STONE-FACED ALUMINUM HONEYCOMB COMPOSITES — QUALITY CONTROL AND TESTING

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Abstract

Stone-faced aluminum honeycomb composite panels are engineered building products that provide an alternative to traditional stone cladding and are increasingly being used as a lightweight exterior building cladding. Stone-faced composites use only a thin stone veneer, which minimizes the influence of the stone on mechanical properties and variability of the composite. Based on independent laboratory testing of certain strength and durability characteristics of stone-faced composite panels from different manufacturers, several variables that can affect the performance of these composites will be provided, along with guidance for evaluating and specifying stone-faced composite panels.

Speakers


Since joining WJE in 2003, DAREN KNEEZEL has been involved in projects ranging from investigation of high-rise building façades to laboratory testing of stone and other construction materials. He has also performed structural and finite element analyses and developed repairs for thin-stone cladding and its anchorage systems. Kneezel has performed laboratory testing of various materials with a concentration on stone (marble, limestone, granite, slate, travertine, and composite stone panels) to evaluate structural performance and to determine compliance with project specifications and industry standards. This includes testing of materials in accordance with the standards of ASTM International (ASTM).


Since joining WJE in 1980, MICHAEL SCHEFFLER has been involved in more than 1,000 investigations of deterioration and distress in buildings and other structures. The investigations have included high-rise exterior façades of limestone, marble, granite, masonry, and terra cotta. He has extensive experience in the investigation and testing of distressed thin-stone façades. Scheffler has performed laboratory and in-situ testing of building assemblies related to stone material performance and structural performance and has performed long-term monitoring and instrumentation of distress on several types of structures. He has also given professional seminars on building envelope maintenance and repair.
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INTRODUCTION

Stone-faced aluminum honeycomb composite panels are engineered building products that provide an alternative to traditional stone cladding and are increasingly being used for exterior building cladding. Stone-faced composite panels provide a very similar aesthetic to traditional thin-stone cladding, with the advantage of being lighter weight, which can result in a lower installed cost.

While the mechanical properties of many stone types are intrinsically highly variable, stone-faced composites use only a thin stone veneer, which minimizes the influence of the stone on composite panel variability. Understanding and controlling the manufacturing variables of these composites related to adhesive, aluminum honeycomb, and honeycomb facing in order to produce a uniform composite with the desired behavior and performance requires significant research and development by the composite manufacturer during product development, as well as quality control during production.

Based on evaluation of stone-faced composite panels from different manufacturers, this paper will describe several variables that can affect the performance of stone-faced aluminum honeycomb panels and will summarize independent laboratory testing that has been performed by the authors to measure certain strength and durability characteristics of stone-faced aluminum honeycomb products. Based on the test results and findings, guidance is provided for testing and evaluating specific physical, mechanical, and fabrication aspects of stone-faced composite panels prior to their procurement, as well as during their fabrication.

PRODUCT DESCRIPTION

Aluminum Honeycomb

Aluminum honeycomb is typically fabricated using the expansion method, in which sheets of aluminum are stacked and adhered with staggered lines of adhesive. After curing, the stack of adhered aluminum sheets is sliced to the desired thickness and expanded to form a honeycomb. Facings are then adhered to the expanded honeycomb to form a laminated honeycomb.

Stone-Faced Aluminum Honeycomb

Stone-faced aluminum honeycomb panels are a relatively recent engineered building product that provides a lightweight alternative to traditional stone cladding. These panels weigh approximately 3.5 pounds per sq. ft., compared to 15 pounds per sq. ft. for 3-cm-thick, 150-pcf stone. First developed in the early 1970s, these lightweight stone-faced panels have been used on buildings in the U.S. for over 30 years. Stone-faced honeycomb is produced by adhering laminated aluminum honeycomb to each side of a single stone panel, as shown in Figure 1. The stone is then wire-cut at midthickness to produce two stone-faced panels. A typical stone-faced honeycomb panel is shown in Figure 2.
For new construction projects, the lighter weight of stone-faced honeycomb panels can simplify installation and minimize cladding dead loads. For existing projects with deteriorated stone that would otherwise require cladding replacement with a thicker or denser stone, the use of stone-faced honeycomb can eliminate the need for structural retrofit. In addition, since composite panels utilize only a thin-stone veneer, a stone with limited availability can be optimized. In some cases, reliance upon the strength of the honeycomb may allow the use of a stone with marginal mechanical properties or the use of stone in applications or sizes that would otherwise be unsuitable for traditional stone cladding. The size of these panels is typically limited by the size of the stone slab.

While stone-faced honeycomb offers several advantages over traditional stone cladding, there are a number of material and manufacturing variables that can greatly influence the performance and durability of the finished product. Understanding and controlling these variables, in combination with periodic quality control testing, is important in ensuring a product with uniform properties and expected performance.

