Date	Panel A			Panel B			Panel C			Panel D		
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
5/4/2004	19.36	20.30	19.26	20.46	18.42	19.01	19.27	20.74	20.48	19.51	19.60	18.68
5/10/2004	19.34	20.30	19.25	20.46	18.42	18.99	19.25	20.73	20.47	19.50	19.58	18.67
5/18/2004	19.35	20.29	19.25	20.47	18.43	19.01	19.25	20.72	20.47	19.49	19.59	18.67
5/21/2004	19.33	20.28	19.24	20.45	18.43	19.00	19.23	20.69	20.45	19.48	19.58	18.66
5/25/2004	19.34	20.27	19.23	20.43	18.41	18.98	19.22	20.69	20.45	19.47	19.56	18.65
5/28/2004	19.34	20.26	19.24	20.43	18.41	18.98	19.22	20.69	20.47	19.47	19.56	18.64
6/1/2004	19.34	20.24	19.23	20.44	18.41	18.98	19.22	20.69	20.46	19.47	19.55	18.65
6/4/2004	19.34	20.24	19.22	20.44	18.40	18.97	19.22	20.68	20.45	19.46	19.55	18.65
6/8/2004	19.33	20.24	19.21	20.43	18.40	18.97	19.21	20.67	20.45	19.45	19.53	18.64
6/11/2004	19.33	20.21	19.21	20.43	18.40	18.96	19.21	20.68	20.44	19.46	19.53	18.63
6/15/2004	19.34	20.22	19.21	20.43	18.40	18.95	19.21	20.67	20.45	19.46	19.54	18.64
6/18/2004	19.33	20.22	19.21	20.43	18.41	18.96	19.21	20.67	20.44	19.46	19.53	18.64
6/23/2004	19.33	20.21	19.21	20.43	18.40	18.97	19.20	20.67	20.45	19.46	19.54	18.64
6/28/2004	19.33	20.20	19.21	20.42	18.39	18.95	19.20	20.66	20.45	19.45	19.54	18.64
6/30/2004	19.32	20.21	19.20	20.43	18.38	18.95	19.20	20.66	20.44	19.46	19.54	18.64
7/5/2004	19.33	20.20	19.21	20.44	18.41	18.96	19.21	20.67	20.44	19.46	19.54	18.64
7/13/2004	19.34	20.22	19.22	20.43	18.40	18.96	19.21	20.67	20.45	19.46	19.54	18.64
7/16/2004	19.33	20.22	19.22	20.43	18.40	18.95	19.20	20.67	20.45	19.45	19.53	18.64
7/20/2004	19.35	20.22	19.22	20.42	18.39	18.94	19.19	20.66	20.44	19.45	19.53	18.64
7/22/2004	19.34	20.21	19.23	20.44	18.39	18.93	19.19	20.67	20.45	19.44	19.53	18.63
7/27/2004	19.32	20.19	19.19	20.40	18.38	18.92	19.18	20.64	20.44	19.43	19.52	18.63
7/30/2004	19.34	20.20	19.21	20.41	18.38	18.92	19.18	20.65	20.44	19.42	19.53	18.64
8/3/2004	19.34	20.20	19.21	20.41	18.38	18.92	19.19	20.66	20.44	19.43	19.52	18.63
8/6/2004	19.32	20.19	19.19	20.41	18.38	18.92	19.18	20.64	20.43	19.43	19.52	18.62
8/10/2004	19.31	20.18	19.19	20.40	18.37	18.90	19.18	20.64	20.43	19.42	19.51	18.62
8/13/2004	19.33	20.18	19.19	20.40	18.37	18.91	19.17	20.64	20.44	19.43	19.52	18.63
8/19/2004	19.34	20.19	19.21	20.40	18.36	18.91	19.17	20.64	20.44	19.43	19.52	18.63
8/25/2004	19.33	20.19	19.20	20.40	18.36	18.91	19.18	20.64	20.44	19.42	19.51	18.63
8/27/2004	19.33	20.20	19.21	20.41	18.36	18.91	19.19	20.62	20.43	19.40	19.52	18.61

FINAL REPORT
RELATIONSHIP BETWEEN MOISTURE CONTENT AND MECHANICAL PROPERTIES OF GYPSUM SHEATHING
PHASE II

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March 23, 2006

File: 505-0065

This project was funded by Canada Mortgage and Housing Corporation (CMHC) under the terms of the External Research Program, but the views expressed are the personal views of the authors and do not represent the official views of CMHC.

Disclaimer

This study was conducted for Canada Mortgage and Housing Corporation by Levelton Consultants Limited under Part IX of the National Housing Act. The analysis, interpretations and recommendations are those of the consultant and do not necessarily reflect the views of Canada Mortgage and Housing Corporation or those divisions that assisted in the study and its publication. Neither Canada Mortgage and Housing Corporation nor Levelton Consultants Limited assume liability for any damage, injury, expense or loss that may result from the use of this report, particularly the extrapolation of the results to specific situations or buildings.

EXECUTIVE SUMMARY

Canada Mortgage and Housing Corporation (CMHC) retained Levelton Consultants Ltd. to investigate the performance of gypsum sheathing at various levels of moisture content, under the CMHC External Research Program. Phase I of this work was completed in 2005, and is reported under separate cover, in a Levelton report dated January 31, 2005.

The stated objective of this phase of the project was to examine the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum wallboard intended for use as exterior sheathing on buildings) at more specific moisture contents (Phase One did not include testing at 1% moisture content, which appeared to be a critical value for the performance of these materials).

A second objective was to determine whether gypsum sheathing could be rehabilitated by drying it out once it had been wetted. Several samples of fibre-faced and exterior-grade gypsum sheathing were wetted to various levels of moisture content (1%, 4%, 8% and 16%), then dried out and tested for flexural strength and resistance to fastener pull-through. The results were compared to testing of specimens that were initially oven-dry.

The following conclusions are summarized in this report:

This study has confirmed a strong correlation between moisture content and the mechanical properties of various types of gypsum sheathing.

Taken together, the test results suggest that the mechanical properties of gypsum sheathing would not meet the criteria defined in relevant ASTM standards (C1177 for exterior-grade gypsum, C1396 for fibre-faced gypsum) at moisture-content levels above 1%, as a general rule of thumb.

There is some question, however, as to whether the ASTM Standards are appropriate indicators of in-service performance (this is noted in the Standards), as some of the specimens tested did not meet the criteria even oven-dry.

When these specimens are wetted and re-dried, the resistance to flexural loading of the fibre-faced gypsum sheathing essentially recovered to their original values. Exterior-grade gypsum sheathing recovered to approximately 94% of their original values, except where the facer-to-gypsum adhesion was lost (in that case, the resistance to flexural load was tested to be 66% of the original value). The resistance to fastener penetration of all sheathing tested did not appear to be affected by wetting, once the specimens were dried out.

It is interesting to note that the 5/8" exterior-grade sheathing never dried out, and only reached 1% moisture content even after several days of drying in the oven. Also, mould appeared on the surface of all of the exterior-grade gypsum specimens during the wetting and conditioning cycles, but none of the specimens with glass-fibre facers were affected.

RÉSUMÉ

La Société canadienne d'hypothèques et de logement (SCHL) a retenu les services de Levelton Engineering Ltd. pour étudier, dans le cadre du Programme de subventions de recherche de la SCHL, la performance d'un revêtement intermédiaire en plaques de plâtre à des taux d'humidité variés. La phase I de cette étude a été terminée en 2005 et fait l'objet d'un compte rendu distinct présenté dans un rapport produit par Levelton le 31 janvier 2005.

L'objectif convenu de cette phase du projet était d'examiner le rapport entre la teneur en humidité et les propriétés mécaniques du revêtement intermédiaire de plaques de plâtre (c.-à-d. les plaques de plâtre devant être utilisées comme revêtement intermédiaire extérieur pour les bâtiments) à des taux d'humidité plus précis (la phase un ne comportait pas d'essai à un taux d'humidité de 1 %, qui semble être une valeur critique pour la performance de ces matériaux).

On devait établir, à titre de deuxième objectif, si le revêtement en plaques de plâtre pouvait être remis en état en le séchant une fois qu'il avait été mouillé. Divers échantillons de revêtement en plaques de plâtre recouvertes de fibre et en plaques de plâtre pour l'extérieur ont été mouillés afin d'obtenir des teneurs en humidité différentes (1 %, 4 %, 8 % et 16 %). Ils ont ensuite été séchés et mis à l'essai afin d'en déterminer la résistance à la flexion et la résistance au retrait des pièces de fixation. Les résultats ont été comparés aux essais effectués sur des échantillons originaux qui avaient été séchés au four.

Les conclusions suivantes sont résumées dans le présent rapport :

Cette étude a permis de confirmer qu'il existe une forte corrélation entre la teneur en humidité et les propriétés mécaniques des divers types de revêtement de plâtre.

Considérés dans leur ensemble, les résultats des essais donnent à penser que les propriétés mécaniques des revêtements intermédiaires constitués de plaques de plâtre ne satisferaient pas, en règle générale, aux critères définis dans les normes pertinentes de l'ASTM (C1177 pour les plaques de plâtre extérieures, C1396 pour les plaques de plâtre recouvertes de fibre) à un taux d'humidité supérieur à 1 % (en règle générale).

Il faut toutefois se demander si les normes de l'ASTM constituent des indicateurs adéquats de la performance en service (ce fait est souligné dans les normes), étant donné que certains des échantillons à l'essai ne respectaient pas les critères même lorsque séchés au four.

Lorsque ces échantillons ont été mouillés et séchés à nouveau, la résistance à la charge de flexion du revêtement de plâtre recouvert de fibre est revenue à ses valeurs originales. Le revêtement constitué de plaques de plâtre pour emploi extérieur a récupéré environ 94 % de ses valeurs originales, sauf qu'il n'y avait plus d'adhérence entre le matériau de surface et la plaque de plâtre (dans ce cas, on a évalué que la résistance à la charge de flexion était à 66 % de la valeur initiale). Une fois les échantillons séchés, le mouillage n'a pas semblé avoir d'incidence sur la résistance à la pénétration des pièces de fixation de tous les revêtements intermédiaires mis à l'essai.

Fait intéressant, le revêtement composé de plaques pour l'extérieur de 5/8 de po n'a jamais séché totalement, et sa teneur en humidité n'a atteint que 1 % même après plusieurs jours de séchage au four. De la moisissure est apparue à la surface de tous les revêtements en plaques de plâtre pour l'extérieur pendant le mouillage et les cycles de conditionnement, mais aucun des échantillons comportant des matériaux de surface en fibre de verre n'ont été touchés.

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1. TERMS OF REFERENCE/SCOPE OF INVESTIGATION

Levelton Engineering Ltd. applied for a housing research grant under the Canada Mortgage and Housing Corporation (CMHC) External Research Program, to study the response of gypsum sheathing products to various levels of moisture content. This work was completed in 2005, and is reported under separate cover, in a Levelton report dated January 31, 2005.

The project examined the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum wallboard intended for use as exterior sheathing on buildings). Specific properties examined included:

- water absorption;
- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper, depending on the sheathing type);
- ability of the sheathing to resist fastener pull-through; and
- flexural strength of the sheathing, as a common index of overall mechanical integrity

The previous work concluded that:

1. Handheld moisture meters are generally accurate for paper-faced gypsum sheathing up to approximately 6%, but above that level the moisture meter reads lower than the actual value. The moisture meters read higher than gravimetric values for fibre-faced sheathing, over the range of moisture contents investigated.
2. A strong correlation was found between moisture content and the mechanical properties of various types of gypsum sheathing.
3. ASTM tests for flexural strength and fastener pull-through suggested that the mechanical properties of gypsum sheathing are dramatically reduced when the moisture content is increased from 0% to 2%. The mechanical properties still decreased above 2% moisture content, but not as quickly.
4. Paper-faced gypsum sheathing (GWB and XGG) generally does not meet the performance criteria established in ASTM C1396 above a moisture content of approximately 1%, and fibre-faced sheathing (FFG) does not meet the criteria set out in ASTM C1177 above a moisture content of approximately 0.5%.
5. The tested products also did not meet some of the requirements of the ASTM Standards when oven-dry, so it is not clear that the ASTM criteria are appropriate indicators of in-service performance (this is noted in the ASTM Standards).

The previous work was not conclusive, however, in that no specimens were explicitly tested at 1% moisture content. Conclusion #4 above was interpolated from the results for 0% and 2% specimens.

