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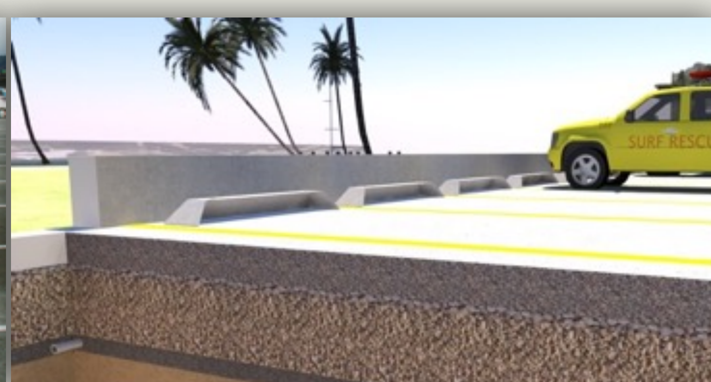
30th Anniversary of Excellence in the Training of Transportation Officials at Municipal, State and Federal Level in Puerto Rico and Virgin Islands

Pervious Concrete Pavement: Hype and Hope



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LTAP
Local & Tribal Technical Assistance Program

March 17, 2016

Pervious Concrete Pavement

Hype and Hope

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Environmental Engineering
Department of Civil Engineering and Surveying
University of Puerto Rico at Mayagüez

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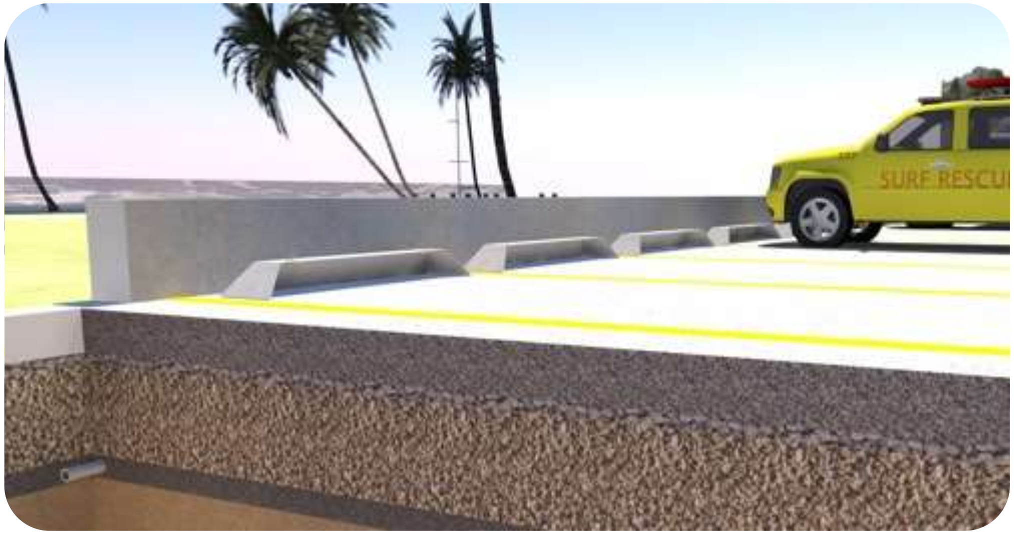
Seminar synopsis

Hwang Eco-friendly Development for Green Environment

perviouspavement.org

Chapter 1.

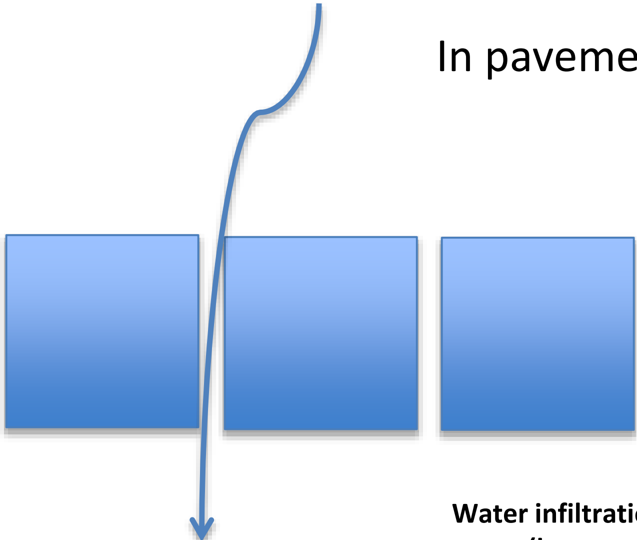
Introduction to Pervious Concrete



SketchUp by Valerie López Carrasquillo

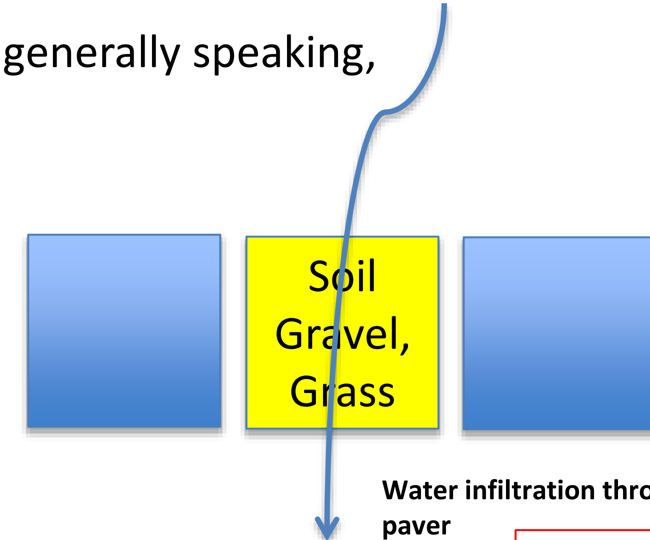
Permeable? Porous?

