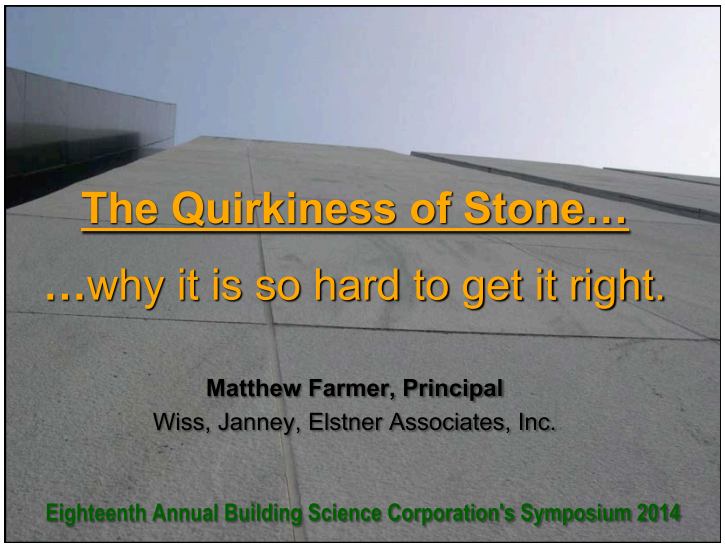


SUGGESTIONS

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.

GEOLOGY 101

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.

ROCK VS. STONE

Rock is…

A. …a popular music genre.

B. …an action movie actor and reality TV show host.

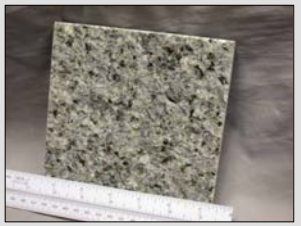
C. …a naturally occurring aggregate formation of minerals and chemicals.

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**

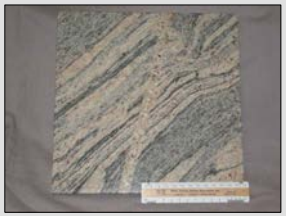


ROCK CLASSIFICATION - SEDIMENTARY

- **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

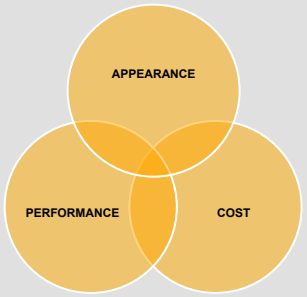
- **Bearing Wall**
  - Full thickness of the wall.
  - Load Bearing - Structural
- **Thick Cladding**
  - Greater than 2 inches thick.
  - Does not support building loads, but can be stacked.
- **Thin Cladding**
  - 2 inches or thinner.
  - Does not support building loads.
- **Paving**
  - Thickness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

STONE INDUSTRY REFERENCES

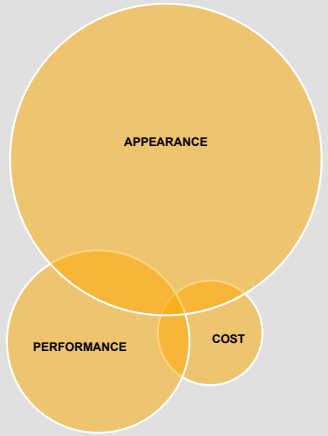
- **Indiana Limestone Institute (ILI) Handbook**
  - http://www.iliai.com
- **Marble Institute of America (MIA) Design Manual**
  - http://www.marble-institute.com
- **National Building Granite Quarries Association (NBGQA) Specification**
  - http://www.nbgqa.com
- **Tile Council of North America (TCNA)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

STONE SELECTION

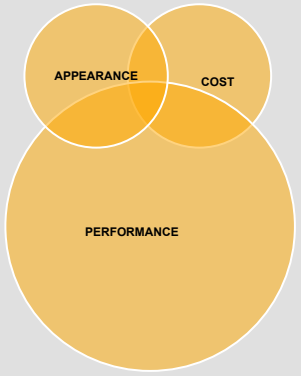
STONE SELECTION CRITERIA



STONE SELECTION CRITERIA - ARCHITECT



STONE SELECTION CRITERIA - ENGINEER



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

Granite		C880	**1200** psi
Marble		C880	**1000** psi
Limestone Class III	(High Density)	C99	**1000** psi
Limestone Class II	(Med. Density)	C99	**500** psi
Limestone Class I	(Low Density)	C99	**400** psi
Sandstone Class III	(Quartzite)	C99	**2000** psi
Sandstone Class II	(Quartzitic)	C99	**1000** psi
Sandstone Class I		C99	**350** psi
Travertine Class I	(Exterior)	C880	**1000** psi
Travertine Class II	(Interior)	C880	**700** psi