Another interesting question arose during the Phase One testing: would it be possible to rehabilitate gypsum sheathing that had been wetted? Gypsum sheathing could accidentally become wet in storage (due to a plumbing leak, improper protection from weather, or several other probable events). Gypsum sheathing in service could also become wet by exposure to weather, interstitial condensation, high humidity levels in a building, or several other probable events. In either case, the previous study showed that it does not require much moisture for the gypsum sheathing to lose its desirable mechanical properties. Rather than throwing away the damaged material, it might be possible to dry it out, if the mechanical properties could be recovered to a suitable level.

2. BACKGROUND

As in Phase One, the objective of this project was to assess the mechanical properties of various gypsum-based sheathing products at varying levels of moisture content. Specific properties to be examined include:

- ability of the sheathing to resist fastener pull-out; and
- flexural strength of the sheathing, for seismic considerations and as an index of overall mechanical integrity

There are several reasons why it is important to understand the mechanical properties of gypsum sheathing, and how these properties vary with moisture content:

1. Although gypsum sheathing by itself is not part of the structure that holds up the building, the Building Code does give credit for gypsum sheathing in terms of providing shear strength. Most cladding systems are attached to the framing components of the building, and do not rely on the strength of the gypsum sheathing to support the cladding. Nevertheless, some exterior insulation finish systems (EIFS) are adhered to the sheathing, and in this way the sheathing can play a role in keeping the cladding on the building for EIFS-clad designs.

2. Many designs rely on the sheathing to support an air-barrier membrane, whether this is a self-adhered membrane (e.g., in coastal climates with high exposure to wind-driven rain) or a spun-bonded polyolefin. If the gypsum sheathing loses its structural integrity, the air barrier may not perform as expected, which could lead to significant consequential damage and deterioration of building-envelope performance.

3. In some cases, cladding has fallen off of a building onto the street below, or onto a ground-floor patio (which, fortunately, was unoccupied). Some of these failures appear to have been related to wet gypsum sheathing: the sheathing held water in place for an extended period of time, which accelerated the corrosion of the cladding fasteners. The wet sheathing was not strong enough to resist being crushed, so the fasteners were subjected to shear and rotational forces that caused them to fail. A better understanding of the mechanical properties of gypsum sheathing – and how these properties vary with moisture content – would help avoid catastrophic failures.

4. Gypsum can hold a substantial amount of moisture: Phase One of this study discovered that a sample of gypsum sheathing could hold up to 200% of its weight in water. This can result in damage to water-sensitive building components adjacent to the sheathing (e.g., wood or metal framing).

5. Building scientists who conduct diagnostic investigations of buildings require accurate performance criteria against which to evaluate the condition of existing assemblies. Some practitioners cannot obtain professional liability insurance in cases where mould is involved. In that case, it could be useful to have performance criteria for building materials that are not related to the formation of mould.

In the case of new construction, designers need some way to effectively specify the expected performance of gypsum sheathing. ASTM C1396 provides a method for determining performance levels, but specifiers need to know when the material has become so wetted that it will no longer meet the criteria.

3. METHODOLOGY

With these questions in mind, an experimental method was devised to determine whether wetted gypsum would regain its original mechanical properties when dried. The experimental procedure was as follows:

1. Samples of gypsum sheathing were obtained from local suppliers, representing typical materials available to builders. Specimen types included
   - 12.7mm (1/2”) exterior-grade gypsum sheathing (XGG);
   - 15.9mm (5/8”) exterior-grade gypsum sheathing (XGG);
   - 12.7mm (1/2”) fibre-faced gypsum sheathing (FFG); and
   - 15.9mm (5/8”) fibre-faced gypsum sheathing (FFG)

   These samples represented the same manufacturers as the Phase I study, in an attempt to obtain comparable results.

2. The specimens were cut to 305mm x 405mm (12x16”), per the requirements of the ASTM C473 testing standard. The XGG samples were cut to obtain specimens with the facer grain parallel to the longest dimension and perpendicular to the longest dimension, as different loading criteria are applied to both types. FFG sheathing is faced with randomly oriented glass-fibre strands, so the directional aspect of the testing was not applicable to those specimens.

3. Six specimens of each type of sheathing were oven-dried to obtain a baseline dry weight, and to provide baseline test specimens for comparison with subsequent results. As in Phase One of this project, the samples were dried at 30°C to avoid dehydrating the gypsum, as it is a hydrated molecule ($CaSO_4 \cdot 2H_2O$). Excessive heat could drive off the bonded water molecule, changing the material properties. Each sample was removed from the oven and weighed every three hours: when the weight changed by less than 0.02%, the specimen was considered to have reached steady-state, and the value recorded at that point was taken as the dry weight.

4. Water was added to the specimens to obtain specimens with predetermined moisture-content levels:
   - Six of each sheathing type at 1% moisture content;
   - Six of each sheathing type at 4% moisture content;
   - Six of each sheathing type at 8% moisture content; and
   - Six of each sheathing type at 16% moisture content

   The specimens were conditioned to promote uniform distribution of moisture, which involved sealing the specimens in plastic wrap to minimize evaporative losses and turning the specimens over every 24 hours to promote moisture distribution. Specimens were typically stored for two weeks in this manner, to ensure moisture equilibrium within each specimen (there is no “Standard” protocol for this procedure).

5. Flexural and fastener pull-through testing was conducted for the oven-dried specimens and the 1% specimens, and on half of the 4%, 8% and 16% specimens.

6. The remaining 4%, 8% and 16% specimens were oven-dried, following the procedure described above. The wetted-and-oven-dried specimens were tested for flexural strength and fastener pull-through.

4. RESEARCH RESULTS

As with Phase One, a bead of wax was applied to the perimeter of each specimen to seal the edges from absorbing excess moisture, and to prevent the edges of the specimens from crumbling. The dry weight was measured again, including the weight of the added wax seal, and the calculations for moisture content as a percentage of dry weight were adjusted to account for the weight of the wax. It was discovered early in Phase One that allowing the edges of the specimens to crumble could have introduced a significant error in the results (because the final mass of the specimens would be difficult to determine),

Mould developed on the surface of the specimens during the conditioning period. The initial oven-drying period (to obtain the dry weight of all specimens) took three days. It took an additional 15 – 23 days to achieve the target moisture contents and complete the conditioning process for all specimens (15 days for all 1/2" XGG samples, 22 days for all 1/2" FFG samples, and 23 days for the 5/8" XGG and FFG samples). After nine days of adding moisture and conditioning the specimens, a dark brown mould was observed on the 1/2" XGG specimens, and a very light-coloured stain was observed on the 5/8" XGG specimens. Mould developed on all of the specimens more or less equally in density (i.e., irrespective of the moisture content of the specimen), but the paper facers on the XGG specimens did not appear to deteriorate during the course of the experiment. The mould species were not identified, as that was not part of the scope of the study. None of the FFG specimens developed mould.

Once the target moisture content was achieved and the specimens were fully conditioned, some of the specimens were tested to determine their mechanical properties and the remainder were oven-dried (this took an additional 6 days for the 5/8" FFG specimens, 7 days for the 1/2" FFG specimens, and 12 days for the 1/2" XGG specimens (the 5/8" XGG specimens were not included in this part of the study, so that we could obtain statistically significant data with the other three sample sets within the project budget).

4.1 MECHANICAL PROPERTIES

As noted in Section 1, each material was tested to evaluate the ability of the sheathing to resist fastener pull-through, and flexural strength of the sheathing, both perpendicular and parallel to the length of the specimens (to include the effect of the facer grain for the XGG specimens).

4.3.1 Fastener Pull-through

Each specimen was tested for fastener pull-through, as described in ASTM C473. As that Standard explains, "The ability of gypsum panel products to resist nail pull-through is evaluated by determining the load required to push a standard nail head through the product." The "standard nail head" is represented by a steel shaft with a step change in the diameter of the shaft (see Figure 1). The diameter of the "nail shank" and "nail head" are defined to precise tolerances in C473. This study uses the C473 "Method B" of applying the test load, which moves the head of the test apparatus at a constant speed. While this procedure does not provide a true constant rate of strain (the strain on the specimen actually increases up to the point of failure), it is easier to control and measure the load applied on the specimen.

The "test nail" is pushed through the specimen up to the "nail head", and the maximum applied load is recorded: this represents the amount of force that the specimen can resist just before the "nail head" breaks through the facer. This test was repeated on five separate specimens, for each type of sheathing material. The results of the testing are provided in Appendix A and summarized graphically in Figures 2 and 3.

FIGURE 1. TESTING APPARATUS FOR FASTENER PULL-THROUGH

The data in Appendix A represents test results for 160 specimens (40 of each type of sheathing). Figures 2 and 3 include the test results from Phase One of this project, and therefore do not show test results at 16% nominal moisture content. The test results for all specimens show a consistent pattern of decrease in resistance to fastener pull-through as moisture content increases (trendlines are added to indicate a pattern of behaviour for all three types of sheathing). The Figures also include threshold values of applied force described in ASTM C1177 and C1396. Thus, a technical specification for gypsum that reads “shall conform to ASTM C1396” can be considered to read “shall have a fastener pull-through strength of at least 77 pounds of applied force…” (for 1/2” sheathing, or 87 pounds for 5/8” sheathing).

Figures 2 and 3 show consistent results, with very little scatter in each specimen group. These figures also show reasonably good agreement between the Phase One (FFG #1 or XGG #1) and Phase Two (FFG #2 or XGG #2) data, as the shape of the trendlines is very similar between the two groups of data. The ½” XGG results are approximately the same for both phases, but otherwise the Phase Two specimens appear to have slightly higher test results than the Phase One specimens.

The only products that met the fastener pull-through criteria set out in the ASTM Standards were the 1/2” FFG specimens, when tested at 0% or 1% moisture content, and the 5/8” FFG specimens, when tested at 0% moisture content. The data suggest that the 5/8” FFG and XGG specimens would meet the criteria at approximately 0.5% moisture content (see Figure 2). This is similar to the Phase One results, and tends to rule out the possibility suggested in the Phase One report that our specimen selection process accidentally chose a poor sample of materials. We have more than doubled the sample population, and have observed similar test results. It might be interesting to evaluate the ASTM criteria, and to relate those performance levels (in this case, for pull-through loads on various types of gypsum sheathing fasteners) to expected forces encountered in actual service, but such an evaluation is beyond the scope of this study.

We note, however, that the ASTM C473 test method for nail pull resistance (i.e., fastener pull-through) contains the following statement: “The degree of correlation between this test method and service performance has not been fully determined”.

