Relationship between Moisture Content and Mechanical Properties of Gypsum Sheathing

ABSTRACT

A recent research project examined the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum panel products intended for use as exterior sheathing on buildings). Specific properties to be examined in the project included:

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

This paper summarizes the research results for these properties. Gypsum sheathing is typically specified in construction or remediation projects in accordance with the ASTM C1177 or C1396 Standards, which define the performance of gypsum sheathing in terms of the above characteristics. The objectives of the research project could be expressed as determining the moisture content at which gypsum sheathing no longer meets one or more of the above criteria, as defined in ASTM C1177 or C1396.

INTRODUCTION

A CMHC-sponsored research project examined the relationship between moisture content and mechanical properties of gypsum sheathing (i.e., gypsum panel products intended for use as exterior sheathing on buildings). Specific properties to be examined in the project included:

- adhesion or delamination of facer material (either glass-fibre mats, treated paper or untreated paper);
- 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

Previous CMHC-supported research on gypsum sheathing (e.g., References 1 and 2) focussed on 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 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 moisture loads that 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.

Gypsum sheathing is often specified in construction or remediation projects in accordance with ASTM Standards (References 3 and 4), which define the performance of gypsum sheathing in terms of the above characteristics. In a sense, then, the objectives of the research 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 performance criteria defined in ASTM C1396 (or ASTM C1177, in the case of gypsum sheathing faced with glass-fibre mats). The intent is to determine "acceptable" 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-through (which leads to sheathing detachment); or loss of mechanical integrity (which creates several modes of failure in the wall assembly). This project was proposed as a "proof-of-concept study", to determine whether there would be merit in further investigation of the mechanical and other properties of gypsum sheathing as these properties vary with moisture content.

It was also proposed to determine whether hand-held electric resistance meters are suitable for measuring moisture content and are reasonably accurate, 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. This paper does not discuss the results of that part of the research: the reader is referred to the final report of the original project (Reference 5). For building-science practitioners involved in diagnostic investigations, it is hoped that this paper will provide guidelines as to appropriate levels of moisture in existing buildings.

Building scientists are familiar with acceptable ranges for moisture content in wood-framed buildings. This information is also available to the general public, in large part due to the publication of CMHC's Best Practice Guides (e.g., Reference 6). We know, for example, that moisture content of less than 19% in wood is considered acceptable, as it is difficult for fungal colonies to grow in this moisture-content range, and this information 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 possible.

Such limits are not known for gypsum-based products, however, leaving design consultants to develop their own (differing) 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.

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 "exterior-grade" sheathing, with standard gypsum board as a control specimen. All of the following specimens were tested at 1/2" and 5/8" thickness, the most common commercially available thicknesses:

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. This product should NOT be used as sheathing. **Throughout this paper, standard gypsum wallboard specimens are designated "GWB".**
2. "Exterior-grade" gypsum, with moisture-resistant core and moisture-resistant paper facers. **Throughout this paper, moisture-resistant "exterior-grade" gypsum sheathing specimens are designated "XGG" (for exterior-grade gypsum).**
3. Exterior-grade sheathing 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. **Throughout this paper, fibre-faced gypsum specimens are designated "FFG".**

Testing was 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 treated-core product was not readily available in the Vancouver area at the time we were procuring specimens for this project. In that case, treated-core product was imported 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, at least 100 mm away from ends and edges of the sheet stock, as specified in ASTM C473 (Reference 7). 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 for approximately two weeks. This is a slight deviation from ASTM C473, which requires that samples are to be conditioned at 29.5 °C (± 8.5°C) and 50% RH (± 2%).

TEST PROTOCOL

The objective of the project was to assess 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-through; and

- flexural strength, 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. An earlier phase of the project (as described in Reference 5) had attempted to define the "saturation" moisture content of the specimens, so that all results of the project could be presented both in terms of "% saturated" and in standard moisture-content values (typically expressed as a percentage of dry weight). Some of the specimens did not reach saturation (defined for this project as the moisture-content level at which no additional moisture is adsorbed) until nearly 200% moisture content, so this approach was abandoned. The near-saturated samples were easily friable, and testing of mechanical properties would have been pointless.