In pavement engineering, generally speaking,



Water infiltration around the paver (between the joints)

Permeable pavement

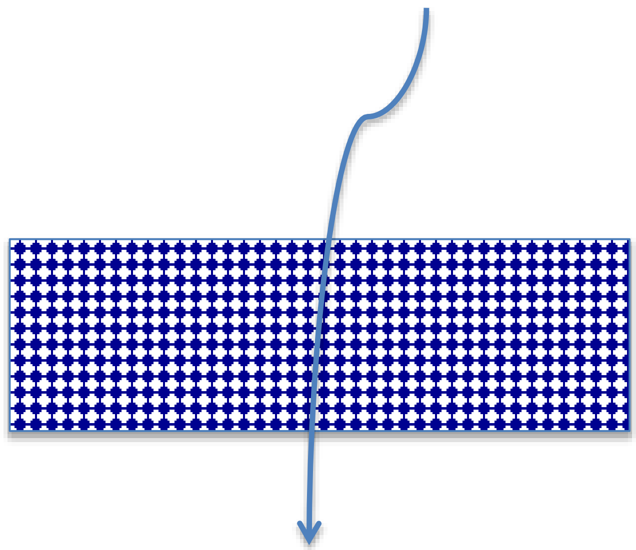


Water infiltration through the paver

In this sense, porous pavement ≈ pervious pavement

Porous pavement

Pervious?



Pervious concrete pavement
Porous concrete pavement

Porous asphalt pavement

Permeable? Porous? Pervious?

Depending on how we explain “perviousness”……

Permeability is a measure of the ease with which a fluid (water in this case) can move through porous media.

- Connected open spaces

Porosity is a measure of how much of porous media is open space. This space can be between grains or within cracks or cavities of the porous media.

- Open spaces are not necessarily connected

“Pervious”

- Capable of being penetrated by water
- Include “permeable” and “porous”
    - *The permeability of pervious concrete provides increased safety to drivers.*
    - *The void content of pervious concrete ranges between 15 to 35%.*
- Connected pores

Pervious concrete

- Drainage rate
  - 190 to 1720 in/hr (12000 to 105000 mm/hr)
  - 2 to 18 gal/min/ft^2 (80 to 730 L/min/m^2)
- Void content, 15 to 35%
  - Interconnected pores, 0.08 to 0.32” (2 to 8 mm)
- Compressive strength
  - 400 to 4000 psi (2.8 to 28 MPa)
    - Dense concrete, 2500 to 6000 psi (17 to 40 MPa)
- Flexural strength
  - 150 to 600 psi (1 to 4 MPa)
- Drying shrinkage
  - 0.02-0.03%
- Density
  - 115 lb/ft^3 (1800 kg/m^3)
    - Dense concrete, 150 lb/ft^3 (2300 kg/m^3)

History of pervious concrete

- 1852
  - Construction of two houses in UK (coarse gravel + cement)
- In the later 1930s
  - Scottish Special Housing Association Limited adopted the use of pervious concrete for residential construction
- 1939 to 1945, World War II
  - European countries needs a new method of construction
  - Less cement per unit volume, scarce/expensive manpower
- After WW II in many countries in Europe
  - Presence of unlimited supplies of hard aggregates (brick rubbles) + absence of good facing bricks

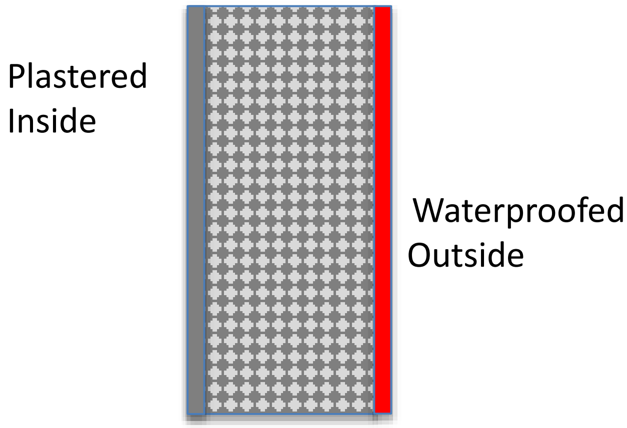
  → Material recycle! → Pervious concrete booming!

History of pervious concrete

- After WW II in North America
  - No such a material shortage
  - 1951, USA
    - Valore R.C., Jr., Green W.C.. “Air replaces sand in ‘no-fines’ concrete”, Proceeding of the American Concrete Institute, Detroit, ACI, 1951.
      - Focused more on its light weight than on its pervious qualities, though.

History of pervious concrete

- European no-fine pervious concrete walls in the 1970s
  - Lighter weight and better insulating value



History of pervious concrete

- Utilization of “pervious” property of water infiltration
  - In the 1970s, England
    - A pavement with a pervious concrete topping (Nottinghamshire, England)
      - Maynard D.P. “A fine no-fines road”. Concrete Construction, April 1970, 116-117.
    - No-ponding on sports facilities
      - Enoch M.D. Concrete for sports and play areas, Wexham Springs, UK Cement and Concrete Association, 1976
      - Enoch M.D. Concrete bases for non-turf cricket pitches, Wexham Springs, UK Cement and Concrete Association, 1980
  - In the 1970s, USA
    - Central Florida, parking lot for stormwater control
    - USEPA adopted pervious pavements as part of the Best Management Practices (BMPs) for stormwater management

In Puerto Rico

- 2015
  - Industry pioneers in PR
    - Victor Diaz, Jr. (Star Ready Mix, Inc)
    - Ruben Segarra (Essroc San Juan)
    - Angel Morales (Grupo Titan AE Corp)
  - Reconstruction of the entrance of the Yunque
    - Yunque’s Palmer Portal project

In Puerto Rico

- Hwang's research group
  - Since ca. 2010
  - University pioneer in PR
  - First in PR with scientific publications of pervious concrete in 2015
- December 2015
  - Formal University-Industry collaboration
  - El Puente, a newsletter of PRT2 Center

Construction and Building Materials 93 (2015) 22–28

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Optimization of pervious concrete containing fly ash and iron oxide nanoparticles and its application for phosphorus removal

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Construction and Building Materials 93 (2015) 1097–1104

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Materials and Design 86 (2015) 22–29

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Response Surface Methodology to optimize the cement paste mix design: Time-dependent contribution of fly ash and nano-iron oxide as admixtures