FIGURE 2. FASTENER PULL-THROUGH TESTS FOR 1/2" GYPSUM PANEL

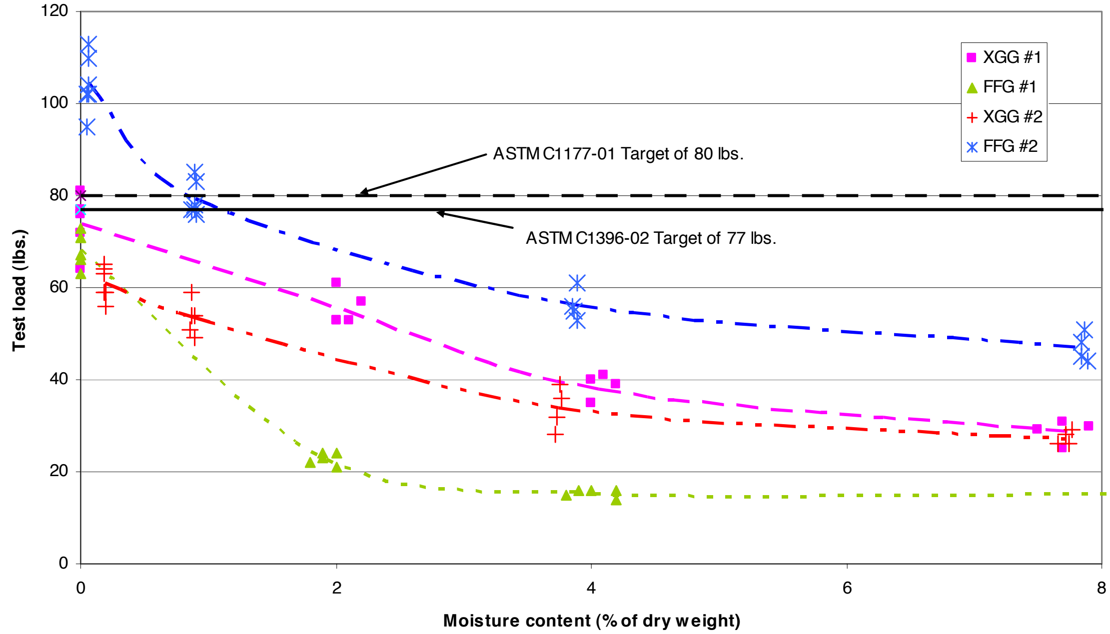
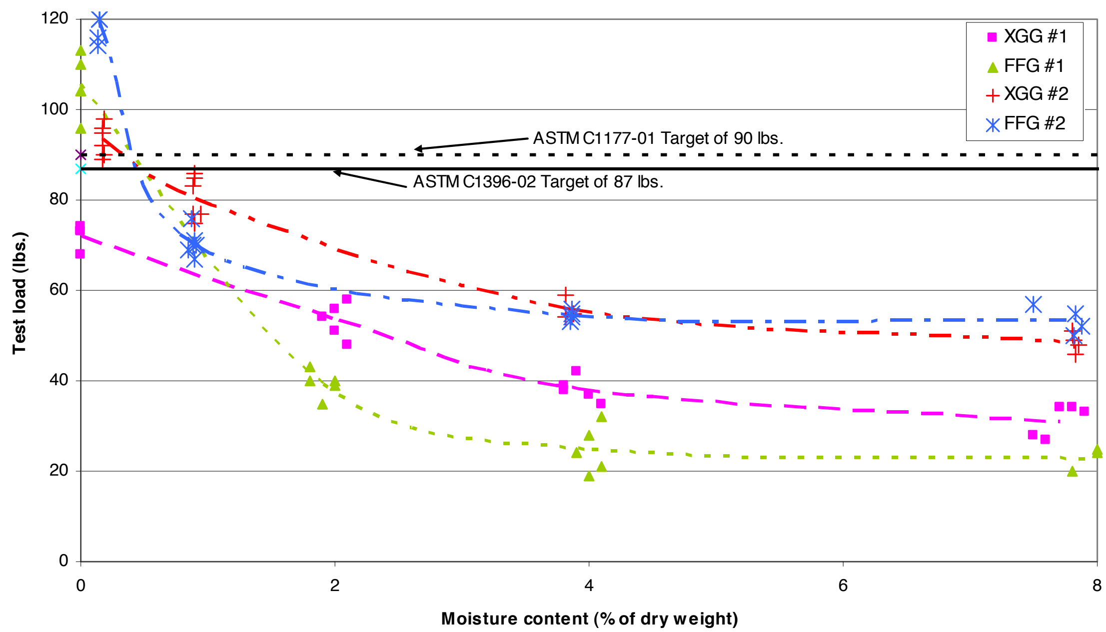


FIGURE 3. FASTENER PULL-THROUGH TESTS FOR 5/8" GYPSUM PANEL



4.3.2 Flexural Strength

The flexural-strength test is also described in the C473 Standard (see Figure 4). The specimen is simply supported at each end, and a load is applied at the centre of the specimen. The specific dimensions of the supports, the test specimens, and the load applicator are described in the C473 Standard, as is the method and rate of load application. The test apparatus shown in Figure 4 was constructed to meet the exact specifications of ASTM C473. Again, the maximum recorded load represents the applied force just prior to failure of the specimen in flexure.

The C473 Standard describes two methods of applying flexural loads. This study also uses "Method B" for flexural testing, which uses a Universal Tester to apply a load at a constant cross-head speed (the cross-head is just visible at the top of Figure 4).

Each type of specimen was tested for flexural strength in four different configurations: face-up with the grain of the facer parallel to the supports, face-up with the grain of the facer perpendicular to the supports, and face-down in both directions.

FIGURE 4. TESTING APPARATUS FOR FLEXURAL STRENGTH

The results of flexural testing are tabulated in Appendix A. Figures 5 and 6 present the results for flexural tests with the load applied perpendicular to the grain of the paper facers (not applicable to FFG, but those specimens were tested in a similar orientation). The curves represent two data points for each product type at each moisture-content level: one test with specimens "face up", and one "face down", per the ASTM C473 protocol. As with all materials testing results in this project, the data show very good repeatability, with data points from each product type clustered in reasonably tight groupings (except for the results for FFG in Figure 6).

The agreement between Phase One and Phase Two data is very good: again, 1/2" FFG shows a marked improvement in its material properties, but the shape of the curves in Figures 5 and 6 are otherwise similar for all data sets. The ASTM C1177 and C1396 criteria targets are included in the graphs: Figure 5 suggests that the 1/2" specimens meet the ASTM criterion at a moisture content of between 0.5% and 0.7%. Figure 6 shows that the 5/8" FFG specimens meet the criteria at a moisture content of between 0.3% and 0.5%, but the newer XGG specimens did not meet the ASTM criteria at all, even when oven-dry (note that the XGG specimens are compared against the C1177 target, and the C1396 target applies to the FFG specimens for all graphs).

FIGURE 5. FLEXURAL STRENGTH TESTS (PERPENDICULAR) FOR 1/2" GYPSUM PANEL

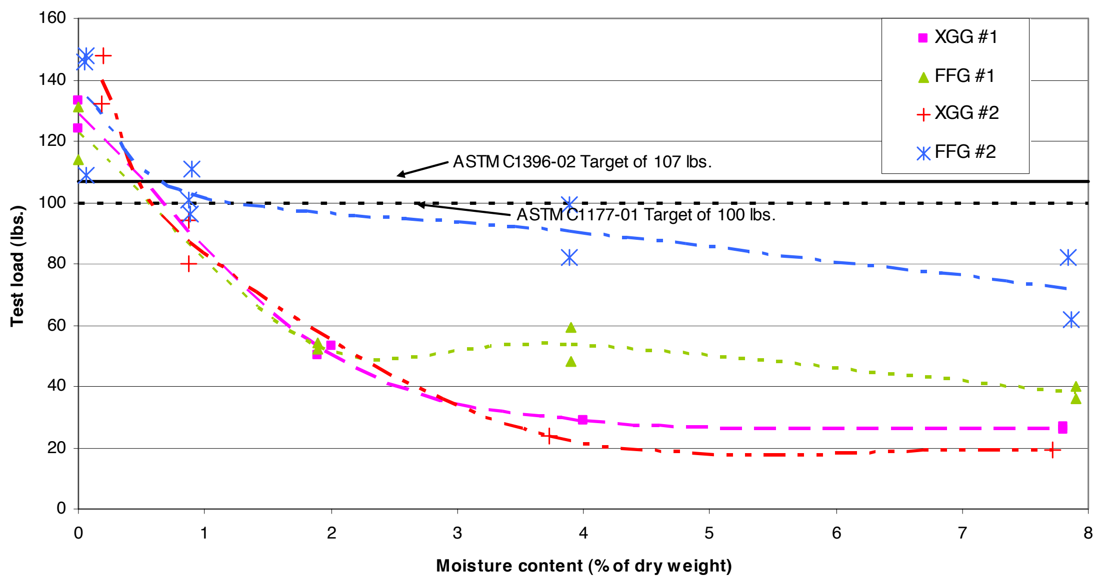
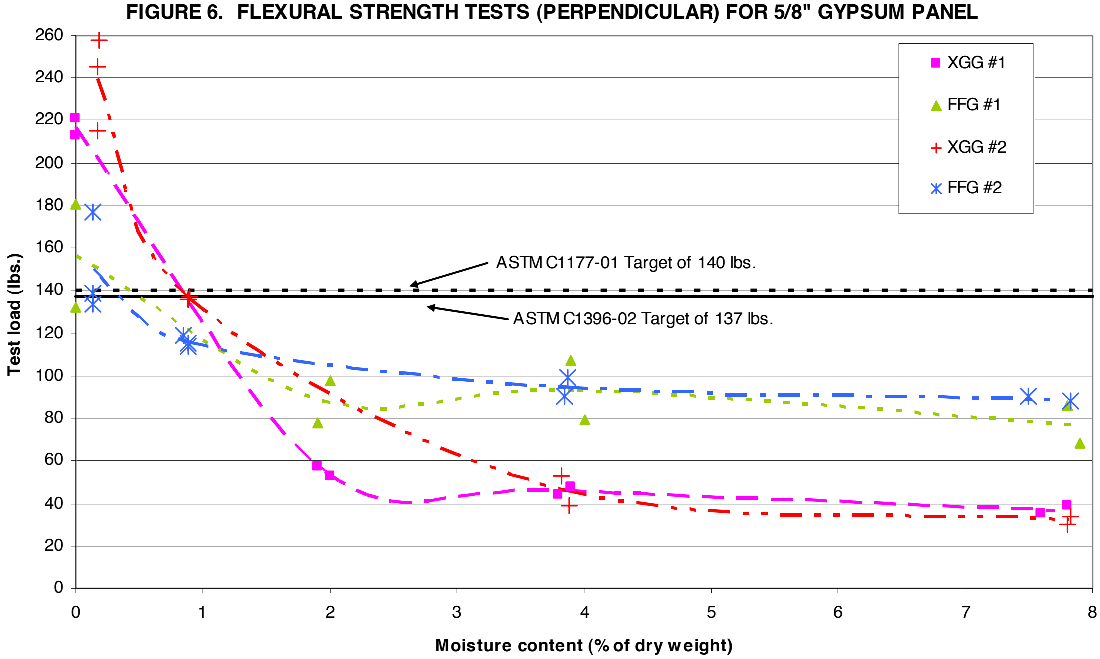


FIGURE 6. FLEXURAL STRENGTH TESTS (PERPENDICULAR) FOR 5/8" GYPSUM PANEL



Results for sheathing tested parallel to the facer grain are shown in Figures 7 and 8. These values are much lower than the results represented in Figures 5 and 6, but the ASTM targets are also lower. Figure 7 shows that 1/2" XGG sheathing meets the C1177 criterion at less than 1.1% moisture content, and new 1/2" FFG specimens meets C1396 at any moisture content.