Instead, we used a trial-and-error method to determine appropriate levels of moisture content to be used in this project. Starting at 8% moisture content, we evaluated the results to determine whether testing at a higher moisture content would be useful. If not (which turned out to be the case), testing was repeated at 4% moisture content and 2%, as well as the base-case testing at 0% moisture content (i.e., at the dry weight of the specimens).

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 8) 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 calcination. We wanted to keep this project simple, and phase change due to calcination would unnecessarily complicate our study. As we were concerned that some partial calcination 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 9), 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).

Each specimen was then 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.

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.

The flexural-strength test is also described in the C473 Standard (see Figure 2). 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 clearly described in the C473 Standard, as is the method and rate of load application. Again, the maximum recorded load represents the applied force just prior to failure of the specimen in flexure.

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 1. TESTING APPARATUS FOR FASTENER PULL-THROUGH

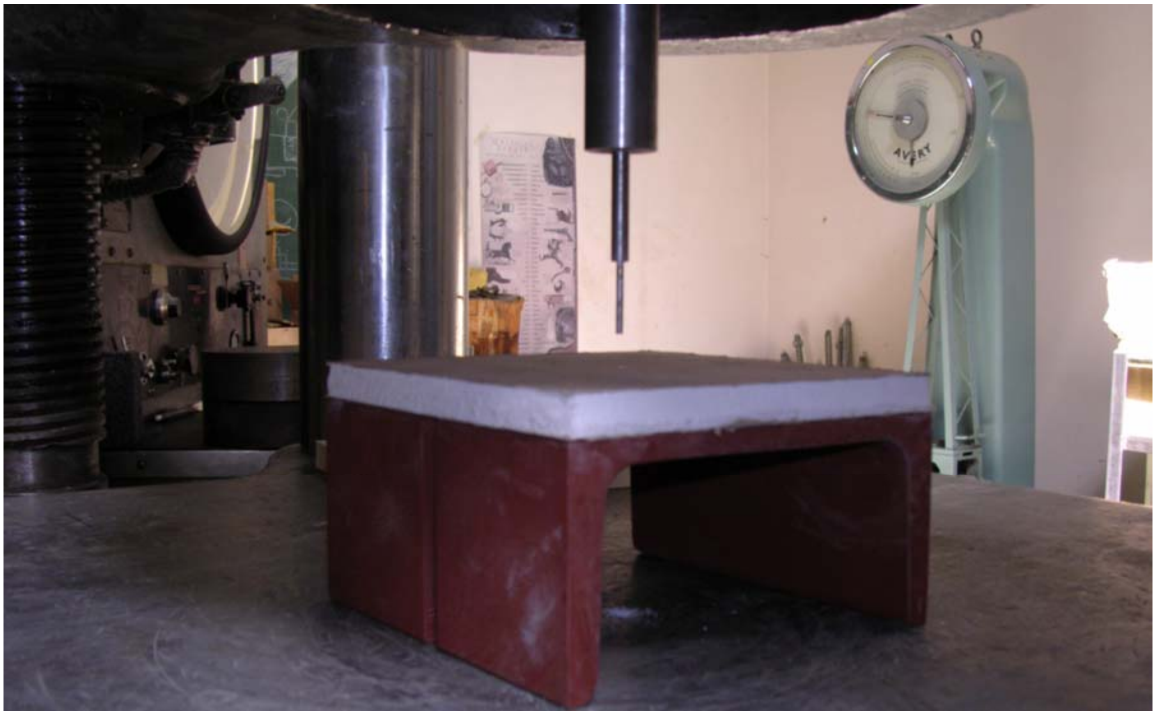


FIGURE 2. TESTING APPARATUS FOR FLEXURAL STRENGTH

The test for facer delamination was a modified version of CSA A23.2-6B (Reference 10), 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 3).

The tests for fastener pull-through, flexural strength and facer delamination were conducted at four different nominal moisture-content levels: 0% (dry), 2%, 4% and 8%, all expressed as a percentage of dry weight. Prior to testing, the actual moisture content of all specimens was verified using gravimetry, and all were within 5% (or between 0.95 and 1.05 of nominal) of the target moisture content (e.g., the actual moisture content of specimens measured at "2% moisture content" ranged from 1.8% to 2.2%).