Linoshka Soto-Pérez, Valerie López, Sangchul S. Hwang *

Department of Civil Engineering and Surveying, University of Puerto Rico, Mayagüez, 00681-904 Puerto Rico

Eco-Friendly Pervious Concrete Pavement: Concerted Efforts in Puerto Rico

In Puerto Rico

- January 2016
  - First nanotechnology-enabled pervious concrete implementation in PR with structural and hydrologic designs
  - UPR-Mayagüez campus

HEDGE
Hwang Eco-friendly Development for Green Environment

Grand Opening Day. Ribbon cutting by Juliana St John, HEDGE PRO
El Nuevo Dia (Feb 2016)

Hype

- It often claims, by extreme promoters, that pervious concrete is

or

- **Is pervious concrete the greatest construction materials ever?**
- **Are you going to bulldoze the rain forest to put pervious concrete instead?**

Nope

- “Pervious” is NOT a cure-all.
- “Pervious” does NOT ALWAYS mean “Green”
- Limitations / challenges

Limitations & challenges

- Limited use in heavy vehicle traffic areas
  - Speeds <35 mph
  - Light truck traffic
  - Limited turning operations
- Special design and construction practices
- Lack of standardized test methods
- Site specific
  - Soil types, weather, groundwater table
- Maintenance

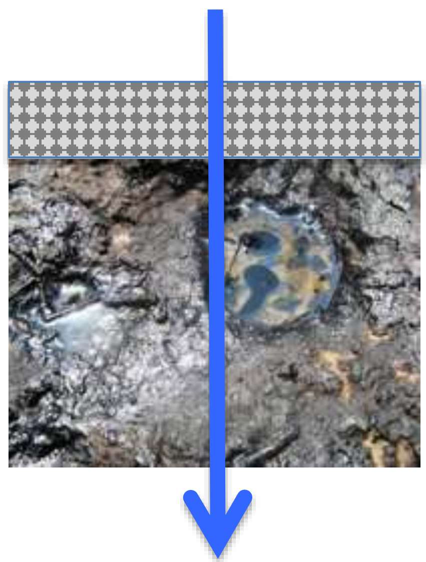
Nope

- **Sediment-loaded runoff?**

Nope

journalpioneer.com

overtheedge.com



Contaminated subgrade soil

Hope

- Limited use in heavy vehicle traffic areas
  - Speeds <35 mph
  - Light truck traffic
  - Limited turning operations

We, if not I, are capable of design/construction of strong and durable pervious concrete pavement

- Special design and construction practices → Education / training / experience

- Lack of standardized test methods → ACI and NRMCA are working on this

- Site specific
  - Soil types, weather, groundwater table

Obey the laws of nature

- Maintenance → Education / training of the owners

"Pervious" is a team player for sustaining the world with green infrastructure

Advantages over impervious pavements

- Controlling stormwater pollution at the source
- Controlling stormwater runoff
- Eliminating/reducing the size of storm sewers
- Recharging groundwater
- Eliminating the need for soakaways and ponds
  - At least smaller and cheaper
- No need of 2 to 3% slope to prevent ponding
  - Complication with construction
  - Sports surface

Advantages over impervious pavements

- Reducing hydroplaning
- Reducing the interaction noise
- Reducing icing
- Cooler air temperature over PCP parking lots than asphalt
- Reducing snow and ice buildup
- Increasing parking area by eliminating the need for water detention (or, retention) areas

Advantages over ponded impervious pavements

- At least, visible potholes

pinterest.com

- Reducing road spray

metro.co.uk

Pervious concrete pavement parking areas

- Most applications

Ewa Beach Elementary School, Hawaii

Pearl Harbor Memorial, Hawaii

Advantages over impervious pavements

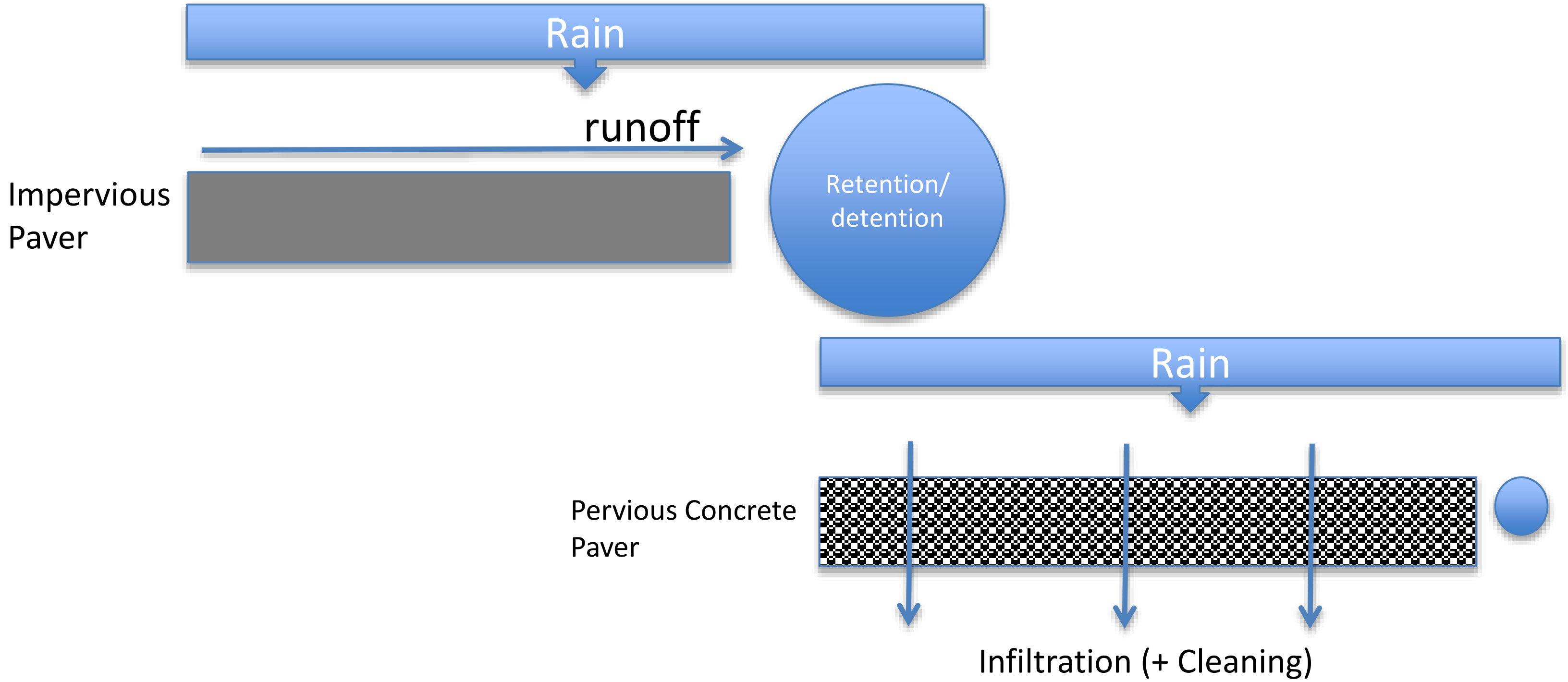
- Passive cooling of pavement
  - Air voids are good thermal insulation
  - Thermal conductivity of pervious concrete is ~half that of dense concrete
- Making tree roots happy with air and water
  - Shading, evapotranspiration → Reduce energy use → Decrease the production of associated air pollution and greenhouse gas emissions
  - Remove air pollutants and store/sequester CO_2
  - Enhance stormwater runoff management and improve water quality by trees
  - Shading → Reduce pavement maintenance
  - Improve livability
    - Aesthetic value, habitat for many species, and reduce noise