MATERIAL AND MANUFACTURING VARIABLES

The mechanical properties of many stone types are inherently highly variable. By using only a thin-stone veneer, stone-faced honeycomb minimizes the influence of the natural material (stone) on the variability of the composite. The remainder of the materials (adhesive, aluminum honeycomb, and honeycomb facing) are synthetic, allowing the manufacturer to control several material and manufacturing variables to produce a composite that is relatively uniform. Understanding and controlling these variables to produce a uniform composite with the desired behavior requires significant research and development by the composite manufacturer during product development and a high degree of quality control during production.

Material variables include stone type, adhesive type, honeycomb facing type, and aluminum honeycomb gauge, cell size, thickness, and orientation. Manufacturing variables include degree of honeycomb core expansion, surface preparation prior to adhering stone to the honeycomb, adhesive application, lamination procedures, and cutting methods. The method of attachment is also a material (type and composition of anchor) and manufacturing (spacing and adhesive-curing) variable. Considering these variables, the manufacturer makes decisions during product development to balance cost with desired performance. For instance, a manufacturer may determine that it is more cost-effective to space anchors more closely than to optimize the strength/span of a panel. The product specifier should be aware of the variables that can affect the mechanical properties, durability, uniformity, and cost of stone-faced honeycomb so that they can anticipate an appropriate level of preconstruction testing and monitoring during production.

As with any product, the variables associated with the manufacture of stone-faced honeycomb panels should be reviewed during preconstruction testing and periodically throughout production to confirm that the honeycomb product remains consistent. This will help to ensure that tested performance is representative of the supplied product. Several of the material and production variables are described below in greater detail.

MATERIAL VARIABLES

Stone Type

The durability of the stone is an important consideration, because a nondurable stone may crumble or delaminate within itself, regardless of how well it is bonded to the honeycomb. Prior to selection, it should be confirmed that the stone facing has been used successfully in an environment similar to the intended environment, or physical/mechanical testing should be performed to review facing properties. This should include absorption, compressive strength, and flexural strength testing; and pass/fail criteria should be established based on the intended application. For material to be used in severe weathering environments, simulated weathering testing may be advisable, depending on the size and significance of the project as well as availability of information regarding the material's weathering durability.

In addition, a stone with significant...
voids, such as traver-tine—or a more absorptive stone, such as limestone—will provide less resistance to water penetration than a more impervious stone such as polished granite. If water is able to bypass the stone facing, it may degrade the bond between the stone and honeycomb facing and may also affect the long-term durability of honeycomb. The durability and water resistance of the stone should be considered when selecting a stone facing, and the potential effect of moisture on the adhesive and honeycomb should be considered when developing a testing program.

While the stone facing contributes to the strength of the composite, it may be possible to ignore the contribution of a low-strength or highly variable stone if the honeycomb alone provides sufficient strength.

Aluminum Honeycomb Core

Variables in the aluminum honeycomb core include cell shape and size, aluminum alloy and gauge, adhesive used to adhere aluminum sheets prior to expansion, and honeycomb thickness. Changing any of these variables can have a significant impact on the mechanical properties and durability of the composite. In order to ensure uniform properties of the laminated honeycomb product, it is desirable to obtain periodic quality control testing of the product without stone facing.

Honeycomb Orientation

Expanded honeycomb has a weak and strong orientation relative to the direction in which it is expanded. The strong (ribbon) orientation consists of continuous strips of metal, while the weak (transverse) orientation is interrupted by adhesive. Figures 3 and 4 show the strong and weak orientations of honeycomb core specimens. If the honeycomb is distorted, as shown in Figure 5, it may not be possible to distinguish a strong and weak orientation. The strength of each orientation should be well understood so that the panel span can be oriented to optimize the strength of the panel.

Adhesive and Honeycomb Facing Type

The facings applied to the aluminum honeycomb core behave similar to the flanges of a structural steel beam, while the honeycomb core behaves similar to the web. A stronger facing will provide greater resistance to tensile and compressive forces imposed on the composite. Common honeycomb facings include fiber-reinforced epoxy (typically woven carbon or woven glass coated in epoxy), aluminum sheet metal, and plywood.

The strength of the laminated honeycomb is primarily derived from the composite behavior of the facings and core. As such, the strength and durability of the adhesive between the core and facing is critical to panel performance.

MANUFACTURING VARIABLES

Degree of Honeycomb Expansion

The degree of honeycomb expansion has a direct impact on the strength of the honeycomb core. If the honeycomb is over-expanded, panels that span in the strong (ribbon) orientation will have reduced strength, and panels that span in the weak (transverse) orientation will have increased strength. Conversely, if the honeycomb is under-expanded, panels that span in the strong orientation will have increased strength, and panels that span in the weak orientation will have reduced strength.