FIGURE 7. FLEXURAL STRENGTH TESTS (PARALLEL) FOR 1/2" GYPSUM PANEL

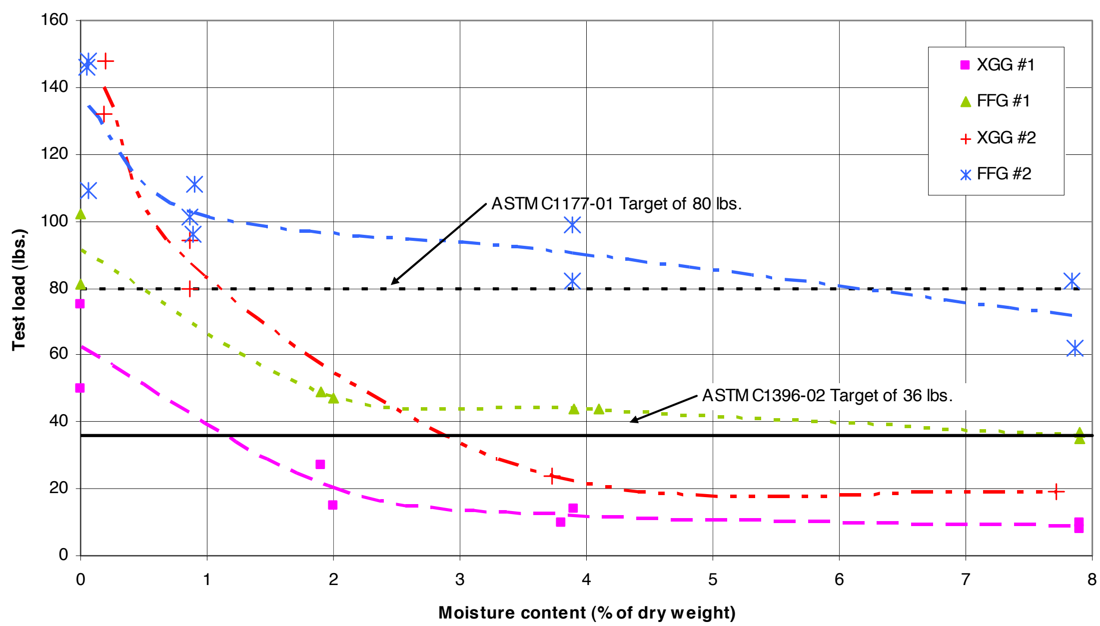


FIGURE 8. FLEXURAL STRENGTH TESTS (PARALLEL) FOR 5/8" GYPSUM PANEL

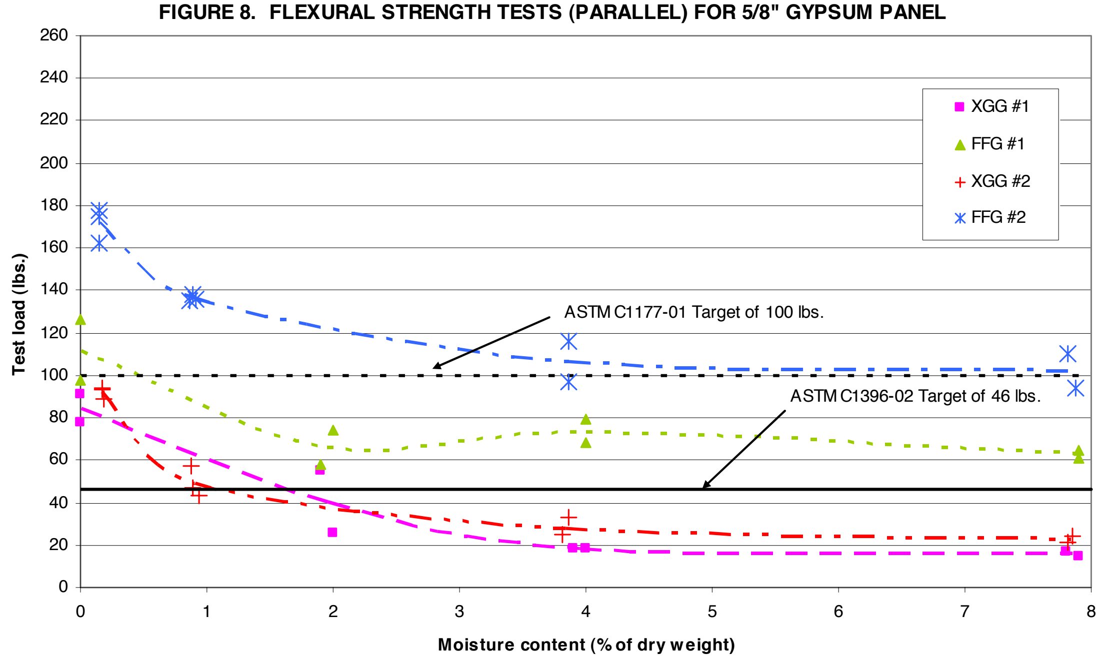


Figure 8 shows that all 5/8" FFG specimens also meet the ASTM C1396 criterion at all moisture contents, but the 5/8" XGG specimens failed to meet the criteria when tested at any moisture content (including oven-dry). This unusual result was consistent with some of the Phase One testing. It again raises the concern that the ASTM criteria may not be appropriate indicators of in-service performance (this is noted in the ASTM Standards).

Unfortunately, building designers have no other option for specifying the required field performance of gypsum sheathing at the design stage. They can require field testing of the desired mechanical properties, but this is a destructive test that would be conducted after all of the sheathing has been shipped to the site, and is therefore not an effective way to screen the quality of the building material before it is used in construction. The real value of being able to specify that the material must meet some industry standard is that, when it can be shown that the material supplied to a specific job site does not meet that standard, the material can be replaced at no cost to the Owner (and perhaps at no cost to the Contractor, if the cost of replacement can be contractually passed back to the supplier). This approach would not be effective, however, if it could be shown that the sheathing never met the industry standard, and never *could have met* the industry standard. These results seem to show that the latter is the case, but it is not clear whether the problem is with the quality of the material or the criteria of the C1177 and C1396 Standards.

4.2 Rehabilitating Wetted Gypsum Sheathing

The remaining samples were oven-dried, following the procedure described in Section 3 of this report. As stated, the objective was to determine whether these specimens, wetted to various moisture contents, would recover their original mechanical properties when dried. The complete results of testing are included in Appendix A, with mean values summarized in Table 1.

	Mean moisture content (wetted→dried) %	Mean Flexural Load Parallel, lbs (% of oven-dry load)	Mean Flexural Load perpendicular, lbs (% of oven-dry load)	Fastener Pull-through Load, lbs (% of oven-dry load)
1/2" XGG	0.187 (initial oven-dry)	37 (-)	140 (-)	61 (-)
	3.73 → 0.26 (4% → 0)	35 (94.6)	94 (67.1)	64.5 (105.7)
	7.67 → 0.39 (8% → 0)	35 (94.6)	96.5 (68.9)	67.5 (110.7)
	15.66 → 0.32 (16%→0)	32.7 (88.4)	88.7 (63.4)	60.5 (99.2)
	Average of 1/2" XGG	**34.2 (92.4)**	**93.1 (66.5)**	**64.2 (105.2)**
1/2" FFG	0.057 (initial oven-dry)	113.3 (-)	134.3 (-)	104.3 (-)
	3.85 → 0.22 (4% → 0)	127.5 (112.5)	158.5 (118)	119.2 (114.3)
	7.72 → 0.09 (8% → 0)	114 (100.6)	152 (113.2)	115 (110.3)
	15.55 → 0.18 (16%→0)	133.3 (117.6)	141 (105)	114 (109.3)
	Average of 1/2" FFG	**124.9 (110.2)**	**150.5 (112.1)**	**116.1 (111.3)**
5/8" XGG	0.173 (initial oven-dry)	92 (-)	239.3 (-)	93.3 (-)
	3.88 → 0.98 (4% → 0)	86 (93.4)	209.5 (87.5)	111.8 (119.8)
	7.86 → 0.94 (8% → 0)	90.5 (98.4)	226 (94.4)	104 (111.5)
	15.67 → 1.12 (16%→0)	91 (98.9)	221.7 (92.6)	105.7 (113.3)
	Average of 5/8" XGG	**89.2 (96.9)**	**219.1 (91.5)**	**107.2 (114.9)**
5/8" FFG	0.145 (initial oven-dry)	150 (-)	171.7 (-)	119.2 (-)
	3.83 → 0.12 (4% → 0)	116 (77.3)	182.5 (106.3)	121.2 (101.7)
	7.82 → 0.18 (8% → 0)	152 (101.3)	174.5 (101.6)	119 (99.8)
	15.74 → 0.11 (16%→0)	131.3 (87.5)	180.7 (105.2)	115.3 (96.7)
	Average of 5/8" FFG	**133.1 (88.7)**	**179.2 (104.4)**	**118.5 (99.4)**

Table 1. Results of Re-drying experiment for gypsum sheathing

Table 1 shows that some of the specimens did not completely dry out in the re-drying procedure. The column labeled “Mean moisture content” shows the average actual and nominal moisture content for the wetted and re-dried specimens. The “initial oven-dry” specimens achieved a moisture content of 0.19% or less during the first part of the experiment, which was the practical limit of drying for these specimens. In other words, these specimens showed less than 2% change in their mass over several consecutive measurements, so these values are considered to be the practical limit of drying for specimens taken from typical “room-dry” conditions under normal hygric sorption down to a state approaching zero moisture content.

The specimens that were wetted to varying degrees were then taken back down to nominally “0% moisture content” to simulate the situation where gypsum sheathing has been wetted by some incident in service (i.e., plumbing leak, storage in wet conditions, or rain wetting of an installed sheathing panel) and then dried in an attempt at rehabilitation. The FFG specimens were typically brought back to something approaching the initial oven-dry condition, but the XGG specimens never did regain that initial state. It appears that the treated paper facer locks in some of the moisture once the panel is wetted, and practical attempts to remove it by normal oven-drying could not reduce the moisture content to the original condition. The 1/2" XGG specimens actually dried out to between 0.26% and 0.39%, which is 35-70% more than the “initial oven-dry” measurement of 0.19%. The 5/8” specimens were not able to dry out (within practical limits) to much less than 1% moisture content – and this was after several days of oven drying. This result was observed for 14 different specimens (see Appendix A), so it cannot be considered an experimental anomaly or artifact.

In general, Table 1 shows a tendency for the mechanical properties of most re-dried specimens to be lower than the initial values. Flexural load of the wetted 1/2" XGG specimens that were re-dried is 92% of the initial value in parallel loading, and only 66% of the initial value in perpendicular loading. The difference in strength is due to the difference the grain of the paper facer, relative to the longest dimension of the specimen. In the 1/2" specimen, it is clear that almost all of the resistance to flexural loading is provided by the paper, and wetting reduces this resistance – slightly along the grain of the paper, but substantially across the grain of the facer. This effect is also seen with the 5/8” XGG specimens, but is less noticeable. The maximum flexural load of the wetted-and-redried 5/8” XGG specimens was 97% of the initial value when measured with the grain, and 91% when measured across the grain. Thus, the direction of the grain in the paper facer does make a difference, but perhaps the increased mass in the core of the 5/8” specimen (relative to the 1/2" sheathing) provides some additional strength.

The 1/2" FFG specimens actually showed an increase in the maximum flexural load when the specimens were wetted and re-dried. The direction of the flexural loading makes almost no difference in the result for the FFG samples, as the facers are constructed of randomly woven glass fibres. The wetted-and-redried 5/8” FFG specimens produced slightly lower results than the 1/2" FFG samples.

Ultimately, the flexural strength of gypsum sheathing depends on the strength of the adhesive bond between the facers and the gypsum core. The specimens tested were not disturbed after they were wetted, and the oven-drying procedure was conducted to avoid damaging facer adhesion. Any damage to the facer that might occur in the field would likely remove any resistance to flexural loading. These results should therefore be viewed with caution when applying them directly to field conditions, especially if evidence of physical damage is observed along with water-staining of the gypsum sheathing. This may also explain why the resistance to perpendicular flexural loading is greatly reduced for the 1/2" XGG specimens, but not for the other flexural tests. If facer adhesion were lost, flexural strength might be retained in the direction of the facer grain, but there would be no lateral resistance (as seen in Table 1).

The results of wetting and re-drying appear to have little effect on fastener pull-through tests. If anything, increased moisture content actually increased the resistance to fastener pull-through. This could be because an increase in moisture content swelled the gypsum core and provided some pre-stressing of the facer, but there may be many other reasons for these results.

5. CONCLUSIONS AND RECOMMENDATIONS

This study confirms a strong correlation between moisture content and the mechanical properties of various types of gypsum sheathing, as was indicated in Phase One. ASTM tests for flexural strength and fastener pull-through produced the following results:

- 1/2" exterior-grade gypsum sheathing failed the fastener pull-through testing at all moisture-content levels, even oven-dry (nominal 0%);
- 1/2" fibre-faced gypsum sheathing failed the fastener pull-through testing at moisture-content levels above 1%;
- 5/8" exterior-grade and fibre-faced gypsum sheathing failed the fastener pull-through testing at moisture-content levels above 0.5%;
- 1/2" exterior-grade and fibre-faced gypsum sheathing failed the flexural testing (perpendicular) at moisture-content levels above 0.5%;
- 5/8" exterior-grade gypsum sheathing failed the flexural testing (perpendicular) at all moisture-content levels;
- 5/8" fibre-faced gypsum sheathing failed the fastener pull-through testing at moisture-content levels above 0.3%;
- 1/2" exterior-grade gypsum sheathing failed the flexural testing (parallel) at moisture-content levels above 1.1%;
- 1/2" fibre-faced gypsum sheathing passed the flexural testing (parallel) at all moisture-content levels, even over 8%;
- 5/8" exterior-grade gypsum sheathing passed the flexural testing (parallel) at all moisture-content levels, even over 8%;
- 5/8" fibre-faced gypsum sheathing passed the flexural testing (parallel) at all moisture-content levels, even over 8%;

Taken together, a consideration of how these test results were intended to predict field performance would suggest that the mechanical properties of gypsum sheathing would not meet the ASTM standards (C1177 for exterior-grade gypsum, C1396 for fibre-faced gypsum) at moisture-content levels above 1%, as a general rule. There is some question, however, as to whether the ASTM Standards are appropriate indicators of in-service performance (this is noted in the Standards), as some specimens tested did not meet the criteria even when oven-dry.

When these specimens are wetted and re-dried, the resistance to flexural loading of the fibre-faced gypsum sheathing essentially recovered to their original values. Exterior-grade gypsum sheathing recovered to approximately 94% of their original values, except where the facer-to-gypsum adhesion was lost (in that case, the resistance to flexural load was tested to be 66% of the original value). The resistance to fastener penetration of all sheathing tested did not appear to be affected by wetting, once the specimens were dried out.