Material/Structural Properties

Variability

- **Between Different Stone Classifications**

Material/Structural Properties

Variability

- **Within a Stone Classification**

2000 psi

1000 psi

1600psi

Material/Structural Properties

Variability

- **Between Stones of the Same Type!**

Material/Structural Properties

Bedding Planes, Veins, and Rifts

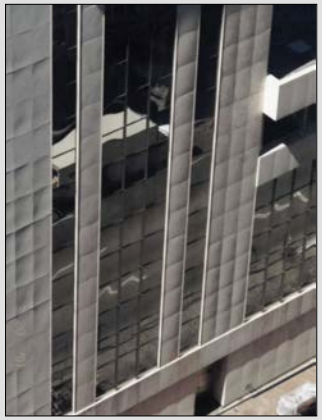
- **Material Properties**
  - **Flexural Strength**
  - **Absorption**
- **Weathering/Erosion**
- **Discoloration**

Material/Structural Properties

Strength Loss due to Weathering

Material/Structural Properties

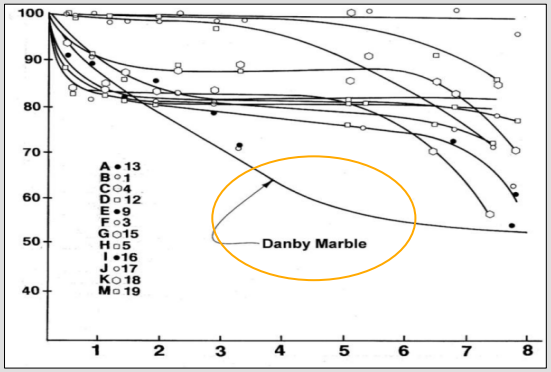
Strength Loss due to Weathering



Material/Structural Properties

Strength Loss due to Weathering

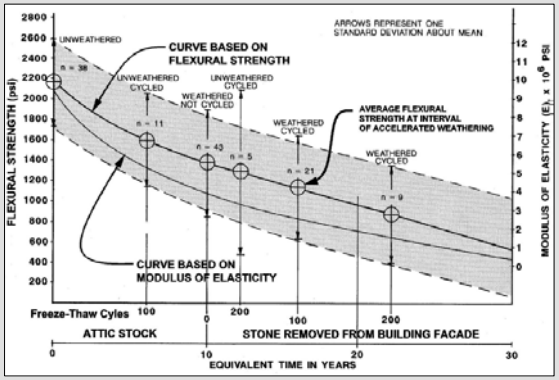
Real Time Weathering



Material/Structural Properties

Strength Loss due to Weathering

Accelerated Weathering



Material/Structural Properties

Durability

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

Material/Structural Properties

Durability

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)	19,000	7,500	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

Testing Standard	Physical Property	Granite	Marble*	Travertine**	High Density Limestone	Medium Density Limestone	Low Density Limestone
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ASTM C170	Compressive Strength, Min. (lb/in²)	19,000	7,500	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

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Durability

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Material/Structural Properties

Durability

Material/Structural Properties

Durability

Material/Structural Properties

Durability

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

- **ASTM D2203, "Standard Test Method for Staining from Sealants"**
- **Changes in Formulation**
- **Primer Influence**
- **Cleaning**
- **An old problem…**

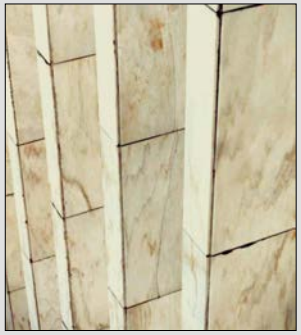
Material/Structural Properties

Salt Crystallization Resistance

Material/Structural Properties

Color Changes

- **Weatherization Chamber Testing (Accelerated Aging)**
- **ASTM C 1721, "Standard Guide for Petrographic Examination of Dimension Stone"**