Surface Preparation

The bond between the honeycomb and stone is reliant on proper surface cleaning. Variables in surface cleaning include type of cloth, type of cleaner, number of cleaning passes, frequency of cloth replacement, and surface protection measures between cleaning and adhesive application. Quality control during production should include procedures for reviewing dirt/contaminant pickup just prior to application of adhesive and additional cleaning if dirt/contaminant is observed.

Surface preparation may also include measures such as surface roughening. Grinding of the stone and/or honeycomb facing can increase surface roughness and enhance bond. Poor surface cleaning or inadequate roughening can result in significantly reduced bond strength between the stone and honeycomb.

Adhesive Application

Another manufacturing variable is the uniformity and coverage of adhesive on the stone prior to application of the honeycomb. A uniform thickness can be achieved by applying a consistent amount of adhesive per unit surface area and always spreading the adhesive with the same trowel type. Trowel types include smooth or notched and a variety of notch depths. Quality control during adhesive application should ensure that 100% adhesive coverage is achieved, that the honeycomb is applied within the adhesive working time, and that adhesive mix proportions and mixing procedures are verified regularly. Special attention to adhesive application at panel corners is important to ensure complete coverage.

Lamination Procedures

Variables in lamination procedures include duration and magnitude of applied pressure, ambient conditions during adhesive curing, and panel stacking parameters (e.g., maximum stacking height). Quality control should include methods to ensure that pressure is applied equally to all panels and that temperature and humidity are consistent (or carefully monitored) throughout pressing and curing of panels.

Wire-Cutting Methods

Variables in wire-cutting methods for cutting the stone at midthickness include...
the cutting wire type, cutting speed (rpm), and panel feed rate. Modifications to cutting methods may have an effect on production efficiency but are not likely to have a significant impact on composite panel strength and durability.

Due to the many material variables associated with the various layers of stone-faced honeycomb panels, preconstruction testing may be important for certain projects to establish strength and durability characteristics of the composite. In addition, periodic testing of representative specimens may be warranted during production to confirm uniformity and to monitor the many manufacturing variables associated with panel production.

TESTING PROCEDURES

In some cases, such as projects with limited use of the material, reliance upon manufacturer-provided test results may be sufficient. Where use of the material is more extensive or requires a greater degree of quality control, preconstruction and periodic testing during panel production is likely appropriate.

Preconstruction testing of stone-faced aluminum honeycomb typically includes flexural strength, tensile bond strength, and anchor strength testing of representative specimens cut from completed panels in order to establish the basic mechanical properties of the stone-faced composite. For stone-faced honeycomb to be used in exterior applications, consideration should also be given to testing the composite while exposed to anticipated temperature extremes and after simulated weathering exposure. Additional testing to provide information on the performance characteristics of the composite panels may include full-scale flexural strength, impact load testing, full-scale heating and cooling, and flame spread.

Periodic testing during production should include, at a minimum, tensile bond strength testing to confirm full adhesive coverage and uniform bond strength. Periodic testing may also include flexural strength and anchor strength testing. The frequency of periodic testing should be based on project surface area, and it may be appropriate to decrease the frequency of testing if the product consistently meets performance requirements. For instance, testing could be performed on ten specimens for the first 100 sq. ft. of material produced, then ten specimens for the next 1,000 sq. ft., then ten specimens from every 5,000 sq. ft. thereafter, assuming it continues to meet requirements.

As with any testing, the test results are only representative of the actual materials and production methods used to fabricate the composite. Additional testing should be performed each time there is a change in raw materials (adhesive, stone facing, honeycomb backing) or production methods. The basic tests for establishing and confirming the mechanical properties of the stone are discussed in greater detail below.

Flexural Strength

Flexural strength testing provides the basis for establishing maximum spans and deflection limits for the composite panels. Testing of the honeycomb with and without stone facing provides information on the contribution of the stone to the strength of the composite. For some stone-faced honeycomb products, it may be determined that the majority of the strength is derived from the honeycomb core, in which case flexural strength testing of multiple types of stone facings may not be warranted.

Flexural strength testing of stone-faced honeycomb panels was performed by the authors in general accordance with ASTM C393, Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure. This test method is used to determine the flexural strength of test specimens cut from the composite panels through quarter-span loading of simple beam specimens. During testing, composite specimens were tested with the stone face in tension, where it contributes least to the composite’s strength. Deflection was measured during the flexural strength testing to evaluate the stiffness and ductility of the composite.

Offsets in the load-deflection graphs also clearly showed the load at which the stone facing initially cracked relative to honeycomb failure. This can be an important consideration to panel performance, as cracking of the stone facing at loads that are within the anticipated service load range may affect panel aesthetics and weathering durability. This was evaluated for one of the products tested, and cracking of the stone facing did not occur within the anticipated service load range for this product. Flexural strength testing of a stone-faced honeycomb specimen is shown in Figure 6.