Advantages over asphalt pavement

- Mitigation of urban heat islands
  - Heat island?
    - Buildings and pavements absorb more solar radiation than the surrounding natural surfaces → Localized warm area
    - To much smaller extent, anthropogenic heat production
  - Based on solar reflectance index (SRI, = Albedo), pervious concrete pavement is better than asphalt pavement, but is not better than dense concrete pavement
    - SRI: 0 (black) to 100 (white)
    - New asphalt pavement, ~0
    - New dense concrete pavement, 35 to 55
    - New pervious concrete pavement, often >29
      - Why do I say here “29”?

LID

- Low Impact Development (LID) with pervious concrete pavement
  - In a context of urban storm runoff, LID is an approach to land (re)development that works with nature to manage stormwater as close to its source as possible



LEED certification

- Leadership in Energy and Environmental Design
- “29” SRI is the point at which a pavement qualifies for LEED credit
  - In this context, dense concrete pavement is better than pervious concrete pavement
  - However, pervious concrete pavement generates more benefits such as healthier tree growth and effective stormwater management, etc.
    - More LEED credits after all

LEED certification

- For construction practices and materials that reduce harm to the environment
- A maximum of 100 points
  - Basic certification, at least 40 points
  - Silver, 50 to 59
  - Gold, 60 to 79
  - Platinum, >80
- LEED ≠ Green
  - Example) LEED is a design tool, not a performance evaluation tool for buildings

Pervious concrete contribution to LEED certification

http://www.usgbc.org/leed

- Stormwater management
  - LEED Credit SS-C6.1 and SS-C6.1
  - Volume reduction and quality improvement
- Harvesting of stormwater for landscape irrigation
  - LEED Credit WE C1.1
  - Storage layer under pervious concrete
- Reduction of heat islands effect by using materials with SRI of 29 or higher
  - LEED Credit SS-C7.1
- Use of recycled materials
  - LEED Credit MR-C4.1 and MR-C4.2
  - Pre-consumer recycled materials
    - Supplementary cementitious materials (SCMs): fly ash, slag, silica fume
  - Post-consumer recycled materials
    - Recycled aggregates from demolition projects
- Use of regional materials
  - LEED Credit MR-C5.1 and MR-C5.2
  - To reduce the environmental impacts resulting from transportation
  - To support the local economy

Pervious concrete pavement (PCP) materials

- Aggregates
  - Open-graded coarse aggregates
    - Open-graded?
      - A narrow range of particle size, with most retained on one or two sieves
    - >4.75 mm (>3/16”)
    - 9.5 to 19 mm (3/8 to 3/4”)
    - Rounded or crushed
    - Normal or lightweight
    - In compliance with ASTM D448 and C33
  - Fine aggregates
    - Seldom used
  - Moisture content at time of mixing!
    - Saturated-surface-dry condition
    - Dry aggregates: poor workability
    - Too wet aggregates: paste draining

PCP materials

- Cementitious materials
  - Portland cement
    - In compliance with ASTM C150, C595, C1157
  - **Supplementary cementitious materials (SCMs)**
    - **Fly ash**, slag, silica fume
    - In compliance with ASTM C618, C989, C1240
- Water
  - Relatively low w/cm of 0.26 – 0.40
  - In compliance with ASTM C94 or AASHTO M157 for use in dense concrete

PCP materials

- Admixtures
  - Water reducers (plasticizers)
    - ASTM C494
    - Improve cement paste flows and coats the coarse aggregate
  - Viscosity modifiers
    - Make paste thicker and stickier, reducing the risk of draindown
  - Set retarders (set stabilizers)
    - Useful in hot weather applications
    - Give more time to place and compact pervious concrete
      - Great benefits for ready-mix suppliers
    - Also works as lubricants
  - Accelerators
    - In cold weather
  - Air-entraining admixtures
    - ASTM C260
    - Not usually recommended for PCP but for freezing/thawing environments
  - Evaporation retarders
    - Windy, dry conditions

In PR?

PCP materials

- Admixtures
  - Nanomaterials
    - nanoSiO_2, nanoFe_2O_3, nanoAl_2O_3
    - As nuclei, react with $Ca(OH)_2$ increasing the C-S-H gel production, leading to a denser microstructure
      - Decreasing permeability
      - Improving durability and mechanical strength
    - and/or as fillers to its microstructure
  - Fibers
    - Plastic (polypropylene) or natural (cellulose)
    - Dosage: 1 lb/yd^3 concrete (0.6 kg/m^3)
    - No steel fibers
    - Improve strength and durability????

