1. Do what Joe says. Or else.
2. Turn your cell phone ringers off.
3. Hold your questions until the end or refer to No. 1.
4. Watch for the “Quirkiness Alerts.”
5. Sit back and relax.

SUGGESTIONS

ROCK VS. STONE

Rock is…

…a naturally occurring aggregate formation of minerals and chemicals.

Stone is…

…rock that is manipulated for a specific use or purpose.

GEOLOGY 101

The Quirkiness of Stone…

…why it is so hard to get it right.

Matthew Farmer, Principal
Wiss, Janney, Elstner Associates, Inc.

Eighteenth Annual Building Science Corporation's Symposium 2014
ROCK VS. STONE

Rock is...

A. ...a popular music genre.
B. ...an action movie actor and reality TV show host.
C. ...a naturally occurring aggregate formation of minerals and chemicals.

Stone is...

...rock that is manipulated for a specific use or purpose.

ROCK CLASSIFICATION - IGNEOUS

• Originated from magma (molten rock)
• Examples: granite, diorite, gabbro, all very common cladding

ROCK CLASSIFICATION - SEDIMENTARY

• Deposition, compaction, and cementation
  • Weathered/eroded rocks and minerals
  • Shells and other fossil-forming organisms
  • Precipitated minerals
  • Often a combination of all of the above
• Examples: Sandstone, Shale, Limestone, Dolomite, Travertine

ROCK CLASSIFICATION - METAMORPHIC

• Original rock altered by exposure to temperature, pressure.
  • Realignment of minerals
  • Recrystallization
  • Chemical alteration
• Metamorphosed igneous: gneiss or schist
• Metamorphosed sedimentary: slate, quartzite, and marble
**STONE BUILDING SYSTEM DEFINITIONS**

- **Bearing Wall**
  - Full thickness of the wall.
  - Load Bearing - Structural
- **Thick Cladding**
  - Greater than 2 inches thick.
  - Does not support building loads, but can be stacked.
- **Thin Cladding**
  - 2 inches or thinner.
  - Does not support building loads.
- **Paving**
  - Thickness varies with application/system.
  - Load bearing – always.

**STONE INDUSTRY REFERENCES**

- Indiana Limestone Institute (ILI) Handbook
  - [http://www.iliai.com](http://www.iliai.com)
- Marble Institute of America (MIA) Design Manual
  - [http://www.marble-institute.com](http://www.marble-institute.com)
- National Building Granite Quarries Association (NBGQA) Specification
  - [http://www.nbgqa.com](http://www.nbgqa.com)
- Tile Council of North America (TCNA) Handbook for Ceramic Tile Installations
  - [http://www.tileusa.com](http://www.tileusa.com)
- European Standards

**STONE SELECTION CRITERIA**

[Diagram showing selection criteria: Appearance, Performance, Cost]
STONE SELECTION CRITERIA - ARCHITECT

- Appearance
- Performance
- Cost

STONE SELECTION CRITERIA - ENGINEER

- Appearance
- Performance
- Cost

STONE SELECTION CONSIDERATIONS

- Stone Availability/Orientation
- Stone Fabrication
- Bedding Planes, Veins, and Rift
- Material/Structural Properties
- Primary Structure
- Loading Conditions (at grade, at elevation)
- Back-up Material/System
- Serviceability

Stone Availability/Orientation

- Limestone (typically >2 inches for cladding)
- Sandstone (typically >2 inches for cladding)
- Granite
- Marble
- Travertine
- Slate
Stone Fabrication

- Stone Finish
  - Material Properties (Strength, Absorption)
  - Slip Resistance
  - Staining
  - Dirt Retention/Cleaning

- Tolerances
  - Joint Widths

Material/Structural Properties

- Engineering Properties – Actual (Near-term)
  - Flexural Strength (ASTM C880)
  - Compressive Strength (ASTM C170)
  - Modulus of Rupture (ASTM C99)
  - Specific Gravity (ASTM C97)
  - Absorption (ASTM C97)

- Engineering Properties – Predictive (Long-term)
  - Accelerated Weathering Test
  - Petrographic Analysis (ASTM C1721)
  - Prior Use and Experience

Test both wet and dry...