Flexural strength testing was performed by the authors in both the wet (submerged in water for 48 hours) and dry (dried in an oven at 140ºF for 48 hours) condition and in the strong (ribbon) and weak (transverse) honeycomb orientation. Wet and dry test results were compared to evaluate the effect of moisture on the composite. Testing in
Tensile Bond Strength

Tensile bond testing provides information on the adhesive strength between laminations of the composite panels. Based on past experience of the authors, the bond between the stone and honeycomb core can vary greatly between stone types, so tensile bond testing is recommended for each type of stone facing to be used.

Tensile bond testing of stone-faced honeycomb panels was performed by the authors in general accordance with ASTM C297, Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions. The tensile bond test is conducted by bonding a metal plate to the front and back face of a specimen and applying a tension load to a rod that is attached to the center of each plate until failure to determine the ultimate tensile bond strength of the weakest layer of the composite. This testing should include specimens removed from the edges of panels so that areas that are least likely to have full adhesive coverage are tested. Tensile bond strength testing of a stone-faced honeycomb specimen is shown in Figure 7.

Anchor Strength

Anchor strength testing provides information on the methods of panel attachment. An appropriate test approach is to test in general accordance with ASTM C1354, Standard Test Method for Strength of Individual Stone Anchorages in Dimension Stone. For this test, individual small-scale anchor specimens are subjected to a test load until failure to determine anchor strength. Anchor strength testing is important for evaluating a proposed panel attachment system; however, it is not the subject of this paper.

Temperature Extremes

Strength testing at hot (170°F) and cold (10°F) temperatures is performed to evaluate the strength characteristics and adhesive bond of the panels at the high and low ends of the typical outdoor service temperature range. Specimens tested at hot temperatures are preheated in an oven for 24 hours and transferred to the test machine in an insulated box, where temperatures are maintained through the use of electrical strip heaters. Specimens tested at cold temperatures are prechilled in a freezer for 24 hours and transferred to the test machine in an insulated box, where temperatures are maintained using dry ice. Figure 8 and Figure 9 are views of the hot and cold tests, respectively.
**Simulated Weathering**

Strength testing is performed after simulated weathering exposure to evaluate the effect of temperature cycling on material durability. Simulated weathering is typically performed in accordance with the “accelerated weathering” conditioning procedures summarized below.

Accelerated weathering conditioning has been used for more than 25 years to evaluate stone durability and employs procedures similar to those outlined in ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. The procedure consists of exposing the test specimens to 100 or 300 cycles between -10°F and +170°F, while the specimens are partially submerged (1/8 to 1/4 in.) in, typically, a 4pH sulfuric acid solution, which simulates exposure to acid rain. For stone-faced honeycomb, the stone facing is oriented downward so that the bond between the stone and honeycomb is submerged. These accelerated weathering test conditions are intentionally made to be harsh to demonstrate the suitability of a stone for exposure to weathering in a harsh environment such as that experienced in the northern Midwest of the United States.

In order to evaluate strength loss associated with accelerated weathering exposure, the flexural strength and/or tensile bond strength of specimens tested after exposure to accelerated weathering is compared to the strength of specimens not exposed. A visual examination of the specimens is also performed before and after accelerated weathering exposure, and deterioration and staining are photographed and recorded. As a way to evaluate the rate of deterioration, testing can be performed at periodic intervals throughout the simulated weathering exposure.

**TESTING PERFORMED**

Testing was performed on three different stone-faced aluminum honeycomb products to evaluate mechanical properties and durability. The following is a brief description of each product and a summary of testing performed on each product.

**“Product A”** consisted of 3/16- to ¼-in.-thick stone adhered to ¼-in.-thick aluminum honeycomb faced with a fiber-reinforced epoxy skin. The honeycomb cells were approximately 0.30 in. wide (between flat edges) by 0.35 in. long (between vertices).

Testing included flexural strength and tensile bond strength of specimens cut from the strong (ribbon) and weak (transverse) orientations of full-sized panels. Specimens were tested in the wet and dry conditions, at hot and cold temperatures, and without exposure and after exposure to 25, 50, 90, and 100 cycles of accelerated weathering conditioning. Testing was performed on specimens removed from newly fabricated panels faced with granite, limestone, and travertine and on specimens removed from travertine-faced panels that had been in service for more than 15 years in the Chicago environment. Flexural strength testing was also performed on laminated core material without a stone facing. Anchor strength testing was performed on two anchorage types.

**“Product B”** consisted of 3/16-in.-thick stone adhered to ¼-in.-thick aluminum honeycomb with aluminum facing. The honeycomb cells were approximately 0.30 in. wide (between flat edges) by 0.35 in. long (between vertices).