HEDGE
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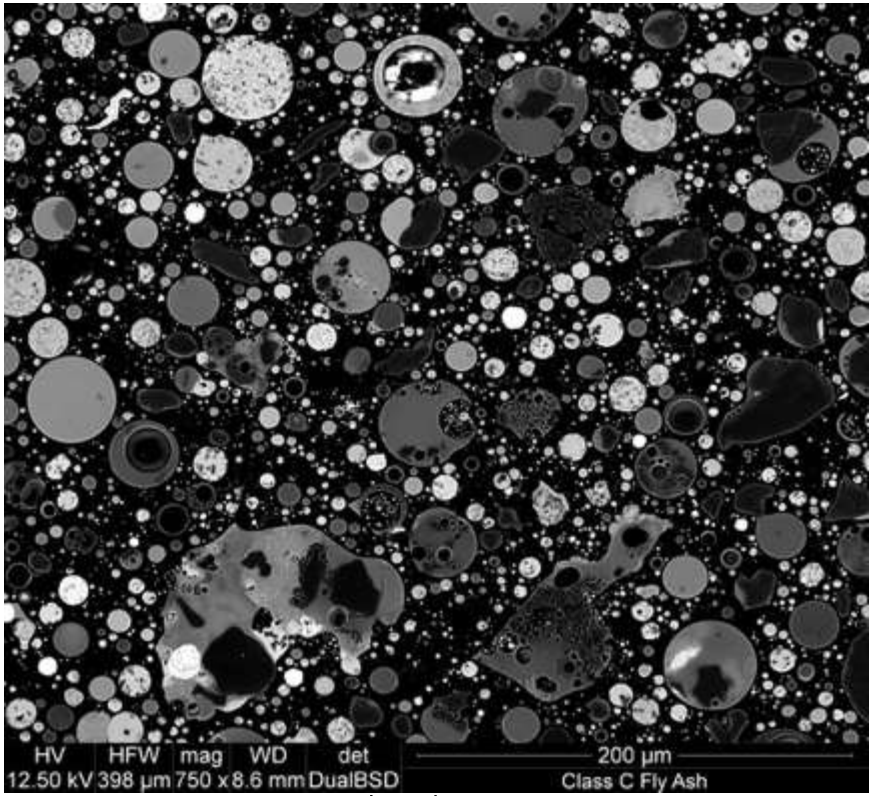
for Green Environment



wikipedia.org

Chapter 2.

Fly Ash as a Supplementary Cementitious Material

Use of fly ash in concrete (**Encapsulated** beneficial use)

- Enhance durability
- Improve resistance to sulfate attack, chloride-induced corrosion
- Mitigate alkali silica reaction (ASR)
- Support concrete sustainability
- Help solid waste management
- Economic savings

Roman Pantheon (ancient.eu)
c. 125 CE

Volcanic ash

romancolosseum.org
c. 80 CE

Hoover Dam spillway tunnel repair
1942

Hungry Horse Dam (Montana)
1948-1953

Reagan Building, DC

Freedom Tower, NYC

Burj Khalifa, Dubai

Trump International, Chicago

Mike O'Callaghan–Pat Tillman Memorial Bridge
(Hoover Dam Bypass, 2010)

Encapsulated beneficial use

EPA Evaluation Finds Use of Coal Ash in Concrete and Wallboard Appropriate

Release Date: 02/07/2014
Contact Information: Enesta Jones, Jones.enesta@epa.gov, 202-564-7873, 202-564-4355

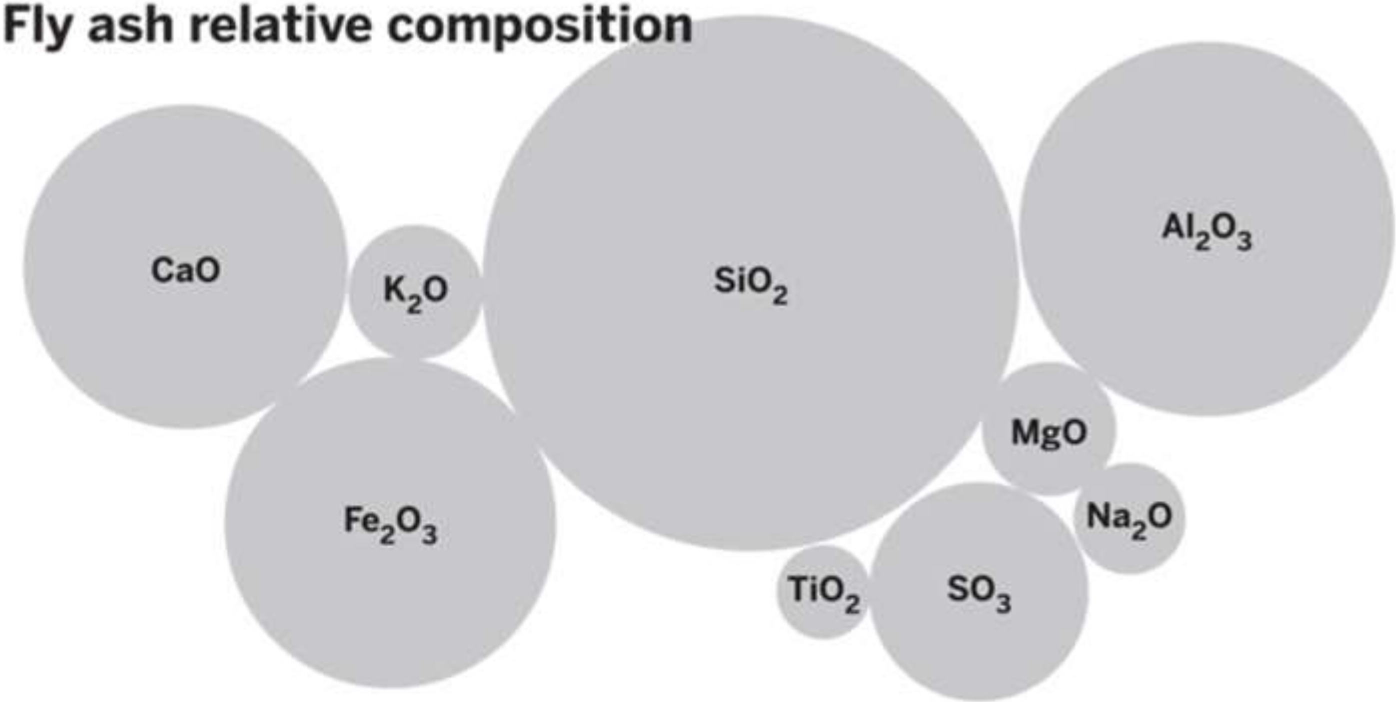
WASHINGTON – Using a newly developed methodology, the U.S. Environmental Protection Agency (EPA) today released its evaluation of the two largest beneficial uses of encapsulated coal combustion residuals (CCR or coal ash): use in concrete as a substitute for portland cement, and the use of flue gas desulfurization gypsum as a substitute for mined gypsum in wallboard. EPA's evaluation concluded that the beneficial use of encapsulated CCRs in concrete and wallboard is appropriate because they are comparable to virgin materials or below the agency's health and environmental benchmarks.