Material/Structural Properties

Stone Flexural Strength Comparison - ASTM C880/C99

<table>
<thead>
<tr>
<th></th>
<th>C880</th>
<th>C99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>1200</td>
<td>psi</td>
</tr>
<tr>
<td>Marble</td>
<td>1000</td>
<td>psi</td>
</tr>
<tr>
<td>Limestone Class III (High Density)</td>
<td>C880</td>
<td>1000 psi</td>
</tr>
<tr>
<td>Limestone Class II (Med. Density)</td>
<td>C99</td>
<td>500 psi</td>
</tr>
<tr>
<td>Limestone Class I (Low Density)</td>
<td>C99</td>
<td>400 psi</td>
</tr>
<tr>
<td>Sandstone Class III (Quartzite)</td>
<td>C99</td>
<td>2000 psi</td>
</tr>
<tr>
<td>Sandstone Class II (Quartzitic)</td>
<td>C99</td>
<td>1000 psi</td>
</tr>
<tr>
<td>Sandstone Class I</td>
<td>C99</td>
<td>350 psi</td>
</tr>
<tr>
<td>Travertine Class I (Exterior)</td>
<td>C880</td>
<td>1000 psi</td>
</tr>
<tr>
<td>Travertine Class II (Interior)</td>
<td>C880</td>
<td>700 psi</td>
</tr>
</tbody>
</table>

Material/Structural Properties

Variability

- Between Different Stone Classifications
**Material/Structural Properties**

- **Variability**
  - **Within a Stone Classification**

- **Material/Structural Properties**
  - **Strength Loss due to Weathering**

- **Bedding Planes, Veins, and Rifts**
  - **Material Properties**
    - Flexural Strength
    - Absorption
  - **Weathering/Erosion**
  - **Discoloration**

- **Material/Structural Properties**
  - **Variability**
    - **Between Stones of the Same Type!**

*Eighteenth Annual Building Science Symposium*

*August 4-6, 2014*

*The Quirkiness of Stone*
Material/Structural Properties
Strength Loss due to Weathering

Real Time Weathering

Material/Structural Properties
Strength Loss due to Weathering

Accelerated Weathering

Material/Structural Properties
Durability
- Material Characteristics (Voids, Veining)
- Density
- Absorption
- Compressive Strength
- Abrasion Resistance
### Physical Properties Relevant to Stone Durability

**Testing Standard** | **Physical Property** | **Granite** | **Marble*** | **Travertine**** | **High Density Limestone** | **Medium Density Limestone** | **Low Density Limestone**  

ASTM C97 | Absorption by Weight, Max. [%] | 0.40 | 0.20 | 2.50 | 3.00 | 7.50 | 12.00  

ASTM C97 | Density, Min. (lb/ft³) | 160 | 162 | 144 | 160 | 135 | 110  

ASTM C170 | Compressive Strength, Min. (lb/in²) | 5,000 | 7,500 | 8,000 | 4,000 | 1,800  

ASTM C241 | Abrasion Resistance, Min. (Ha) | 25 | 10 | 10 | 10 | 10 | 10

* Per ASTM C615, C503, C568, and C1527

** For classification I, calcite

*** For exterior applications

---

### Material/Structural Properties

#### Durability

**Physical Properties Relevant to Stone Durability**

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** For classification I, calcite

*** For exterior applications
Material/Structural Properties

Durability

• Attractive characteristics are not always good.
• Concessions regarding durability may need to be accepted by the project team for certain stone types in certain applications.
• Whatever you think the in-service conditions will be, they will be worse.

Material/Structural Properties

Sealant Stain Resistance

• Changes in Formulation
• Primer Influence
• Cleaning
• An old problem…
Material/Structural Properties

Salt Crystallization Resistance

Primary Structure

- The primary structure can influence cladding performance.
  - Unintended Load Transfer
  - Excessive Structural Displacement
  - Reflective Cracking

Material/Structural Properties

Color Changes

- Weatherization Chamber Testing (Accelerated Aging)

Loading Conditions

Cladding

- Vertical
  - Gravity
  - Stacking
- Lateral
  - Wind
  - Seismic
- Impact (at grade)
- Interaction with other Facade Materials
  - Awnings, Signage
**Loading Conditions**

**Paving**
- Dynamic Loads
  - Pedestrian
  - Vehicular
- Static Loads
  - Planters
  - Bollards
  - Threat Protection Barriers
- Impact Loads

**Back-up Material/System**

**Cladding**
- Material Type
- Attachment to primary structure.
- Integrity/consistency of material.
- Stiffness Compatibility
- Ability to manage water entry (flashing).
- Construction tolerances in back-up.

**Back-up Material/System**

**Paving**
- Material Type
- Attachment to primary structure.
- Integrity/consistency of material.
- Stiffness
- Ability to manage water entry (waterproofing system).
- Construction tolerances in back-up.