Testing included flexural strength and tensile bond strength of specimens cut from the strong and weak orientations of a newly fabricated, full-sized, marble-faced panel. Specimens were tested in the wet and dry conditions, without exposure, and after exposure to 60 and 100 cycles of accelerated weathering conditioning. Due to concerns regarding compatibility between the expansion of the stone facing and the aluminum-faced honeycomb at high temperatures, additional testing was performed to evaluate the effect of temperature cycling on a full-sized panel and included bow measurement and tensile bond testing after 130 cycles from 65°F to 140°F. No measurable bowing occurred during this temperature cycling, and there was no apparent effect on the tensile bond strength of specimens removed from the panel after temperature cycling. Testing of this product did not include any unfaced specimens or specimens at hot and cold temperatures.

**“Product C”** consisted of ¼-in.-thick stone adhered to ¼-in.-thick aluminum honeycomb faced with a glass-fiber reinforced epoxy skin. The honeycomb cells were approximately 0.35 in. wide (between flat edges) by 0.50 in. long (between vertices).

Testing included flexural strength and tensile bond strength of specimens cut from the strong and weak orientations of newly fabricated full-sized panels. Specimens were tested in the wet and dry conditions, at hot and cold temperatures, and without exposure and after exposure to 25, 50, 90, and 100 cycles of accelerated weathering conditioning. Testing was performed on specimens with marble, limestone, and granite facings, and flexural strength testing was also performed on laminated core material without a stone facing.

**TEST RESULTS**

The following provides a summary of flexural strength and tensile bond strength test results for Products A, B, and C. The effect of stone facing (unfaced vs. faced with various stone types), honeycomb orientation (ribbon vs. transverse), conditioning (wet vs. dry), temperature (ambient vs. hot and cold), and accelerated weathering (initial vs. cycled) on the average specimen strength is provided. Comparisons between products are also provided where applicable.

**FLEXURAL STRENGTH**

**Unfaced vs. Stone-Faced**

For Product A, the average strength of limestone-faced, new travertine-faced, old travertine-faced, and granite-faced specimens was approximately 5% greater, 2% less, 10% less, and 22% greater, respectively than the honeycomb core material with no stone facing. With the exception of the granite-faced panels, there was not a significant difference between the flexural strengths of stone-faced and core specimens for this product, indicating that its flexural strength is dominated by the manufactured honeycomb material.

The average flexural strength of Product A core specimens with no stone facing was approximately 6 times greater than Product C core specimens. For Product C, the average strength of limestone-faced, marble-faced, and granite-faced specimens was approximately 59%, 83%, and 77% greater respectively than the honeycomb core material with no stone facing. Because Product C core material has significantly lower average tested strength than Product A material, the relative contribution of the stone facing to the panel strength is fairly significant. No unfaced specimens were tested for Product B.

Based on the testing performed, the stone facing may or may not have a significant effect on the flexural strength of a stone-faced composite, depending on the...
manufacturer. The lower the strength of the honeycomb core material, the greater the influence of the stone facing on the composite strength.

**Variability**

For Products A and B, the flexural strength variability of new (unweathered) test groups with no facing and faced with limestone, travertine, and marble was less than 10%, with most under 5%. The maximum variability of granite-faced specimens was approximately 12%. While the granite appears to be contributing to higher average strengths (as discussed above), the associated higher degree of strength variability mitigates the significance of this contribution.

The flexural strength variability tested for Product A and B material is substantially less than that commonly found in panels made only of stone, likely because the flexural strength of these materials is dominated by the strength of the honeycomb. The significance of this is that design “safety factors” (when “allowable stress” principles are used) or “strength reduction factors” (when “load and resistance factor” principles are used) are, or at least should be, proportional to variability. In other words, as variability decreases, safety factors and strength reduction factors may be decreased. Significant additional testing beyond the limited testing performed would be required to establish appropriate safety factors for each product.

Product C material has much greater variability than the Product A and B material, and more comparable variability to the associated stone facings. This is likely because the stone provides a significant contribution to the panel strength. Product C core material also has slightly greater variability than the Product A core material, which also likely contributes to the greater variability of Product C.

The variability in test results for the stone-faced honeycomb can be very low compared to traditional stone cladding, depending on the contribution of the stone facing to the strength of the composite. A high-strength honeycomb core with low variability will likely result in a stone-faced composite with low variability.

**Orientation**

Product A core specimens tested in the weak honeycomb orientation had approximately 7% lower average strength than specimens in the strong orientation. The strength of Product A stone-faced specimens did not necessarily correlate with the orientation of the honeycomb core. Some stone facings resulted in a higher average specimen strength in the strong honeycomb orientation, and some resulted in higher strength in the weak honeycomb orientation. This is likely due to the orientation of the stone relative to the orientation of the honeycomb (e.g., strong limestone facing orientation in combination with weak honeycomb orientation).