These two uses account for nearly half of the total amount of coal ash that is beneficially used.

"The protective reuse of coal ash advances sustainability by saving valuable resources, reducing costs, and lessening environmental impacts, including reducing greenhouse gas emissions," said Mathy Stanislaus, assistant administrator for EPA's Office of Solid Waste and Emergency Response.

In evaluating these two beneficial uses, EPA used its newly developed, Methodology for Evaluating Encapsulated Beneficial Uses of Coal Combustion Residuals. The methodology is intended to assist states and other interested parties with evaluating and making informed determinations about encapsulated beneficial uses of CCRs.

Fly ash relative composition



Trace elements[a]: Ba, Sr, B, Mn, Zn, V, Cr, As, Pb, Ni, Cu, Mo, Tl, Be, U, Se, Sb, Cd, Hg

NOTE: Circles represent mean concentrations for various fly ash samples, for example, SiO_2 = 215,000 mg/kg.
a In order of relative abundance. **SOURCE:** Electric Power Research Institute

- Today, about half the concrete produced in the U.S. contains some fly ash—up to 40%—as a substitute for limestone-based Portland cement.
- Fly ash is also used as material to make bricks, ceramic tiles, and plaster; as filler in metal and plastic composites and in paints and adhesives; and as structural fill for road construction.

Fly ash classification

ASTM C618 (AASHTO M 295)

TABLE 1 Chemical Requirements

	Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min, %	70.0	70.0	50.0
Sulfur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max, %	3.0	3.0	3.0
Loss on ignition, max, %	10.0	6.0[A]	6.0

[A] The use of Class F pozzolan containing up to 12.0 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

- Class C – $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$
- Class F – $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$
- So… Every Class F is a Class C….. ???

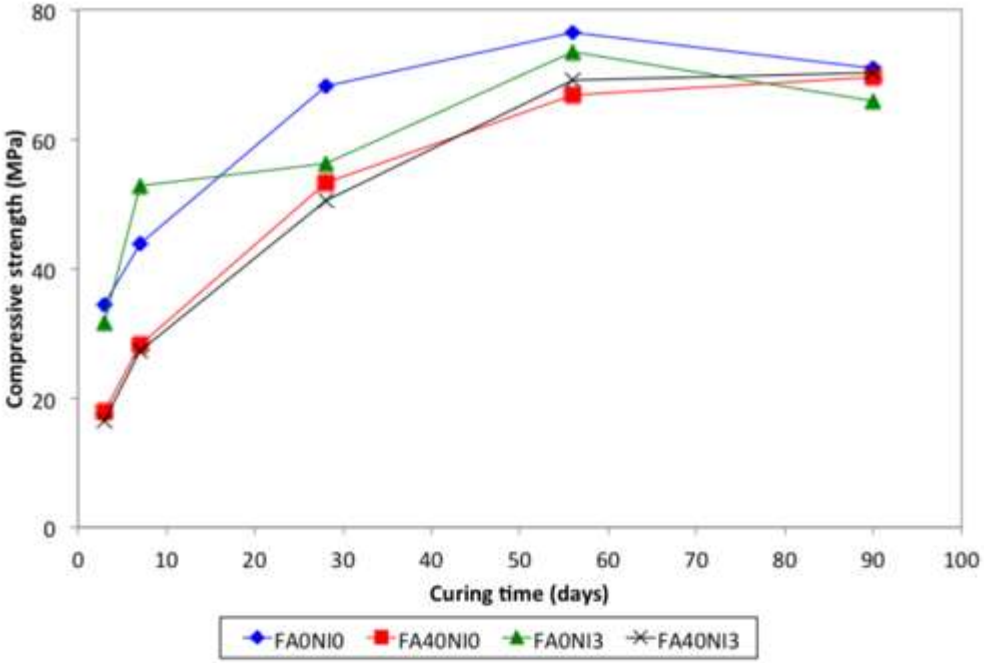
Within-spec fly ash (Compliant fly ash)