It is interesting to note that the 5/8” exterior-grade sheathing never dried out, and only reached 1% moisture content even after several days of drying in the oven. In general, the fibre-faced specimens appeared to take less time to take on water to the nominal target values and less time to dry out. Mould developed on all of the paper-faced samples, and on none of the fibre-faced samples.

The following recommendations can be derived from the above conclusions:

- In general, gypsum sheathing intended for exterior use should not be exposed to sources of moisture that will result in moisture-content levels above 1% (as a percentage of dry weight).
- Gypsum sheathing that experiences moisture levels in excess of 1% can be rehabilitated to some extent, if the gypsum is carefully dried in such a way that the bond between the facer and the gypsum core is not disturbed.
- The ASTM Standards should be reviewed to verify that the criteria are at appropriate levels for in-service performance.
- Additional research would be useful to investigate the effect of prolonged high moisture-content levels on the strength of different types of fasteners and framing components. The gypsum itself may not be adversely affected, but retained moisture may cause deterioration in adjacent materials (e.g., corrosion in fasteners and steel studs, decay in wood framing).

REFERENCES

1. ASTM C473-03: "Standard Test Methods for Physical Testing of Gypsum Board Products and Gypsum Lath". 2003, ASTM International Inc., Consohocken, PA.

2. ASTM C1177/ C1177M-04: "Standard Specification for Glass Mat Gypsum Substrate for Use as Sheathing". 2004, ASTM International Inc., Consohocken, PA.

3. ASTM C1396/ C1396M-02: "Standard Specification for Gypsum Board". 2002, ASTM International Inc., Consohocken, PA.

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APPENDIX A

TEST RESULT DATA

GYPSUM SHEATHING SPECIMENS

1/2" Exterior Grade Gypsum

Specimen ID	Moisture content	Existing Moisture content (%)	March 9 Achieved M.C. (%)	March 21 Final re-dried weight (g)	March 21 M.C. (%) after re-dried	Flexural loading side	Flexural load (lbs.)	Nail pull through Load (lbs.)	Presence of mold
12-XG-L-01	O-D	0.18				Interior	132	64	
12-XG-L-02	1%		0.87			Interior	80	54	March 2
12-XG-L-03	1%		0.87			Exterior	94	59	March 2
12-XG-L-04	1%		0.89				-	54	March 2
12-XG-L-05	4%		3.73			Exterior	24	32	March 2
12-XG-L-06	4%		3.72				-	28	March 2
12-XG-L-07	4%		3.75	1064.0	0.31	Interior	98	64	March 2
12-XG-L-08	4%		3.73	1045.2	0.26	Exterior	90	70	March 2
12-XG-R-01	O-D	0.18						65	
12-XG-R-02	1%		0.87			Interior	25	54	March 2
12-XG-R-03	1%		0.89			Exterior	24	49	March 2
12-XG-R-04	1%		0.86				-	51	March 2
12-XG-R-05	4%		3.75			Exterior	12	39	March 2
12-XG-R-06	4%		3.77				-	36	March 2
12-XG-R-07	4%		3.69	1019.0	0.24	Interior	33	61	March 2
12-XG-R-08	4%		3.74	1056.3	0.23	Exterior	37	63	March 2
12-XG-L-11	O-D	0.20				Exterior	148	59	
12-XG-L-13	8%		7.72			Exterior	19	28	March 2
12-XG-L-15	8%		7.66				-	26	March 2
12-XG-L-16	8%		7.72	1074.7	0.35	Interior	103	71	March 2
12-XG-L-17	8%		7.69	1076.8	0.38	Exterior	90	74	March 2
12-XG-R-11	O-D	0.20				Interior	35	56	
12-XG-R-12	8%		7.74			Exterior	7	26	March 2
12-XG-R-13	8%		7.77				-	29	March 2
12-XG-R-14	8%		7.52	1025.2	0.43	Interior	37	62	March 2
12-XG-R-15	8%		7.74	1023.3	0.41	Exterior	33	63	March 2
12-XG-L-21	O-D	0.18					-	63	
12-XG-L-22	16%		15.63			Interior	14	25	March 2
12-XG-L-23	16%		15.73			Exterior	14	26	March 2
12-XG-L-24	16%		15.68				-	25	March 2
12-XG-L-25	16%		15.70	1040.8	0.31	Interior	87	64	March 2
12-XG-L-26	16%		15.68	1041.8	0.30	Exterior	72	61	March 2
12-XG-L-27	16%		15.64	1046.4	0.33	Interior	107	64	March 2
12-XG-R-21	O-D	0.18				Exterior	39	59	
12-XG-R-23	16%		15.73			Interior	6	25	March 2
12-XG-R-24	16%		15.70			Exterior	7	25	March 2
12-XG-R-25	16%		15.65	1019.3	0.32	Interior	31	57	March 2
12-XG-R-26	16%		15.65	1057.2	0.32	Exterior	32	58	March 2
12-XG-R-27	16%		15.63	1052.3	0.32	Interior	35	59	March 2

5/8" Exterior Grade Gypsum

Specimen ID	Moisture content	Moisture content (%)	March 17 Achieved M.C. (%)	Final re-dried weight (g)	M.C. (%) after re-dried	Flexural loading side	Flexural load (lbs.)	Nail pull through Load (lbs.)	Presence of mold
58 - XG - L - 0 1	O-D	0.17				Interior	215	96	Very light
58 - XG - L - 0 2	1%		0.89			Interior	136	86	white stain
58 - XG - L - 0 3	1%		0.90			Exterior	137	85	on all
58 - XG - L - 0 4	1%		0.88			Interior	136	83	specimens
58 - XG - L - 0 5	4%		3.82			Exterior	53	59	
58 - XG - L - 0 6	4%		3.88			Interior	39	55	
58 - XG - L - 0 7	4%		3.89	1441.7	0.88	Interior	190	108	
58 - XG - L - 0 8	4%		3.90	1430.2	1.25	Exterior	229	112	
58 - XG - R - 0 1	O-D	0.17				Interior	94	92	
58 - XG - R - 0 2	1%		0.89			Interior	47	75	
58 - XG - R - 0 3	1%		0.94			Exterior	43	77	
58 - XG - R - 0 4	1%		0.88			Interior	57	77	
58 - XG - R - 0 5	4%		3.82			Exterior	25	54	
58 - XG - R - 0 6	4%		3.87			Interior	33	56	
58 - XG - R - 0 7	4%		3.88	1404.1	0.96	Interior	84	111	
58 - XG - R - 0 8	4%		3.87	1415.8	0.81	Exterior	88	116	
58 - XG - L - 1 1	O-D	0.17				Exterior	245	89	
58 - XG - L - 1 2	8%		7.80			Exterior	30	51	
58 - XG - L - 1 3	8%		7.83			Interior	34	46	
58 - XG - L - 1 4	8%		7.90	1394.7	0.95	Interior	216	103	
58 - XG - L - 1 7	8%		7.84	1434.3	0.92	Exterior	236	111	
58 - XG - R - 1 4	8%		7.82			Exterior	21	49	
58 - XG - R - 1 5	8%		7.85			Interior	24	48	
58 - XG - R - 1 7	8%		7.87	1396.5	1.04	Interior	92	100	
58 - XG - R - 1 8	8%		7.84	1409.7	0.87	Exterior	89	102	
58 - XG - R - 1 9	O-D	0.18				Exterior	89	90	
58 - XG - L - 2 1	O-D	0.18				Exterior	258	98	
58 - XG - L - 2 2	16%		15.53			Interior	32	52	
58 - XG - L - 2 3	16%		15.82			Exterior	31	48	
58 - XG - L - 2 4	16%		15.77			Interior	30	54	
58 - XG - L - 2 5	16%		15.79	1435.3	1.15	Interior	222	100	
58 - XG - L - 2 6	16%		15.79	1424.1	1.10	Exterior	228	115	
58 - XG - L - 2 7	16%		15.79	1438.7	1.15	Interior	215	102	
58 - XG - R - 2 1	O-D	0.17				Exterior	93	95	
58 - XG - R - 2 2	16%		15.80			Interior	19	47	
58 - XG - R - 2 3	16%		15.68			Exterior	21	47	
58 - XG - R - 2 4	16%		15.79			Interior	22	46	
58 - XG - R - 2 5	16%		15.22	1400.7	1.09	Interior	89	105	
58 - XG - R - 2 6	16%		15.71	1447	1.10	Exterior	91	101	
58 - XG - R - 2 7	16%		15.70	1423.4	1.14	Interior	93	95	

1/2" Fibre-Faced Gypsum

Specimen ID	Moisture content	Moisture content (%)	March 15 Achieved M.C. (%)	March 22 Final re-dried weight (g)	March 22 M.C. (%) after re-dried	Flexural loading side	Flexural load (lbs.)	Nail pull through Load (lbs.)	Presence of mold
12-FG-L-01	O-D	0.05				Interior	146	102	N/A
12-FG-L-02	1%		0.89			Interior	96	77	on all
12-FG-L-03	1%		0.90			Exterior	111	83	specimens
12-FG-L-04	1%		0.87			Interior	101	77	
12-FG-L-05	4%		3.89			Exterior	99	61	
12-FG-L-06	4%		3.89			Interior	82	53	
12-FG-L-07	4%		3.87	1242.10	0.15	Interior	167	122	
12-FG-L-08	4%		3.83	1237.40	0.17	Exterior	150	116	
12-FG-R-01	O-D	0.06				Interior	131	113	
12-FG-R-02	1%		0.89			Interior	80	85	
12-FG-R-03	1%		0.91			Exterior	76	76	
12-FG-R-04	1%		0.89			Interior	84	78	
12-FG-R-05	4%		3.85			Exterior	71	56	
12-FG-R-06	4%		3.87			Interior	74	55	
12-FG-R-07	4%		3.87	1230.2	0.29	Interior	152	122	
12-FG-R-08	4%		3.84	1228.2	0.27	Exterior	103	117	
12-FG-L-11	O-D	0.06				Exterior	109	104	
12-FG-L-12	8%		7.84			Exterior	82	45	
12-FG-L-13	8%		7.86			Interior	62	51	
12-FG-L-14	8%		7.47	1253.6	0.14	Interior	175	120	
12-FG-L-15	8%		7.79	1242.2	0.06	Exterior	129	110	
12-FG-R-11	O-D	0.06				Exterior	110	110	
12-FG-R-12	8%		7.84			Exterior	68	48	
12-FG-R-13	8%		7.89			Interior	59	44	
12-FG-R-14	8%		7.87	1236.9	0.08	Interior	126	115	
12-FG-R-15	8%		7.77	1240	0.08	Exterior	102	115	
12-FG-L-21	O-D	0.06				Exterior	148	102	
12-FG-L-22	16%		15.54			Interior	72	60	
12-FG-L-23	16%		15.74			Exterior	91	54	
12-FG-L-24	16%		15.80			Interior	68	60	
12-FG-L-25	16%		15.83	1251.9	0.25	Interior	145	119	
12-FG-L-26	16%		15.87	1230.6	0.20	Exterior	144	109	
12-FG-L-27	16%		15.80	1214.9	0.16	Interior	134	105	
12-FG-R-21	O-D	0.05				Exterior	99	95	
12-FG-R-22	16%		15.84			Interior	64	55	
12-FG-R-23	16%		15.98			Exterior	69	52	
12-FG-R-24	16%		15.49			Interior	63	51	
12-FG-R-25	16%		15.61	1215.4	0.13	Interior	141	108	
12-FG-R-26	16%		15.16	1216.6	0.18	Exterior	104	116	
12-FG-R-27	16%		15.01	1228.2	0.15	Interior	152	127	