FIGURE 3. TESTING APPARATUS FOR FACER DELAMINATION

TEST RESULTS

Fastener Pull-through:

Typical test samples from the fastener pull-through trials are shown in Figure 4. These photographs show the base-case interior-grade gypsum sheathing, to provide an interesting (and somewhat typical) illsutration of the different behaviour of the specimens at varying moisture contents.

The "dry" specimen (0% m.c., Figure 4a) 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 4a.

Figure 4b 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 4c and 4d 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 4d).

The results of the testing are summarized graphically in Figure 5. Similar results are available for the 1/2-inch specimens, but space limitations prevent their inclusion in this paper, and the 5/8-inch specimens show the same pattern. Figure 5 also includes the threshold value of 87 pounds of applied force, which is the target value for ASTM 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 87 pounds of applied force” (for 1/2-inch sheathing, the C1396 threshold is 77 pounds). Figure 5 displays the results of testing for 60 specimens: five of each type of sheathing, tested at four different moisture contents.

FIGURE 4. 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

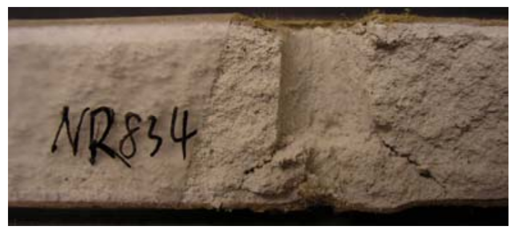


FIGURE 5. NAIL PULL RESISTANCE TESTS FOR 5/8" GWB

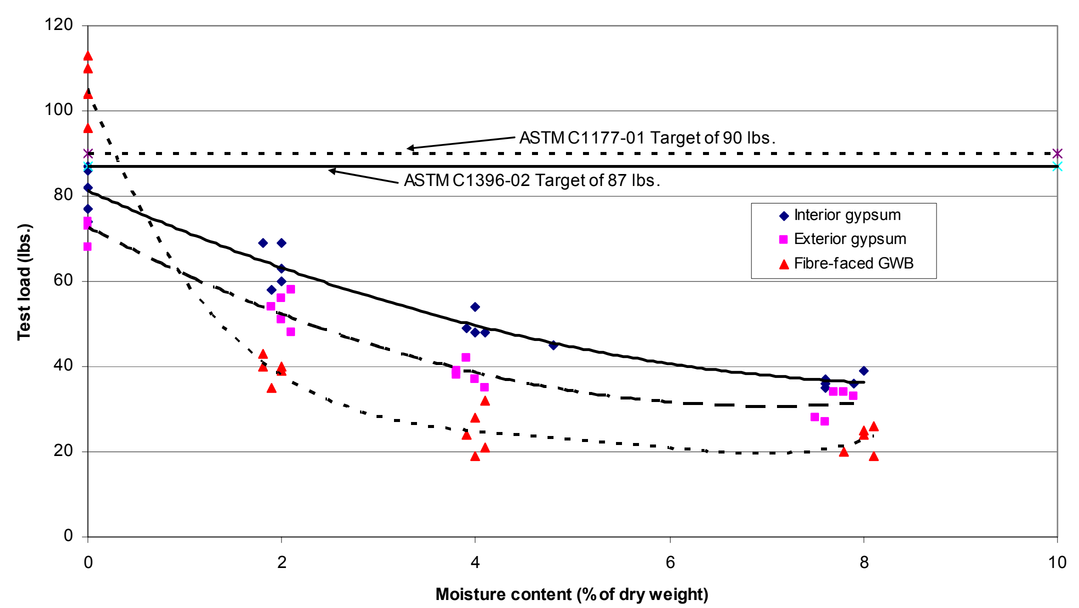


Figure 5 shows good repeatability of the results, with very little scatter for each specimen group. The test results for 1/2-inch specimens actually shows less scatter than the 5/8-inch results shown in Figure 5. Trendlines have been added to indicate a clear pattern of behaviour for all three types of sheathing. The specimens tested did not actually meet the ASTM C1396 requirement, except for the FFG specimens at 0% moisture content. The trendline for FFG can be used to estimate the moisture content at which the FFG sheathing will meet the ASTM C1396 requirements: in this case, it appears that FFG sheathing with less than 0.3% moisture-content levels 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 further testing with different job-lots of sheathing may provide different results.