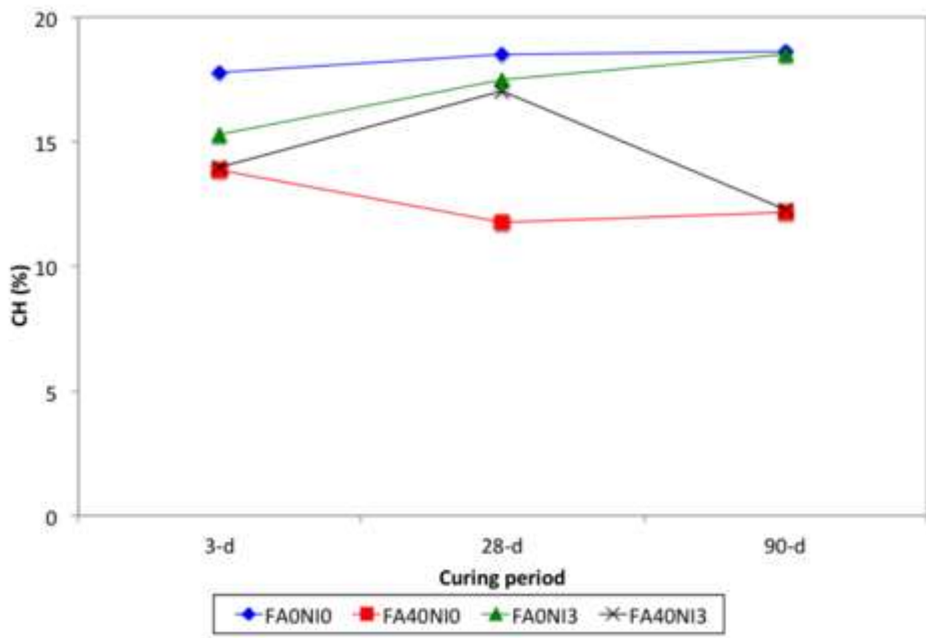
- Class C and Class F (ASTM C618)
  - Bituminous or anthracite coal produces Class F (low calcium) fly ash
  - Lignite or sub-bituminous coal produces Class C (high calcium) fly ash
  - Class F fly ash is pozzolanic
  - Class C fly ash is both self-cementitious and pozzolanic
- The top limit of loss on ignition (LOI) for both Class C and F fly ash, mostly due to carbon
  - 6% by ASTM C618
  - 5% by AASHTO M295

Cementitious vs. Pozzolanic

- Pozzolan
  - Volcanic acid mined at Pozzuoli, Italy
  - Siliceous or siliceous/aluminous material
  - Little or no cementitious value
  - But, in the presence of water, react chemically with calcium hydroxide, $Ca(OH)_2$, at ordinary temperature to form compounds possessing cementitious properties (C-S-H gel)

- Cementitious reaction
  - Cement + water → CSH + CH
    - CSH: calcium silicate hydrate, glue/bond in hardened cement
    - CH: calcium hydroxide
- Pozzolanic reaction
  - Pozzolan + CH + water → CSH
    - Increasing strength
      - But, this reaction is slow, especially with Class F fly ash
    - Decreasing permeability
      - More CSH forming, less CH dissolution → For sulfate resistance; Against chloride-induced corrosion
    - **Mitigating alkali silica reaction (ASR)**
      - **Pozzolanic F fly ash**
        - **Consumes hydroxide central to ASR**
      - Cementitious C fly ash
        - Much less effective than F fly ash, needs higher replacement

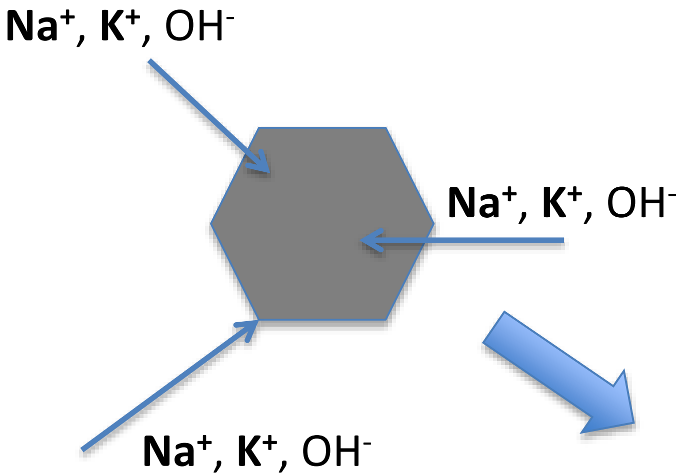

80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100
Compressive strength (MPa)
Curing time (days)
FA0NI0
FA40NI0
FA0NI3
FA40NI3


20
15
10
5
0
CH (%)
3-d
28-d
90-d
Curing period
FA0NI0
FA40NI0
FA0NI3
FA40NI3

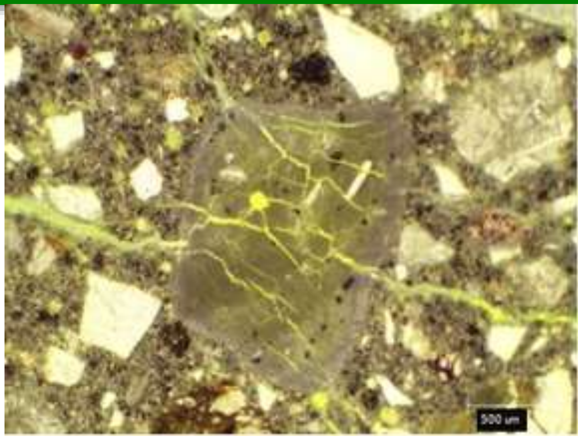
Alkali silica reaction (ASR)

- Alkali aggregate reaction (AAR)
  - Alkali silica reaction (ASR)
  - Alkali carbonate reaction (ACR)
- ASR
  - Aggregates containing certain forms of silica will react with alkali hydroxide ($NaOH$ and KOH) in concrete pore water to form an alkali-silica gel that swells as it adsorbs water from the surrounding cement paste or the environment.
  - These gels can induce enough expansive pressure to damage concrete.