**Serviceability/Maintenance**

**Cladding**
- Weather Resistance
- Repair/Replacement/Maintenance (attic stock)
- Resistance to Soiling/Ease of Cleaning
  - Run-down Staining
Serviceability/Maintenance
Paving
- Repair/Replacement/ Maintenance (Attic Stock)
- Resistance to Soiling/Ease of Cleaning
- Weather Resistance
- Drainage (Lack of Ponding)
- Impact Resistance
- Chemical Resistance
- Slip Resistance

STONE DESIGN

STONE DESIGN PROCESS OVERVIEW

- Pre-design
  - Review Available Test Data
  - Preliminary Stone Selection
  - Preliminary System Selection
- Design
  - Assumed Physical Properties based on Available Test Data
- Production Testing
  - Confirm stone meets project requirements... PRIOR TO DELIVERY!
- Confirm Design
  - Actual Material and Structural Properties

Safety Factors

- Considerations that safety factors take into account:
  - Variability of Load
  - Workmanship
  - Stress Concentrations
  - Construction Tolerances
  - Fabrication Tolerances
  - Variability of the Stone
  - Strength Loss Due to Weathering
Safety Factors

- **Most Commonly Accepted Approach:**
  - Recommendations of the Various Stone Trade Groups
  - Empirical
  - Allowable Stress Design

- **Other methods are used to develop factors of safety for dimension stone design:**
  - Variability of Strength
  - Characteristic Strength (3.0 X 95% strength)
  - Load Application Accuracy
  - Load and Resistance Factors

---

**Safety Factors - Values**

**Recommended Industry Standard Safety Factors for Design of Stone Cladding**

<table>
<thead>
<tr>
<th>Organization</th>
<th>Stone Type</th>
<th>Safety Factor (Bending)</th>
<th>Safety Factor (Connection Zones, Concentrated Loads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Building Granite Quarriers Association</td>
<td>Granite</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(≤50mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marble Institute of America</td>
<td>Granite</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(≤50mm)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Marble</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Slate</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Indiana Limestone Institute</td>
<td>Limestone</td>
<td>8 (6)*</td>
<td>8</td>
</tr>
</tbody>
</table>

*Transient Loads (i.e. wind, seismic)
STONE CLADDING SYSTEM DEFINITION

- Typically individually supported.
- Does not support building loads.
- Flexural loading controls.
- Joints may be filled with sealant or mortar.

STONE CLADDING DESIGN OBJECTIVES

- Transfer applied loads to primary structure.
- Weather Resistant
- Durable
- Attractive
- Innovative

STONE CLADDING SUPPORT SYSTEMS

- Individual Anchors
- Proprietary Systems/Individually Anchored
- Strongback Truss
- Stone-faced Precast Concrete

STONE CLADDING DESIGN RESPONSIBILITIES

- Architect
  - Monitor/participate in stone cladding design process.
  - Provide a basis of design concept.
  - Anticipate cladding interaction with other building systems.
  - Identify known critical interface conditions.

- Engineer
  - Back check applied cladding loads against design assumptions.

- Contractor
  - Coordinate cladding installation requirements with other trades.

- Stone Subcontractor
  - Provide basis of design concept or fully coordinated alternate system.

- Specialty Engineer
  - Retained by Stone Subcontractor
  - Provide final cladding design based on actual physical properties.
**BASICS OF STONE CLADDING DESIGN**

- Safety Factors
- Stone Capacity
- Common Anchor Types
- Anchor/Stone Interaction
- Fabrication Tolerances

Perform separate analyses of stone and anchors, but evaluate interactivity

**COMMON STONE ANCHOR TYPES**

- Edge Supported
- Back Surface-mounted

**Edge-supported Anchors**

Continuous Kerf Anchors
- **SEALANT** installed between anchor and stone.

**Edge-supported Anchors**

Discontinuous Kerf Anchors
- **SEALANT** installed between anchor and stone.
Edge-supported Anchors
Dowels
• Dowels are set in slightly oversized (in diameter) holes filled with SEALANT.