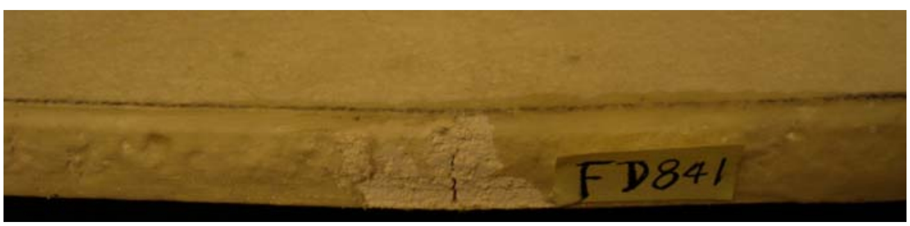
Flexural Strength

Figure 6 shows test specimens subjected to flexural testing to failure. All specimens shown in Figure 6 are of the fibre-faced category. As with the fastener-penetration tests shown in Figure 4, the "dry" (0% moisture content by weight) specimens showed evidence of brittle fracture, as seen in Figure 6a. The damper specimens exhibited more ductile fracture, as the specimen was able to distribute some of the applied load before it ruptured (Figure 6b). 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 6c).

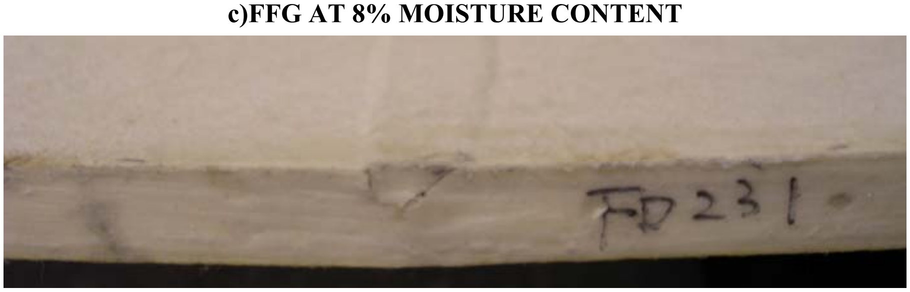
Figure 7 presents the results for all flexural tests of 1/2-inch specimens, tested parallel to the facer grain. These curves represent two data points for each specimen type at each moisture-content level: one test with specimens "face up", and one "face down", per the ASTM C473 protocol. As with all materials testing results in this project, the data show very good repeatability, with the data points from each specimen type clustered in very tight groupings.