Primary Structure

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

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

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

*Transient Loads (i.e. wind, seismic)

Safety Factors - Values

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	Granite (>50mm)	3	3
	Marble	5	5
	Slate	5	5
	Limestone	8	8
	Sandstone	8	10
Indiana Limestone Institute	Limestone	8 (6)*	8

*Transient Loads (i.e. wind, seismic)

STONE DESIGN

CLADDING

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

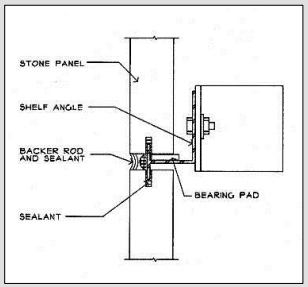
COMMON STONE ANCHOR TYPES

- **Edge Supported**
- **Back Surface-mounted**

Edge-supported Anchors

Continuous Kerf Anchors

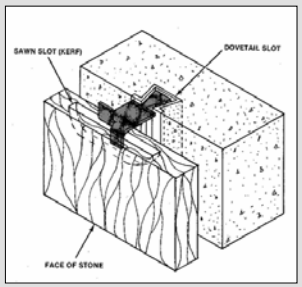
- **SEALANT installed between anchor and stone.**



Edge-supported Anchors

Discontinuous Kerf Anchors

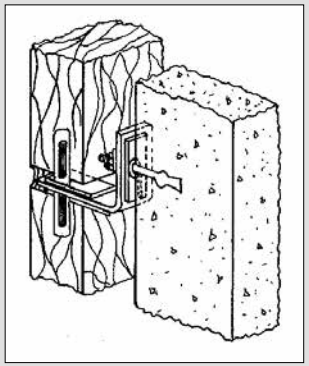
- **SEALANT installed between anchor and stone.**



Edge-supported Anchors

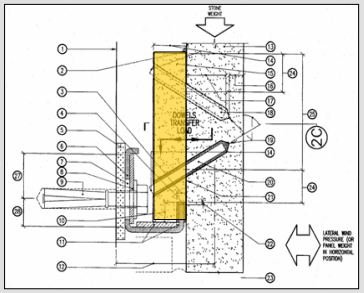
Dowels

- **Dowels are set in slightly oversized (in diameter) holes filled with SEALANT.**