Back Surface-mounted Anchors
Liner Blocks

Back Surface-mounted Anchors
H and J Clips

Back Surface-mounted Anchors
Type 31 Anchor
Back Surface-mounted Anchors

Hair Pin Anchor

ANCHOR/STONE INTERACTION

- Hand Calculations
- Finite Element Modeling
- Pre-construction Testing
  - Small Scale Load Testing of Individual Elements
  - Full Scale Assembly Testing
  - ASTM C 1354

FABRICATION TOLERANCES

- Different stone types have different fabrication tolerances.
- Effect on 3 cm panel (NBGQA):
  - Panel: up to 20% reduction
  - Kerf: up to 50% reduction

CONDITIONS TO AVOID

- Excessive stress concentrations (sharp kerf cuts, complex panel shapes).
- Corrosive materials in contact with stone.
- Difficult installations (i.e., blind connections).
- Excessive gravity loads (i.e. stacking).
CONDITIONS TO AVOID (cont’d)

• Complex load paths.
• Long spans.
• Overhead conditions.
• Un-accommodated volume changes.
• Anchor/back-up systems with differing stiffness.

UNIQUE DETAILING CONDITIONS

• Interface Conditions
• Building Expansion Joints
• Excessive Shimming/Wide Cavities
• Non-horizontal/Non-vertical Joints
• Overhead Conditions

Interface Conditions

• Includes:
  • Ground
  • Windows
  • Doors
  • Roofs
• Critical for air and water management, plus differential movements.

Expansion Joints

• Accommodate movements due to:
  • Expansion/Contraction of Stone
  • Structural Loading
  • Movements of the Back-up
• Assess Overall Structural Design
Excessive Shimming/Wide Cavities

• Should compensate for tolerances, not mistakes.
• Use hard, durable materials.
• Permanent vs. Temporary
• Size
• Stacking/Stability

Non-horizontal/non-vertical Joints

• Asymmetric Loading
• Anchor Orientation
• Avoid Stone Restraint

Overhead Installations

• Avoid Chemical Anchors
• Constant Loading
• Over-design Anchorage

INTERIOR INSTALLATIONS

• Format size affects competence of installation.
• Adhesion reliability is proportional to panel size.
• Mechanical anchorage where possible.
• Installation controls strength requirements.
• Quality control to assess mortar coverage is critical.
• Back-up stiffness and plumbness influences installation.
CRITICALLY RELATED SYSTEMS

• Flashing/Drainage
• Weather Barrier
• Air Barrier
• Insulation
• Fenestration
• Sealant
• Paving

PAVING SYSTEM COMPONENTS

• Pavers
  • Stone, Precast Concrete, Ceramics, Brick
• Joint System
  • Grout (a.k.a. Mortar) or Sealant
• Support System
  • Sand, Asphalt, Mortar, Pedestals
• Drainage Provisions
  • Slope, Drains, Scuppers
• Waterproofing (if over occupied space)
  • Hot Fluid-applied, Cold Fluid-applied, Sheets-applied
• Substrate
  • Post-tensioned Concrete, Cast-in Place Concrete, Slabs on Grade

STONE DESIGN

PAVING

Support Systems
Sand-set
Support Systems
Sand-set
- Well Graded Sand for Drainage
- Constant Sand Depth
- Restraint at Perimeters
- Sand-filled Joints
- Frequent Maintenance
- Limited to Small Formats

Support Systems
Bituminous-set
- Similar to Sand-Set System
- Saturation of Pavers Expected
- Limited to Small Formats
- Surface Drainage Only
- Can “Pump”
- Sand-filled Joints
**Support Systems**

**Mortar-set**
- Bonded
- Unbonded (reinforced)
- Mortar Mix Design Critical
  - Bond Strength
  - Proprietary Systems
  - Mortar Consistency Important
- Expansion Joints Required
- Can use mortar or sealant in joints.

**Pedestal-set**
- Relies on stone strength.
- Thickness depends on span.
- Can be placed level.
- Debris can fill joints and limit drainage.
- Can be used with or without sealant in joints.
- Occasional Maintenance
- Mark drains for cleaning.
- Water WILL collect on surface.

**BASICS OF STONE PAVING DESIGN**

- **Paver Durability**
  - Appropriate & Inappropriate Materials for Exterior Applications
- **Drainage**
  - Above and Below-Grade Drainage Considerations
- **Accommodation of Movement**
  - Expansion Joint Frequency, Location, and Detailing
- **Joint Material Selection**
  - Appropriate & Inappropriate Materials and Mix Designs
- **Loading Conditions**
  - Static and Dynamic Loads
Paver Durability

- Material Characteristics (Voids, Veining)
- Density
- Absorption
- Abrasion Resistance
- Compressive Strength

Drainage

- Primary Drainage at Grade
- Secondary Drainage at Waterproofing Level

Drainage

- Water storage within the system should be limited, particularly in insulated systems.
- Maintenance is critical to ensuring performance of the installed drainage system.
- Secondary at Trench Drains

Drainage

- Drainage Mats
  - Provides paths for water flow at the membrane level.
  - Ensure water can drain from the drainage mat, i.e. sufficient slope and drains.
  - Slope is still necessary to promote drainage.
  - Use appropriate product for compressive loads anticipated.
  - Use in conjunction with protection board to avoid clogging and membrane damage.
**Expansion Joints**
- Reduces Shear Stresses in System
- Frequency/Spacing
- Must align with substrate in bonded systems.
- Proper Detailing
- Plane Changes

**Movement**
- ILI – Recommends joints, but does not provide specific direction.
- MIA – References TCNA for specific recommendations.
  - What is good for ceramic tile is good for Stone?