5/8" Fibre-Faced Gypsum

Specimen ID	Moisture content	Moisture content (%)	March 16 Achieved M.C. (%)	March 22 Final re-dried weight (g)	March 22 M.C. (%) after re-dried	Flexural loading side	Flexural load (lbs.)	Nail pull through Load (lbs.)	Presence of mold
58 - FG - L - 0 1	O-D	0.15				Interior	178	121	N/A
58 - FG - L - 0 2	1%		0.87			Interior	135	76	on all
58 - FG - L - 0 3	1%		0.91			Exterior	136	70	specimens
58 - FG - L - 0 4	1%		0.89			Interior	138	71	
58 - FG - L - 0 5	4%		3.86			Exterior	116	55	
58 - FG - L - 0 6	4%		3.86			Interior	97	56	
58 - FG - L - 0 7	4%		3.84	1561.1	0.11	Interior	180	118	
58 - FG - L - 0 8	4%		3.85	1554.2	0.10	Exterior	185	115	
58 - FG - R - 0 1	O-D	0.14				Interior	177	114	
58 - FG - R - 0 2	1%		0.88			Interior	114	70	
58 - FG - R - 0 3	1%		0.89			Exterior	115	67	
58 - FG - R - 0 4	1%		0.85			Interior	119	69	
58 - FG - R - 0 5	4%		3.87			Exterior	99	54	
58 - FG - R - 0 6	4%		3.85			Interior	90	53	
58 - FG - R - 0 7	4%		3.84	1565	0.15	Interior	128	128	
58 - FG - R - 0 8	4%		3.80	1552.7	0.11	Exterior	102	124	
58 - FG - L - 1 1	O-D	0.15				Exterior	175	120	
58 - FG - L - 1 2	8%		7.82			Exterior	110	50	
58 - FG - L - 1 3	8%		7.88			Interior	94	52	
58 - FG - L - 1 4	8%		7.85	1575.3	0.13	Interior	176	115	
58 - FG - L - 1 5	8%		7.82	1590.4	0.16	Exterior	173	124	
58 - FG - R - 1 1	O-D	0.14				Exterior	139	116	
58 - FG - R - 1 2	8%		7.50			Exterior	90	57	
58 - FG - R - 1 3	8%		7.83			Interior	88	55	
58 - FG - R - 1 4	8%		7.77	1536.1	0.21	Interior	161	116	
58 - FG - R - 1 5	8%		7.86	1556.1	0.21	Exterior	143	121	
58 - FG - L - 2 1	O-D	0.15				Exterior	162	120	
58 - FG - L - 2 2	16%		15.68			Interior	78	52	
58 - FG - L - 2 3	16%		15.45			Exterior	90	50	
58 - FG - L - 2 4	16%		15.59			Interior	84	44	
58 - FG - L - 2 5	16%		15.78	1559.7	0.14	Interior	194	125	
58 - FG - L - 2 6	16%		15.83	1563.8	0.06	Exterior	156	105	
58 - FG - L - 2 7	16%		15.77	1572.9	0.09	Interior	192	115	
58 - FG - R - 2 1	O-D	0.14				Exterior	134	124	
58 - FG - R - 2 2	16%		15.18			Interior	74	51	
58 - FG - R - 2 3	16%		15.71			Exterior	82	47	
58 - FG - R - 2 4	16%		15.52			Interior	77	46	
58 - FG - R - 2 5	16%		15.78	1555.9	0.15	Interior	148	102	
58 - FG - R - 2 6	16%		15.81	1569.5	0.08	Exterior	98	121	
58 - FG - R - 2 7	16%		15.44	1609.2	0.12	Interior	143	124	