Marble-faced Product B specimens tested in the weak honeycomb orientation had approximately 30% lower average strength than specimens tested in the strong orientation. Because no testing was performed on Product B core specimens, it is unknown whether this difference is primarily due to the orientation of the honeycomb core, or is also affected by the orientation of the marble facing. Regardless, the orientation of panels fabricated with Product B is more critical than panels fabricated with Product A.

For Product C, core and stone-faced specimens tested in the weak honeycomb orientation had approximately 20% to 25% lower average tested strength than specimens with honeycomb in the strong orientation. Although the stone facing provides a significant contribution to the panel strength of this product, the orientation of the honeycomb had a similar effect on the strength of core specimens and stone-faced specimens. This indicates that the strong and weak stone orientation likely aligns with the orientation of the honeycomb core.

Based on the testing performed, the honeycomb core materials tested had a definite strong and weak orientation. Depending on the orientation of the stone facing relative to the orientation of the honeycomb, stone-faced specimens may not exhibit a significant difference in strength between strong and weak honeycomb orientations.

**Conditioning**

The average flexural strength of specimens tested in the wet condition is approximately equivalent to specimens tested in the dry condition for Products A and B, indicating that moisture had little effect on flexural strength of these products. For Product A, this is not surprising, given that the honeycomb dominates the strength of the composite and is likely unaffected by short-term moisture exposure. For Product B, this suggests that either the stone facing is not significantly affected by moisture, or the honeycomb core dominates the strength of the composite.

For Product C, the flexural strength of specimens tested in the wet condition was approximately 29%, 13%, and 3% lower than the dry condition for the specimens faced with limestone, marble, and granite, respectively. This indicates that moisture had a significant effect on the strength of material faced with limestone, minor effect on material faced with marble, and little to no effect on material faced with granite. Because stone provides a significant contribution to the strength of this product, the reduced strength likely corresponds to the effect of moisture on the stone. Only dry testing was performed on core material with no stone facing, so no comparisons could be made for the core material.

Based on the minimal difference in wet and dry conditioned specimens for Products A and B (where honeycomb dominated the strength of the composite), short-term moisture exposure did not have a significant effect on the strength of the honeycomb core materials. Moisture often does have an effect on stone strength, so the strength of a composite with significant contribution from the stone facing can be affected by moisture.

**Temperature Effects**

The flexural strength of Product A and C specimens tested at hot temperature was approximately 31% and 53% lower, on average, than panels tested at ambient temperature. Flexural strength of Product A and C specimens increased by approximately 7% and 14% on average at cold temperatures. No specimens were tested in the hot and cold conditions for Product B.

While the granite facing contributed to greater specimen strength of Product A at ambient temperature, and the marble and granite facings provided a greater contribution than the limestone facing for the Product C material at ambient temperature, the magnitude of flexural strength at the higher temperature is similar, regardless of the facing material. This suggests that the flexural strength contributions from stone facing are lost at the elevated temperatures. This loss of the contribution of the stone facing is consistent with a softening of the adhesive between the stone and honeycomb.
The test data indicate that raising the temperature decreases panel strength, and that the effects are significant. Honeycomb panel strength loss is most likely due to softening of the facing material and/or its bond to the aluminum honeycomb core.

**Accelerated Weathering**

For Product A, results show that unfaced test specimens experienced approximately 12% strength reduction from 100 cycles of accelerated weathering exposure. Limestone-, granite-, and marble-faced specimens for Products A and B had an apparent strength loss of 5% to 10% from 100 cycles of accelerated weathering exposure, while travertine-faced specimens had a greater strength reduction of approximately 13% to 18%. The greater strength reduction in travertine-faced specimens is likely due to direct exposure of the honeycomb core to freezing and thawing water from voids in the travertine facing that do not provide a barrier against water. The flexural strength reduction of travertine specimens after each interval of accelerated weathering exposure also varied considerably more than specimens faced with limestone or granite. The greater variation in strength reduction at periodic testing intervals for travertine-faced specimens is likely due to the significant variation in the size and amount of void area in the stone, resulting in significant variations in bond contact area from specimen to specimen.

The fiber-reinforced epoxy facing on nearly every honeycomb core specimen for Product C had partially or nearly fully delaminated without load application after exposure to 100 cycles of accelerated weathering, as shown in Figure 10. The average core specimen strength after accelerated weathering exposure was approximately 72% less than companion specimens not exposed. This is significantly greater strength loss than the honeycomb core of Product A and is likely due to the delamination of the epoxy facing from the core.