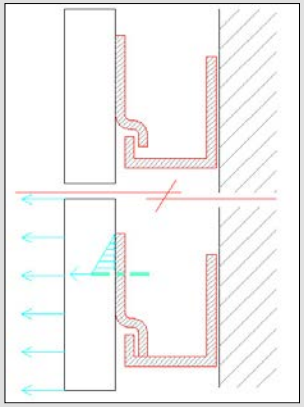
Back Surface-mounted Anchors

Liner Blocks



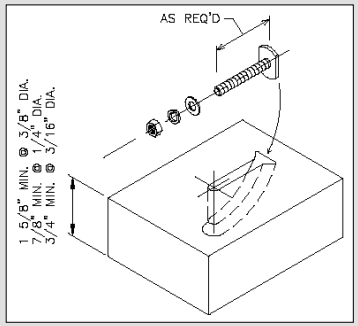
Back Surface-mounted Anchors

H and J Clips



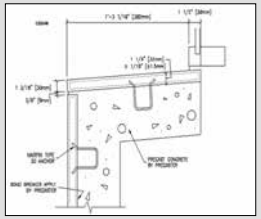
Back Surface-mounted Anchors

Type 31 Anchor



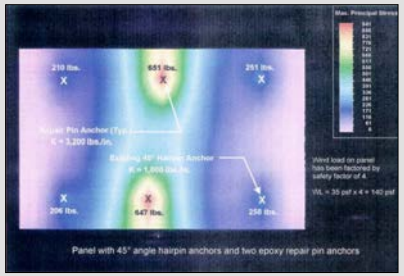
Back Surface-mounted Anchors

Hair Pin Anchor



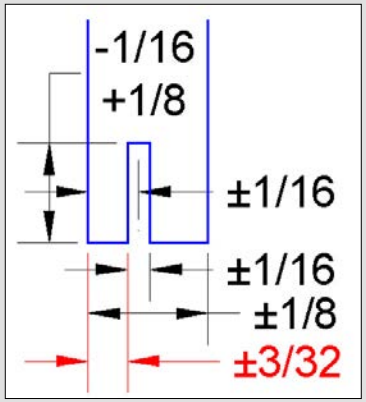
ANCHOR/STONE INTERACTION

- **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

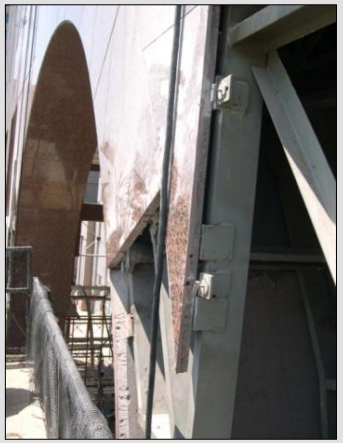
- **Accommodate movements due to:**
  - Expansion/Contraction of Stone
  - Structural Loading
  - Movements of the Back-up
- **Assess Overall Structural Design**