**Movement**
- TCNA Handbook - Method EJ171
  - Spacing – 8 ft. to 12 ft. in Each Direction.
  - Minimum Joint Width of 3/8 in. for 8 ft. Spacing
  - Minimum Joint Width of ½ in. for 12 ft. Spacing
  - Increase Joint Width by 1/16 in. for Every 15° F. Temperatupe Variation

**Movement**
- Exposed plazas in the northern U.S. typically require ¾ in. joints at 12 ft. O.C.
- Architect/Engineer must ensure the adequacy of these recommendations for the specified natural stone paving material selected.
Movement

• Expansion Joint Location
  • Drains or other inset materials.
  • Embedded railing anchorages.
  • Walls from paving system.
  • Fixed elements (stairs).

Joint Filling Material

• Prevents Lateral Movement
• Allows for Accommodation of Minor Stone Size Variation
• Primary Water Ingress Barrier
• Completes Walking Surface
• Prevents Debris Accumulation in Joints

Joint Filling Material - Mortar

• Materials
  • Sand
  • Cementitious Binder
  • Admixtures
  • Water
• Proportioning
• Optimize Bond to Pavers
• Long-Term Durability
  • Freeze-Thaw Resistance

Joint Filling Material - Mortar

• Proportioning: MIA & TCNA
  • Controlled by Joint Width
  • Increase Sand for Larger Joints

<table>
<thead>
<tr>
<th>Material</th>
<th>Specification</th>
<th>Paving Joint Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0-1/8&quot;</td>
</tr>
<tr>
<td>Cement</td>
<td>ASTM C 150, Type I or II</td>
<td>1 Part</td>
</tr>
<tr>
<td>Sand</td>
<td>ASTM C 144</td>
<td>1 Part</td>
</tr>
<tr>
<td>Lime</td>
<td>ASTM C 206 (Type S) or ASTM C 207 (Type S)</td>
<td>1/5 Part (Optional)</td>
</tr>
</tbody>
</table>
Joint Filling Material - Mortar

- **Proportioning:** BIA (ASTM C270)
  - Controlled by Strength

<table>
<thead>
<tr>
<th>Material</th>
<th>Specification</th>
<th>Type M</th>
<th>Type S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>ASTM C 150, Type I or II</td>
<td>1 Part</td>
<td>1 Part</td>
</tr>
<tr>
<td>Sand</td>
<td>ASTM C 144</td>
<td>2-3/4 to 3-3/4 Parts</td>
<td>3-3/4 to 4-1/2 Parts</td>
</tr>
<tr>
<td>Lime</td>
<td>ASTM C 206 (Type S) or ASTM C 207 (Type S)</td>
<td>1/4 Part</td>
<td>1/4 to 1/2 Parts</td>
</tr>
</tbody>
</table>

- **Compressive Strength:**
  - Minimal at 28 days: 2500 psi
  - Minimal at 28 days: 1800 psi

Joint Filling Material - Sealant

- Silicone or Polyurethane
- “Halo” or “Picture Frame” Effect
- Changes in Formulation
- Primer Influence
- Cleaning

PAVING CHALLENGES

- Plane Changes
  - Ramps, Stairs
- Planters
- Water Features
- Penetrations
  - Railings, Bollards

CONDITIONS TO AVOID

- Cracks/Discontinuities in Substrates
- Un-accommodated Volume Changes
- Irregular Joint Patterns
- Changes in Bearing, Depth
- Inadequate System Depth
- High Absorption Stone
- Improper Mortar Types
- Large Formats
- Long Spans
STONE CONSTRUCTION - SUMMARY

• It's Complicated…
  …use common sense as your guide, and do your homework.

• It lasts…
  …we have been building with stone for thousands of years, and will continue, despite its challenges.

• It's natural…
  …which is both a blessing and a curse.

• It's handsome…
  …nothing looks better than a well executed stone building.