The stone facing on several marble-faced Product C specimens fully delaminated from the honeycomb core during accelerated weathering exposure without application of load, as shown in Figure 11. The core for each of these specimens was tested to failure and included in the average test results. While none of the limestone-faced or granite-faced specimens delaminated during accelerated weathering exposure, the limestone facing exhibited slight deterioration after 25 cycles and more heavy deterioration after 50 cycles of accelerated weathering exposure, as shown in Figure 12. Product C specimens faced with limestone, marble, and granite had approximately 57%, 66%, and 28% lower average tested strength, respectively, after accelerated weathering exposure. Each group exhibited less strength loss than the honeycomb core with no

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**Figure 10** – Full delamination of facing on honeycomb core after 100 cycles of accelerated weathering and prior to applied load.

**Figure 11** – Full delamination of marble facing from honeycomb core during accelerated weathering exposure prior to application of load.
stone facing, likely because the facing provides protection to the backup. Because the stone provides a significant contribution to the strength of Product C specimens, the limestone-faced specimens (which exhibited deterioration) and marble-faced specimens (several of which delaminated from the honeycomb core) exhibited greater strength loss than the granite-faced specimens (which did not exhibit deterioration or delamination).

The test data related to exposure clearly indicate that there is an associated loss of flexural strength over time due to exterior exposure in a Midwestern climate for at least Product A. The magnitude of this effect is very difficult to estimate based on the laboratory testing performed, primarily because there is only one small set of data representing actual aged panels (Product A, travertine-faced panels). While the data from the accelerated weathering specimens are useful in a generally qualitative sense, the number of cycles cannot be translated into an equivalent number of years of real-time exposure for the stone-faced composite, based on the limited testing performed.

Structural design of stone-faced composite panels to be used in exterior applications should be based on consideration of the durability of the facing on the honeycomb core and its bond to the aluminum core. For stone-faced composites that rely to some degree on the strength of the stone, additional loss of panel strength caused by exposure can be due to degradation of the stone or the bond between the stone facing and honeycomb facing. Structural design of panels that rely in part on stone strength should also consider the durability of the stone facing and its bond to the honeycomb core.

Panel structural design should take into consideration the reductions in panel strength due to the exposure factors described above, as appropriate, as well as the variability in the strength of the panels.

**TENSILE BOND**

**Product A**

Tensile bond strength testing of Product A was performed at ambient laboratory conditions on specimens not exposed and after exposure to 100 cycles of accelerated weathering. The tensile bond strength of unweathered Product A specimens faced with limestone, new travertine, and old travertine were similar, while specimens faced with granite had approximately 57% greater average strength than the other three facings. Failure in all of the specimens faced with limestone and granite was due to internal fracturing of the stone, while half of the travertine specimens failed within the stone and half at its bond to the honeycomb. Since the bond strength of Product A often exceeded stone strength, the test results only provided a low estimate of the bond strength. The bond strength of the travertine specimens varied more than the other facings, likely because there is significant variation in the void area in the travertine, resulting in significant variations in bond contact area. The greater failure loads of granite-faced specimens only indicate that the granite has a greater internal fracture strength than the limestone.

The average tensile bond strength of the Product A limestone-faced, travertine-faced (new), and granite-faced specimens after 100 cycles of accelerated weathering exposure was approximately 7%, 23%, and 22% lower respectively than companion specimens that were not exposed. The average tensile bond strength of old travertine-faced specimens after exposure was approximately 4% lower than companion specimens. While this indicates that the bond strength in new panels is reduced by accelerated weathering exposure, the test group with the lowest average tensile bond strength even after exposure had a strength of approximately 150 psi, which is considered to be more than adequate for virtually all potential applications.

**Product B**

Tensile bond strength testing of Product B (marble-faced specimens) was performed in the wet and dry conditions on specimens not exposed, and in the dry condition on specimens after exposure to 100 cycles of accelerated weathering. All of the wet specimens failed due to internal fracturing of the stone, while all of the unweathered dry specimens failed at the bond between the marble and honeycomb. Dry specimens had greater variability and approximately 18% lower average strength than wet specimens and similar average strength to Product A specimens that were not exposed. The variability in dry test results is likely in
part due to variability in preparation of the aluminum substrate prior to application of the adhesive. Figure 13 shows the evenly roughened aluminum substrate at the failure plane for a dry test specimen that failed at approximately 180 psi (approximately average), and Figure 14 shows the unevenly roughened aluminum substrate for a dry specimen that had been removed from a panel corner and failed at approximately 80 psi.

The reduction in strength of Product B specimens after exposure to accelerated weathering was approximately 24%. While the reduction in strength was likely in part due to exposure, there were also voids present in several exposed specimens that were not present in the initial test specimens, as typically shown in Figure 15. The reduced bond area due to this manufacturing variability (uneven application of adhesive at areas where certain test specimens were removed from the panel) likely contributed to the lower tested strength of exposed specimens.

**Product C**

Tensile bond strength testing of Product C was performed at ambient laboratory conditions on specimens not exposed and after exposure to 100 cycles of accelerated weathering. The tensile bond strengths of Product C specimens faced with limestone, marble, and granite were similar but had approximately 60% lower average bond strength than Product A and B specimens that were not exposed. All of the limestone and granite-faced specimens failed at the bond between the honeycomb facing and honeycomb core, and all but one of the marble-faced specimens failed at the bond between the stone and the honeycomb.