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**

STONE DESIGN

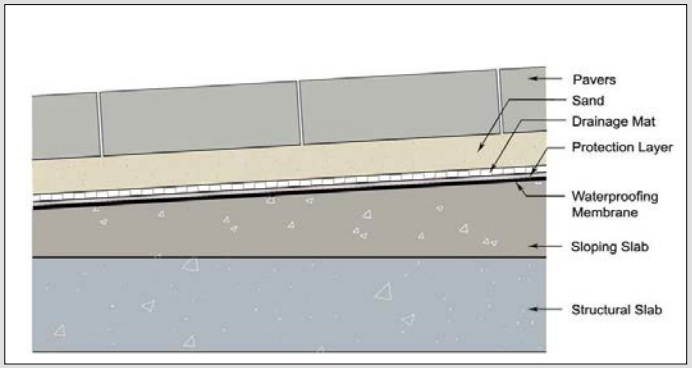
PAVING

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

Support Systems

Sand-set



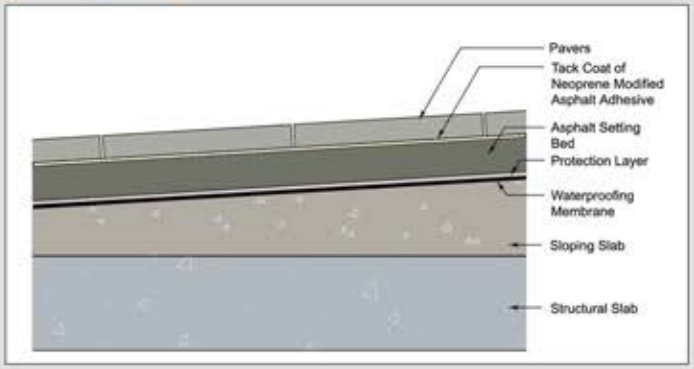
Support Systems

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



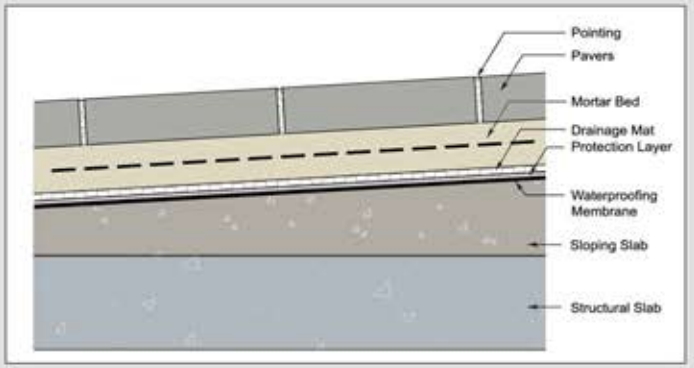
Support Systems

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



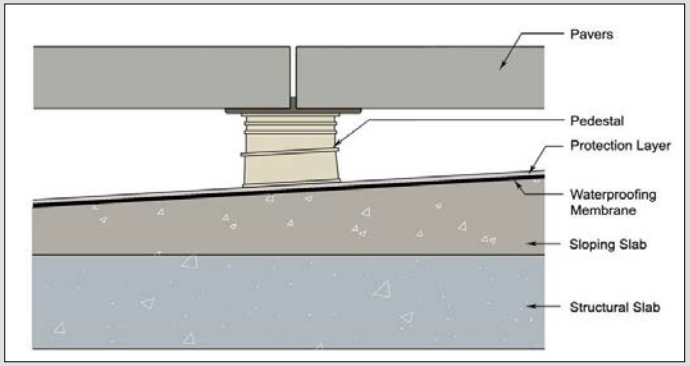
Support Systems

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.**

Support Systems

Pedestal-set



Support Systems

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

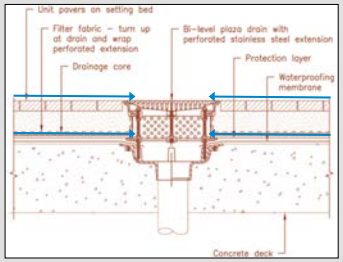
- **Paver Durability**
  - Appropriate & Inappropriate Materials for Exterior Applications
- **Drainage**
  - Above and Below-Grade Drainage Considerations
- **Accommodation of Movement**
  - Expansion Joint Frequency, Location, and Detailing
- **Joint Material Selection**
  - Appropriate & Inappropriate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

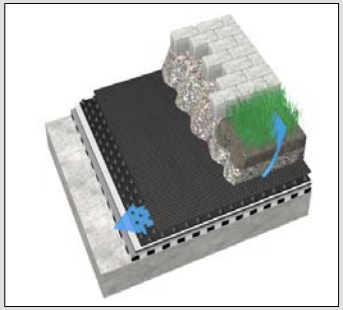


Drainage

- **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.

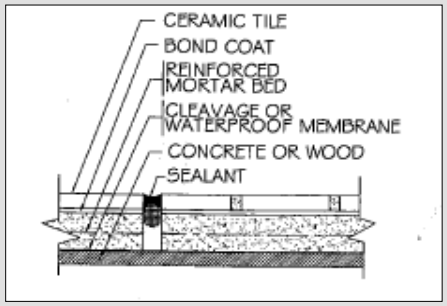


Movement

- **Expansion Joints**
  - Reduces Shear Stresses in System
  - Frequency/Spacing
  - Must align with substrate in bonded systems.
  - Proper Detailing
  - Plane Changes

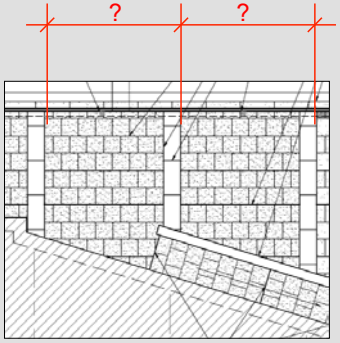
Movement

- **ILI – Recommends joints, but does not provide specific direction.**
- **MIA – References TCNA for specific recommendations.**
- **TCNA – References Method EJ171 in the TCNA Handbook.**
- **What is good for ceramic tile is good for Stone?**



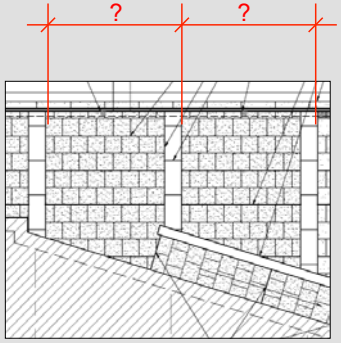
Movement

- **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. Greater than 100° F. Temperature Variation



Movement

- **TCNA Handbook - Method EJ171**
  - 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

Material	Specification	Paving Joint Width		
		0-1/8"	1/8" -1/2"	Over 1/2"
Cement	ASTM C 150, Type I or II	I Part	1 Part	1 part
Sand	ASTM C 144	1 Part	2 Parts	3 Parts
Lime	ASTM C 206 (Type S) or ASTM C 207 (Type S)	1/5 Part (Optional)		

Joint Filling Material - Mortar

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

Material	Specification	Material Proportion by Volume	
		Type M	Type S
		Compressive Strength (min. at 28 days): 2500 psi	Compressive Strength (min. at 28 days): 1800 psi
Cement	ASTM C 150, Type I or II	1 Part	1 Part
Sand	ASTM C 144	2-3/4 to 3-3/4 Parts	3-3/4 to 4-1/2 Parts
Lime	ASTM C 206 (Type S) or ASTM C 207 (Type S)	1/4 Part	1/4 to 1/2 Parts

Joint Filling Material - Sealant

- **Silicone or Polyurethane**
- **ASTM D2203, "Standard Test Method for Staining from Sealants"**
- **"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.