FIGURE 6. SECTIONAL VIEW OF SAMPLES FROM FLEXURAL TESTS
a)FFG AT 0% MOISTURE CONTENT

b)FFG AT 2% MOISTURE CONTENT

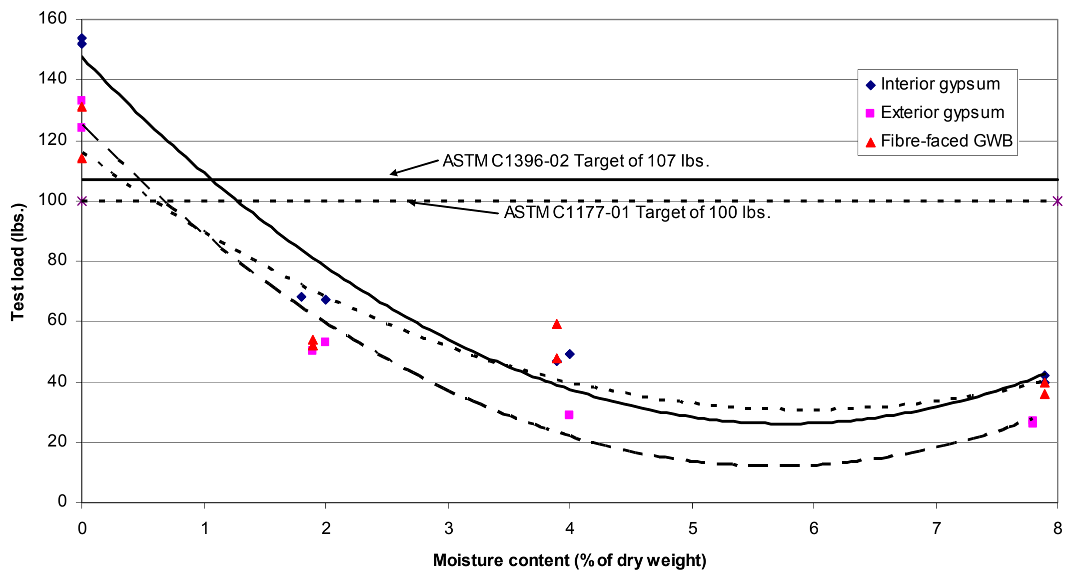


c)FFG AT 8% MOISTURE CONTENT



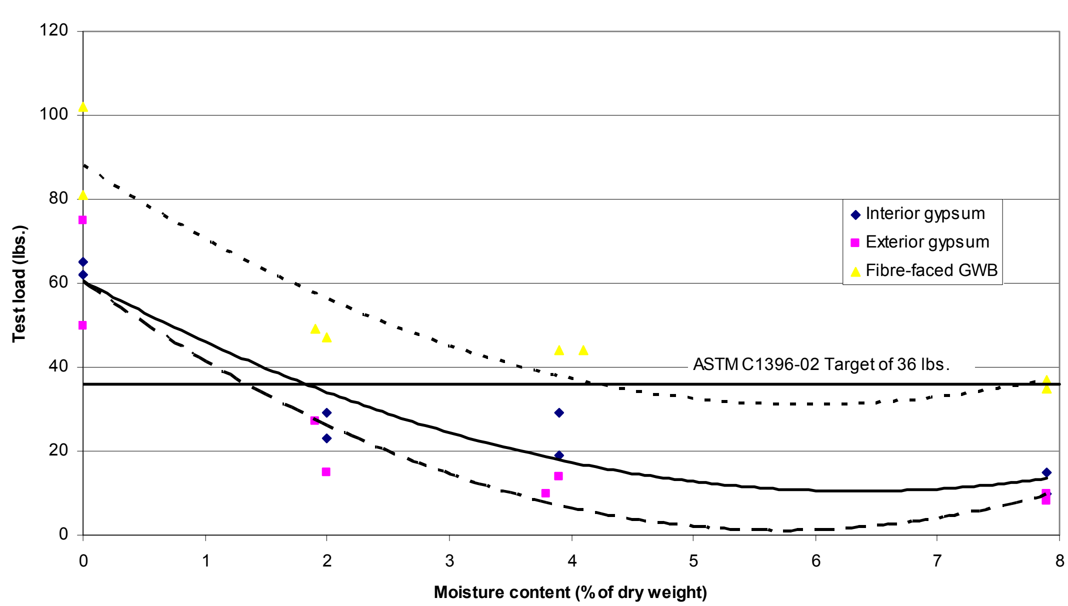
The results show a marked decrease in breaking strength for all specimens when the moisture content is increased from 0% to 2%. With trendlines added (using second-order polynomial approximation functions), the trends are quite clear. It is interesting to note that the GWB specimens generally yielded the highest test results. The ASTM C1396 target is included in Figure 7, and the graph suggests that GWB specimens meet the C1396 specification at a moisture content of 1% or less: XGG and FFG specimens meet the criterion at a moisture content of approximately 0.3% or less.

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



The test results for 1/2–inch sheathing tested perpendicular to the grain are shown in Figure 8. These results show values much lower than the results represented in Figure 7, but the ASTM C1396 criterion for perpendicular tests is also lower (36 lbs., rather than 107 lbs. for the parallel tests). As Figure 8 shows, almost all of the FFG specimens tested meet the C1396 criterion. The trendlines added for all specimens can be used to estimate the maximum moisture contents at which the other sheathing types would comply with the C1396 specification: approximately 1.9% for GWB and 1.3% for XGG.