Figure 1. Saturation of Gypsum Sheathing

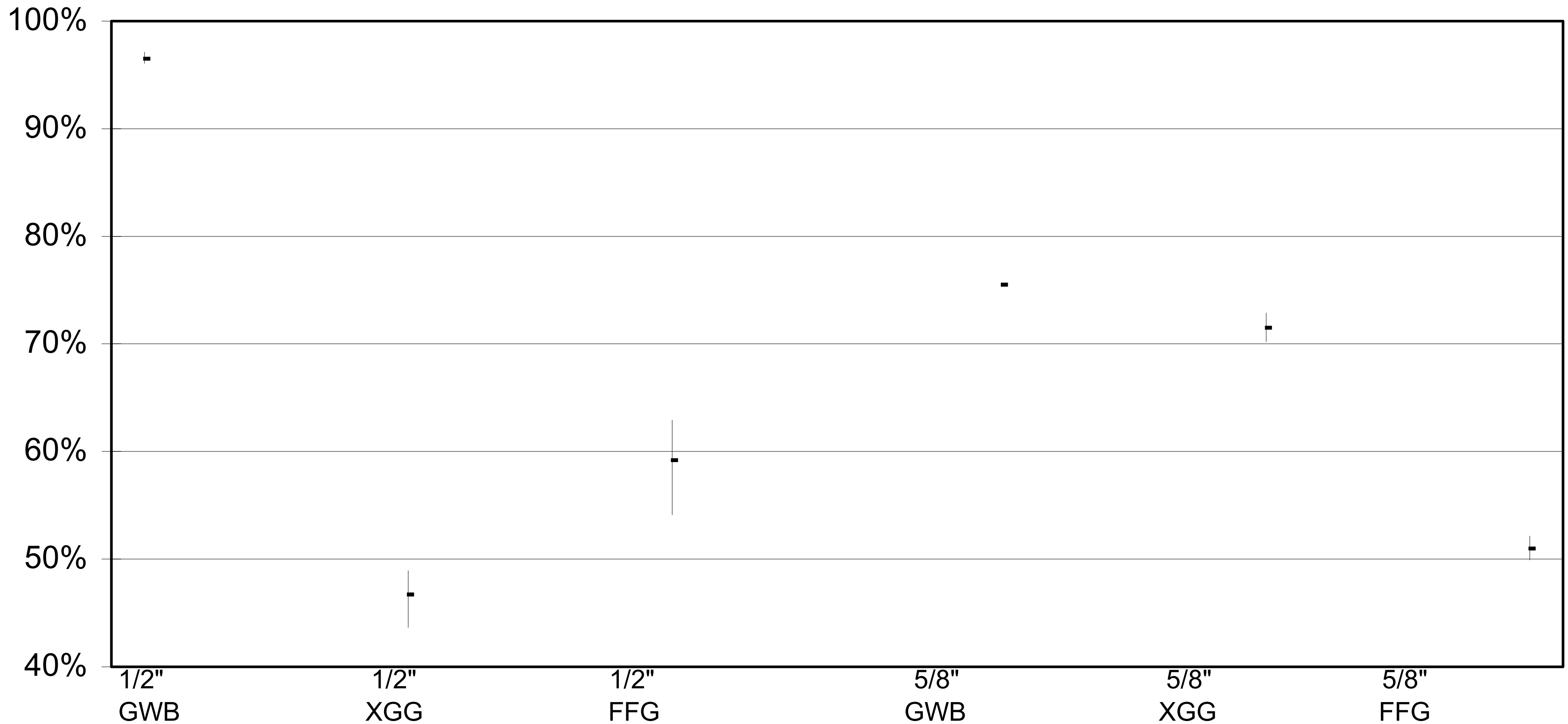

Figure 2. Moisture-meter Accuracy

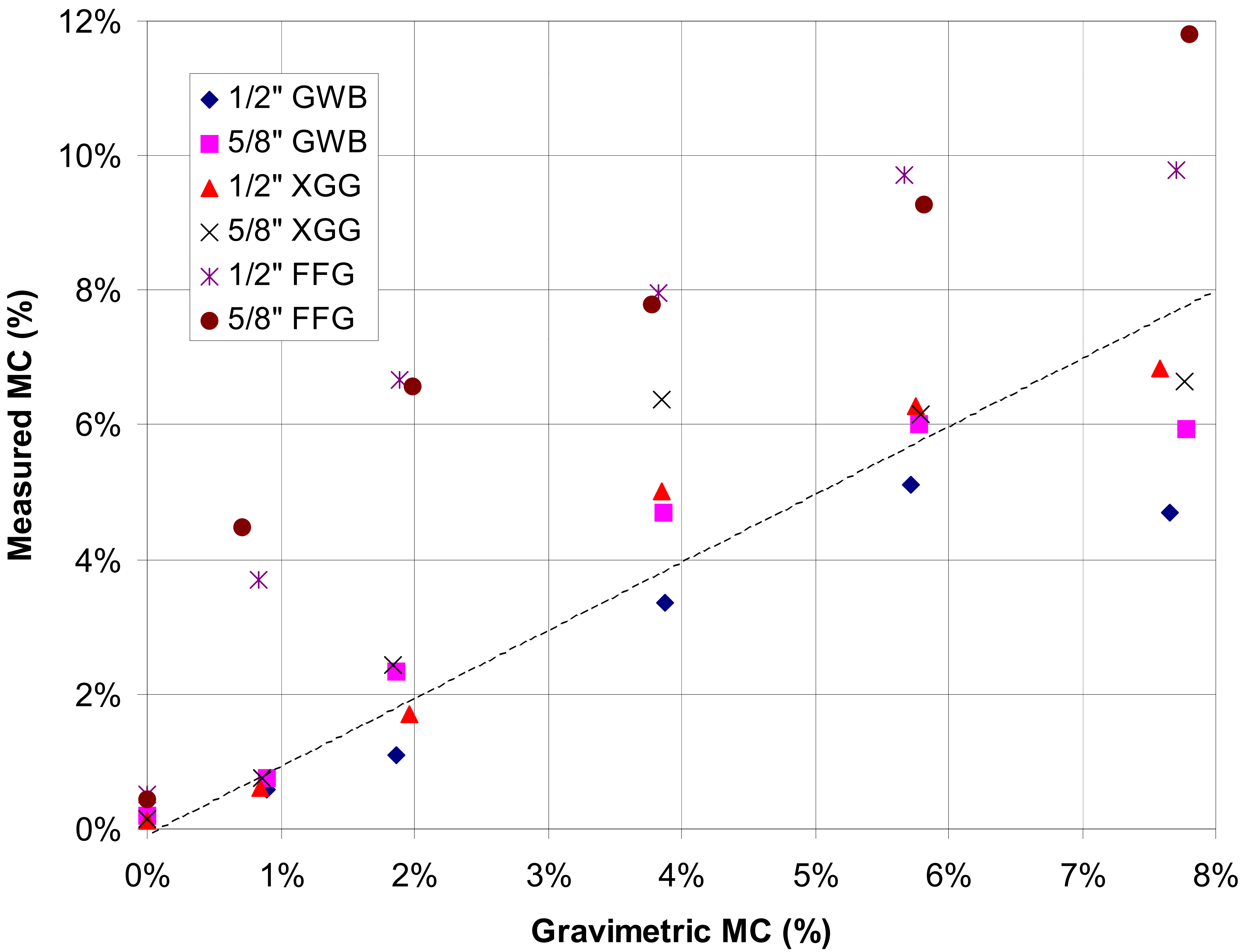

Figure 3. Flexure tests (parallel) for 1/2" GWB

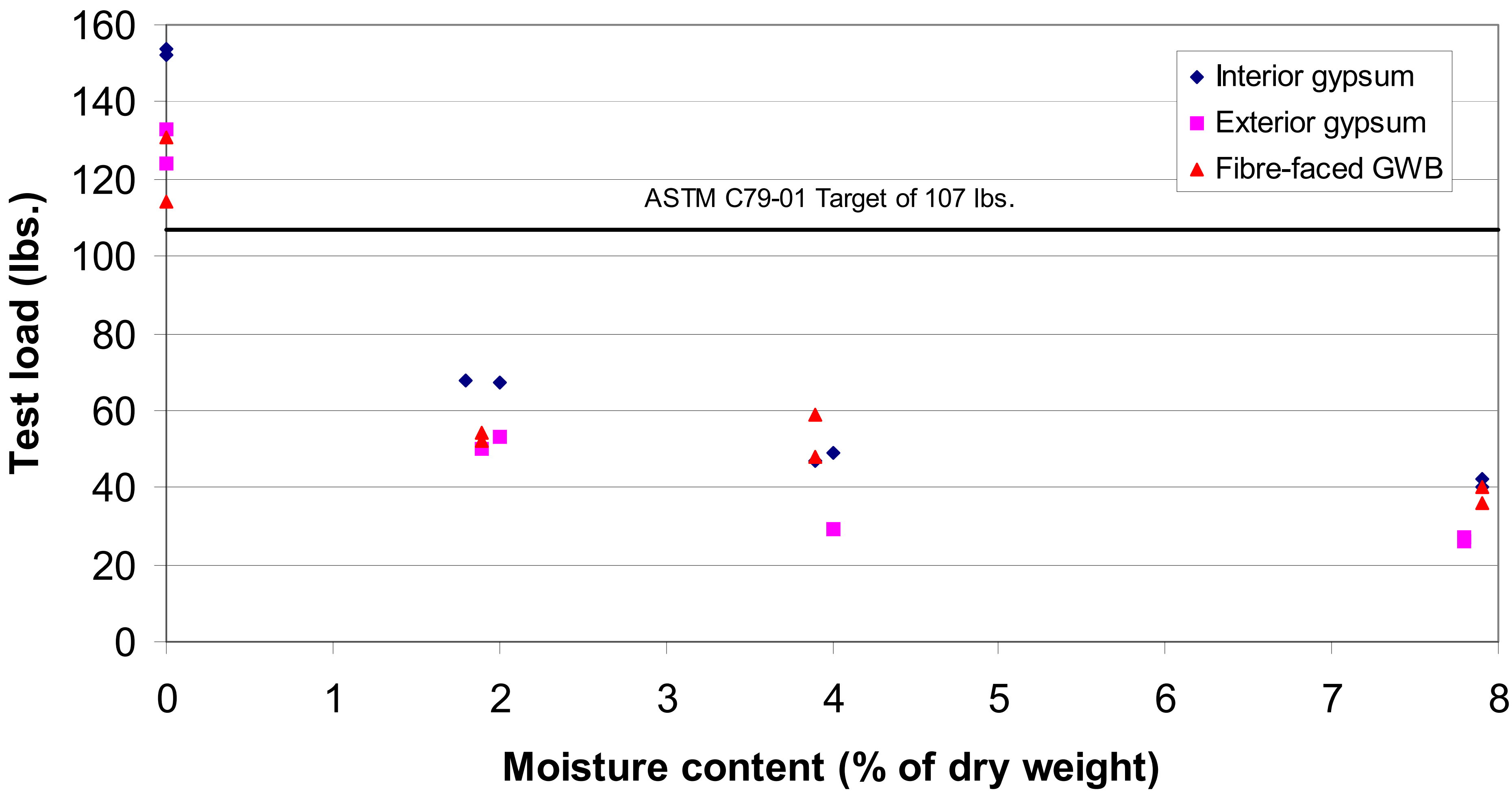

Figure 4. Flexure tests (perpendicular) for 1/2" GWB

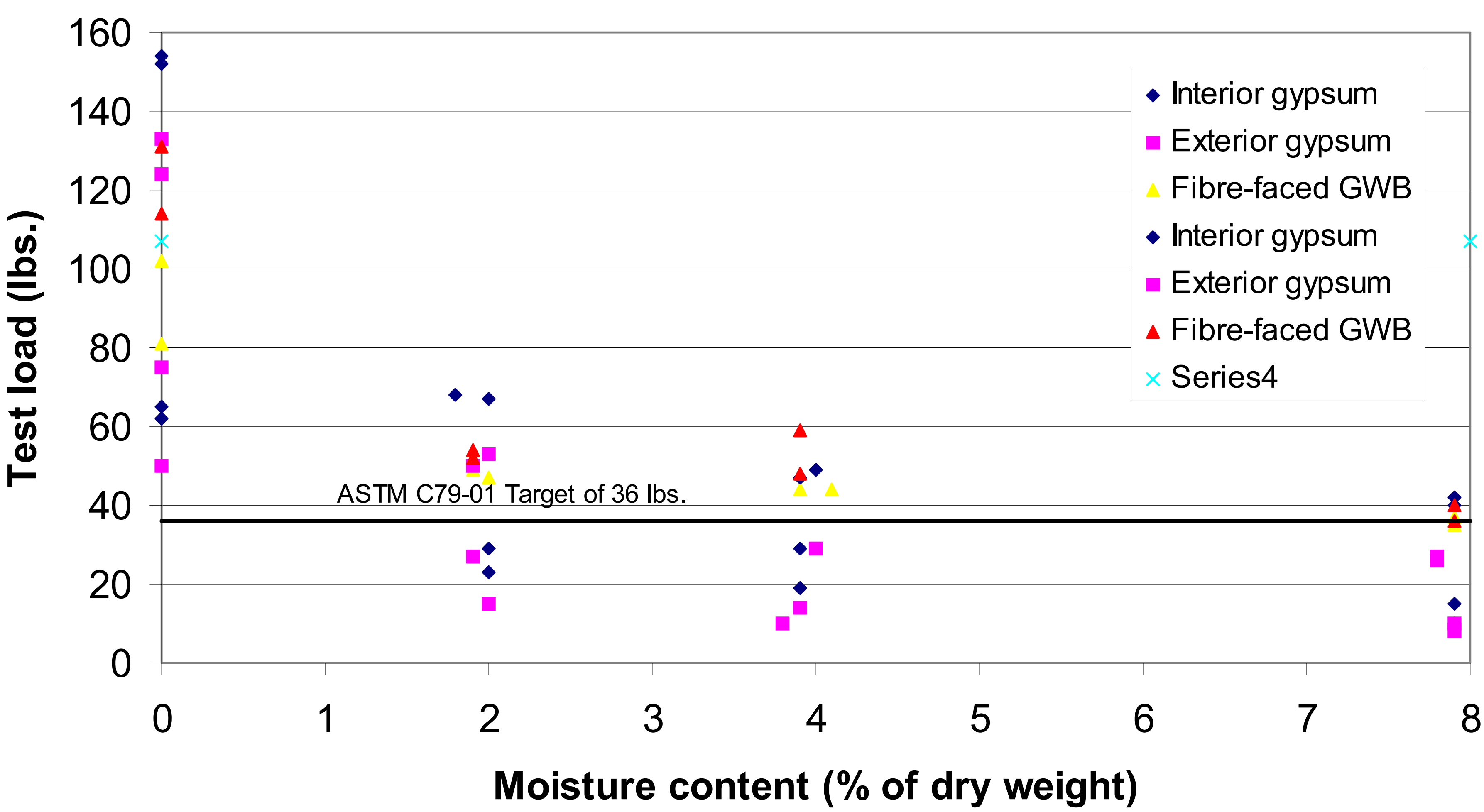

Figure 5. Flexure tests (parallel) for 5/8" GWB