Based on the failure modes, it appears that the adhesive was less effective in adhering to the marble, and that additional surface roughening of the marble would be appropriate prior to adhesion. While the lower tested strength and adhesive failure between the facing and the core indicate a honeycomb material with reduced physical properties, the unweathered test group with the lowest average tensile bond strength was approximately 63 psi, which is still likely to be more than adequate for virtually all potential applications.

The average tensile bond strength of the Product C marble-faced, limestone-faced, and granite-faced specimens after 100 cycles of accelerated weathering exposure was approximately 91%, 53%, and 36% lower, respectively, than companion specimens that were not exposed. The stone facing on nearly half of the marble-faced specimens had delaminated due to exposure, and the remainder failed at the marble-to-honeycomb interface during testing, further indicating that marble surface preparation should be reconsidered.
The limestone facing exhibited deterioration after exposure, and all but one test specimen failed within the limestone. The failure mode for granite specimens remained the honeycomb facing-to-core bond. The reduced strength of these specimens indicates that the adhesive strength between the core and facing is reduced by accelerated weathering exposure.

In general, the tensile bond testing of the three products showed that the bond strength of panels from different manufacturers varies significantly. Bond strength can be affected by material variables such as strength of adhesive and manufacturing variables such as surface preparation and adhesive coverage. Accelerated weathering testing showed that specimens lose some strength due to exposure, although the degree of strength loss also varies among manufacturers. For Products A and B, it should be noted that in no case, even after weathering exposure, was the tensile bond strength significantly low that it resulted in concern that insufficient bond was present.

**SUMMARY**

The test results for stone-faced honeycomb from three different manufacturers clearly show that physical properties and durability can vary significantly among manufacturers. This is due to differences in materials and manufacturing processes. For Product B, the flexural strength reduction due to accelerated weathering and the tensile bond strengths did not meet the manufacturer’s reported values.

The test results also show that certain manufacturers’ stone-faced honeycomb panels have physical properties and durability that can vary significantly for a specific product. The specifier or purchaser of these types of panels should be aware of the variables that can affect the mechanical properties, durability, uniformity, and, ultimately, the cost of stone-faced honeycomb, so that they can anticipate an appropriate level of preconstruction testing and monitoring/testing during production. Material variables include stone type, adhesive type, honeycomb facing type, and aluminum honeycomb gauge, cell size, thickness, and orientation. Manufacturing variables include degree of honeycomb core expansion, surface preparation prior to adhering stone to the honeycomb, adhesive application, lamination procedures, and cutting methods.

Based on the results of the testing performed on specimens selected from stone-faced honeycomb panels manufactured by three different companies, several recommendations are provided for testing and evaluating these types of panels for suitability for exterior use. These include recommendations for testing and evaluation during the design process prior to construction, as well as during construction. These recommendations are most appropriate for projects where significant quantities of stone-faced aluminum honeycomb panels are to be used and where material performance and durability are important.

**Recommended Testing and Evaluation Prior to Construction**

1) Review physical and mechanical test data for the stone facing being considered. If available, review projects with the same stone type in the same environment as proposed for use to evaluate the stone’s durability.

2) Review available test data for the composite product being considered. Confirm that the adhesives and materials used for the reviewed panels and for manufacturer-provided test results are the same as those to be used for the project for which the panel product is being considered.

3) Perform flexural strength testing:
   a) Of composite specimens with each stone facing as well as core material to determine the contribution of the core to the strength of the composite.
   b) In the wet condition to provide the lower bond strength for the composite.
   c) In both honeycomb orientations to provide information on how to optimize panel spans.
   d) At temperature extremes to evaluate their effect on the strength of the composite (for material to be used in the exterior environment).

4) After accelerated weathering exposure to evaluate its durability (for material to be used in the exterior environment).

5) Perform anchor strength testing of each anchor type.

6) Document stone-faced honeycomb material and manufacturing variables to confirm consistency during production.

7) Panel structural design should take into consideration the reductions in panel strength due to the exposure factors, as appropriate, as well as the variability in the strength of the panels.

**Recommended Testing and Evaluation During Production**

1) Review and document stone-faced honeycomb periodically to confirm that the honeycomb material and manufacturing procedures remain consistent.

2) Perform periodic tensile bond testing of representative composite specimens to confirm uniformity during production.

3) Consider performing periodic flexural strength and anchor strength testing, particularly if tensile bond strength testing indicates a lack of uniformity.

Some or all of the above recommended testing and review may be performed as part of the manufacturer’s own internal quality control procedures, and a review of their test reports may provide sufficient information regarding the listed material properties and product variability.