FIGURE 8. FLEXURAL STRENGTH TESTS (PERPENDICULAR) FOR 1/2" GWB

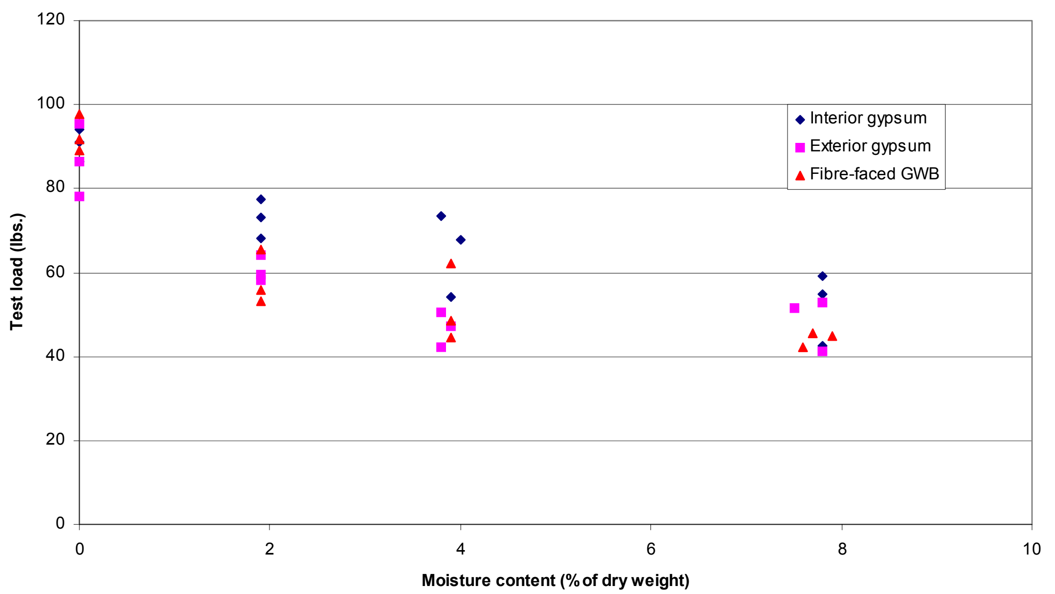


The flexural-test results for 5/8-inch specimens showed generally similar trends as the 1/2 –inch specimens shown in Figures 7 and 8, except almost none of the specimens met the C1396 requirements when tested in the parallel configuration.

Facer Delamination:

Facer-delamination test results for the 5/8-inch specimens trials are shown in Figure 9. These results are similar to those for the 1/2–inch sheathing, and show that the applied forces for facer delamination are of similar magnitude as the fastener pull-through tests. 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 9. FACER ADHESION TESTS FOR 5/8" SHEATHING



SUMMARY AND DISCUSSION

The results of this preliminary study indicate that the mechanical properties of gypsum sheathing products are strongly dependent on moisture content. The flexural strength and fastener pull-through of these products decrease to the point where they no longer meet the criteria established in ASTM C1396 at between 0.3% and 1% moisture content (depending on the product).

Some additional investigation may be warranted, to evaluate the performance of these products at 1% moisture content. This would help to more sharply define the critical threshold of moisture content, as it affects the mechanical properties of gypsum sheathing.

This provides a different result from previous research in this area. Pressnail et al. (Reference 1), who used the onset of mould growth as their limiting design state, suggest that a moisture content of 1.4% is enough to promote mould and mildew. Handegord et al. (Reference 2) mainly dealt with psychrometric effects, and set the maximum moisture content for gypsum sheathing at the value associated with 100% RH. From recent research in this area (Reference 11), this corresponds to approximately 69% moisture content by weight.

The results of the current study have direct implications for EIFS systems, the integrity of which depends upon the adhesion of the cladding to the sheathing, and the sheathing's resistance to fastener pull-through.

The Building Code does not require bracing where sheathing (including gypsum sheathing) is used: "additional bracing is not considered necessary because of the wind bracing provided by these materials". Such support may be absent, however, where (for example) the fasteners can no longer hold the sheathing in place, because the moisture content of the sheathing has exceeded the values identified in this study.

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