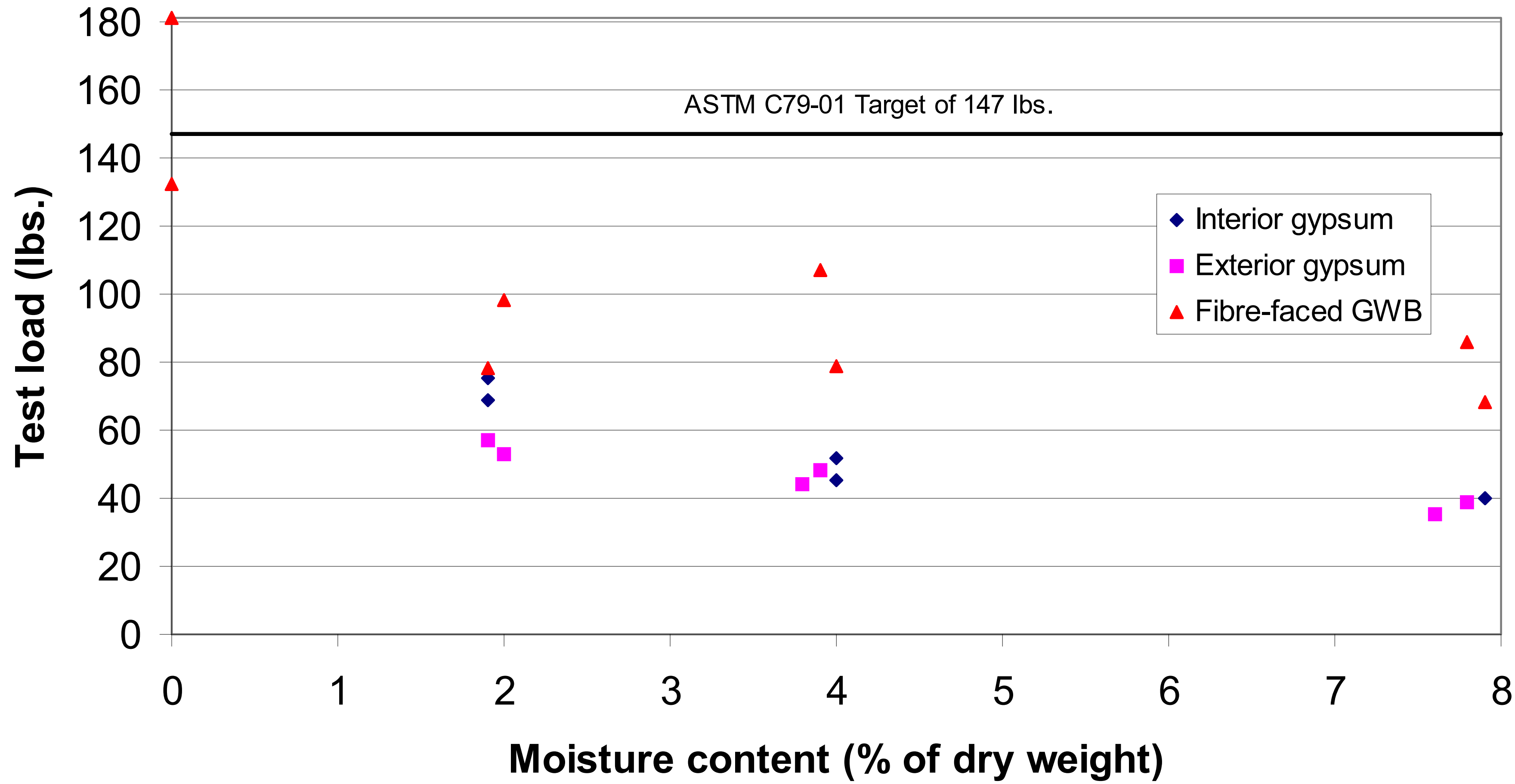

Figure 6. Flexure tests (perpendicular) for 5/8" GWB

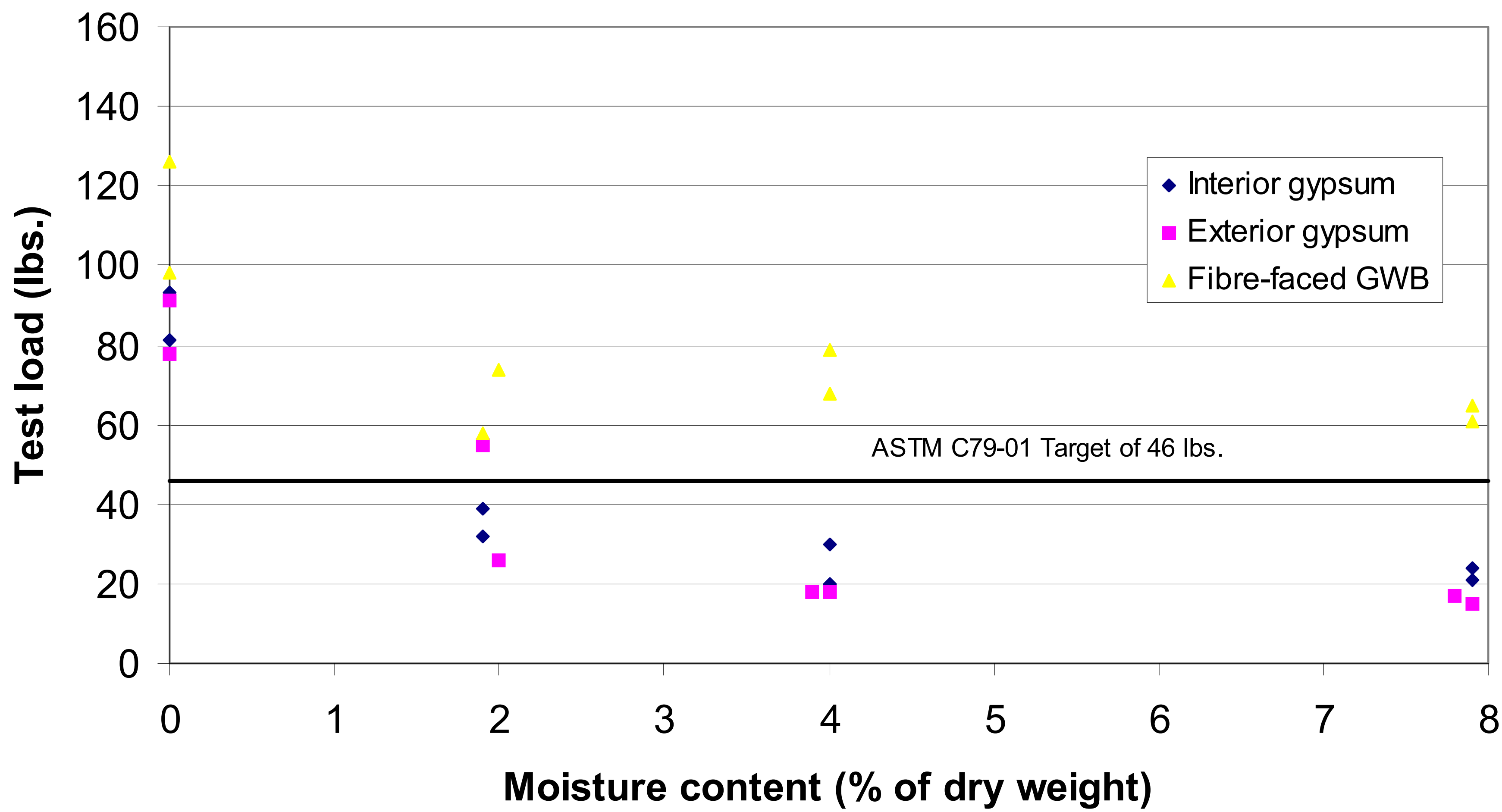

Figure 7. Nail pull tests for 1/2" GWB

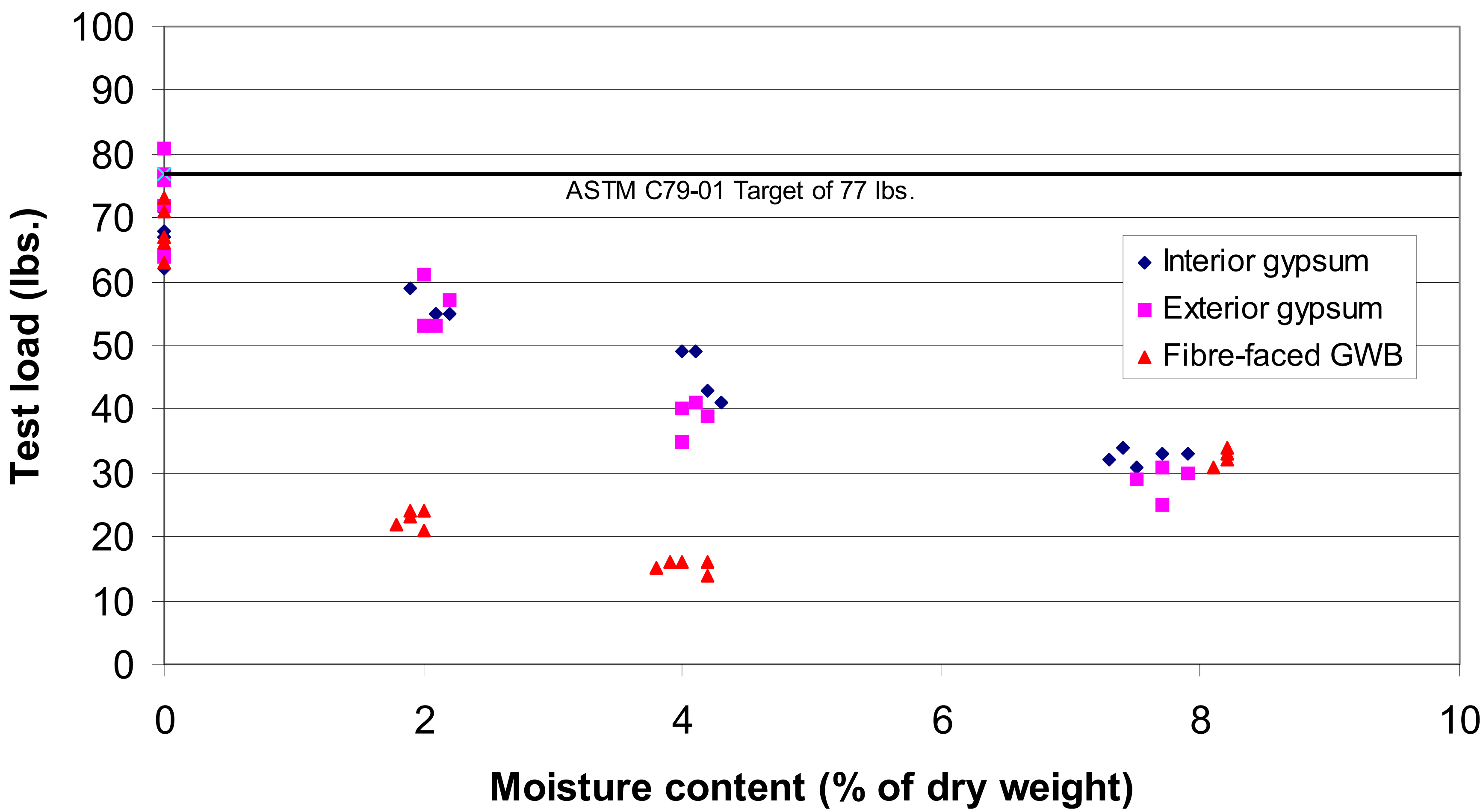

Figure 8. Nail pull tests for 5/8" GWB

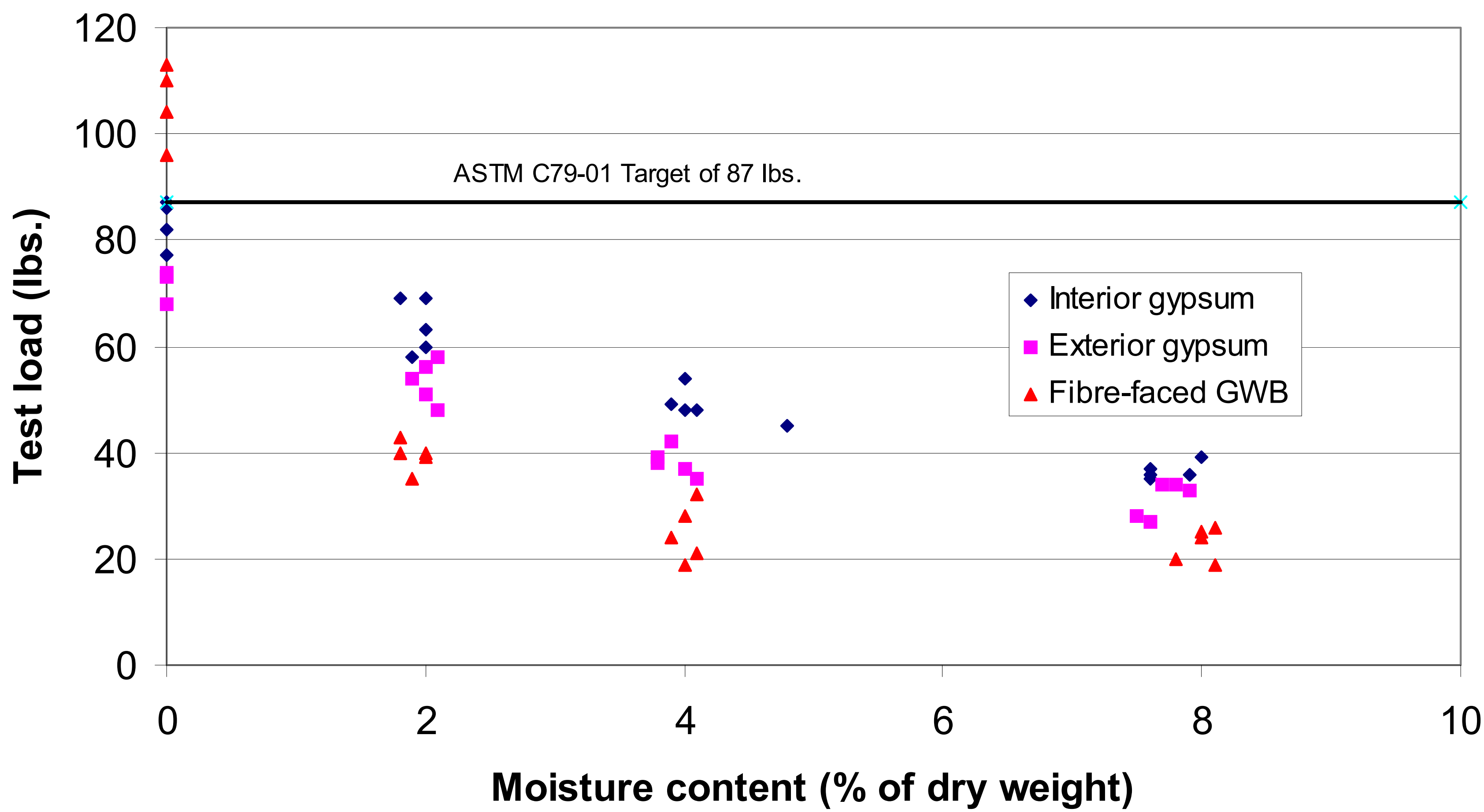

Figure 9. Facer adhesion tests for 1/2" GWB

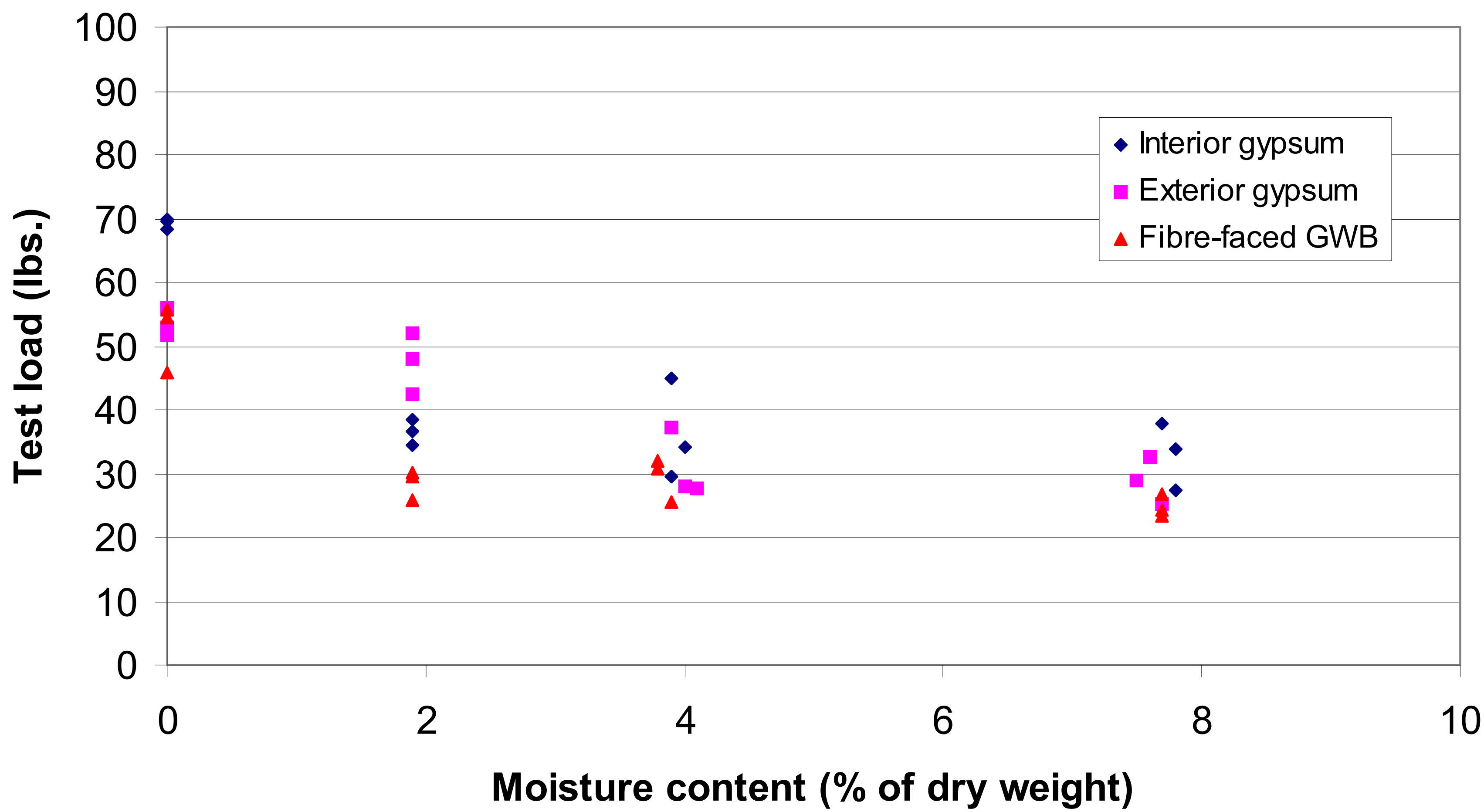

Figure 10. Facer adhesion tests for 5/8" GWB