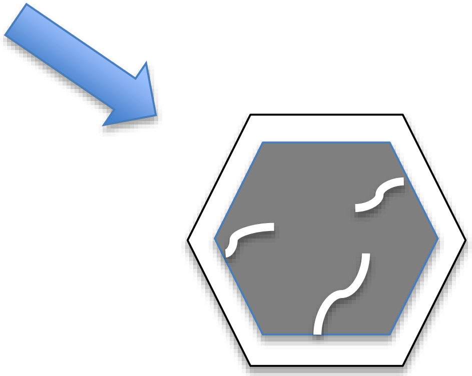
ASR



Alkali elements in cement paste react with reactive aggregates

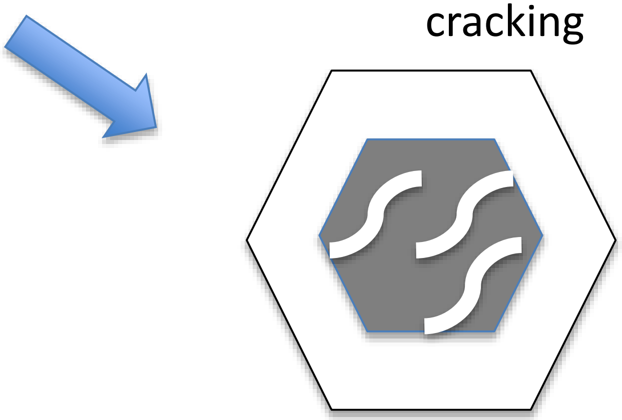


www.rjlg.com

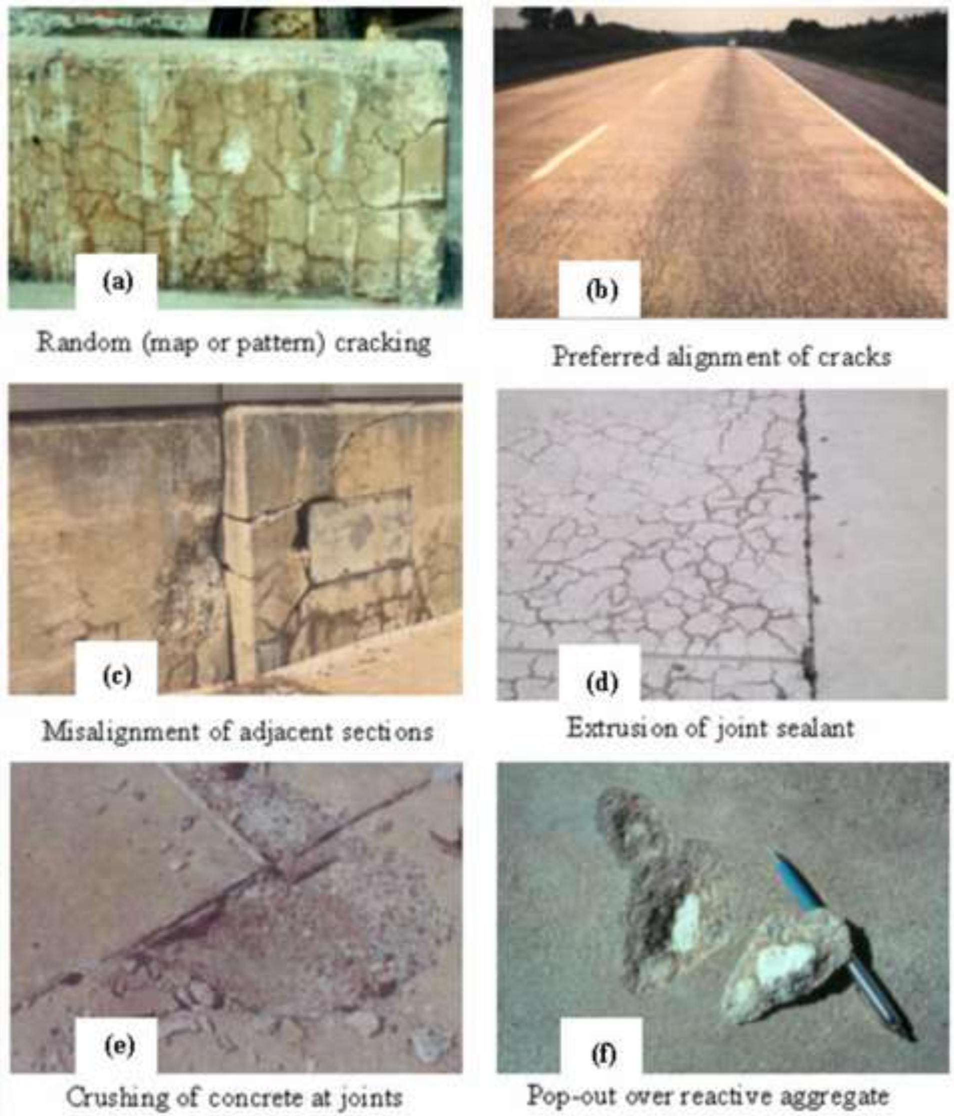


Alkali-silica gel forms around and within the aggregate

ASR gel absorbs water resulting in expansion and cracking



ASR symptoms



Random (map or pattern) cracking

Preferred alignment of cracks

Misalignment of adjacent sections

Extrusion of joint sealant

Crushing of concrete at joints

Pop-out over reactive aggregate

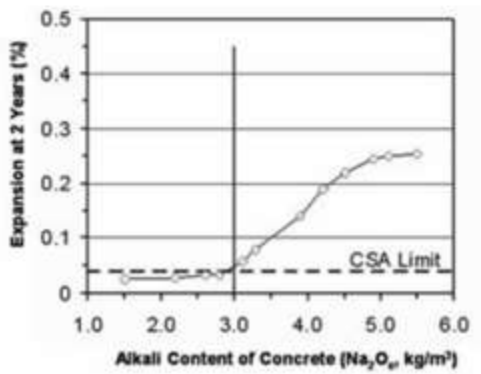
fhwa.dot.gov

ASR remediation

- Caulking cracks with an epoxy grout
- Cutting joints to allow further expansion to take place
- Dry the concrete to eliminate the moisture required to sustain ASR
  - Silane sealer
    - Make the concrete surface hydrophobic but allow water vapor to exit

ASR prevention

- Avoid the use of reactive aggregates
  - Non-reactive aggregates? Where can you get them?
- Limit the alkali content of the concrete mixture
  - Use of low alkali cement (<0.6% Na_2O_e)



Alkali content of concrete (kg/m³ Na_2O_e) =
Cement content of concrete (kg/m³)
x alkali content of cement (percent Na_2O_e)/100

Equivalent Alkalies, $Na_2O_e = Na_2O + 0.658 \times K_2O$

$Na_2O_e = 0.15 + 0.658 \times 0.73 = 0.63\%$

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
Percent	20.55	5.07	3.10	64.51	1.53	0.15	0.73	2.53	1.58

Concrete mixture containing 350 kg/m³ of Portland cement which has an alkali content of 0.63% Na_2O_e:

2.21 kg/m³ Na_2O_e

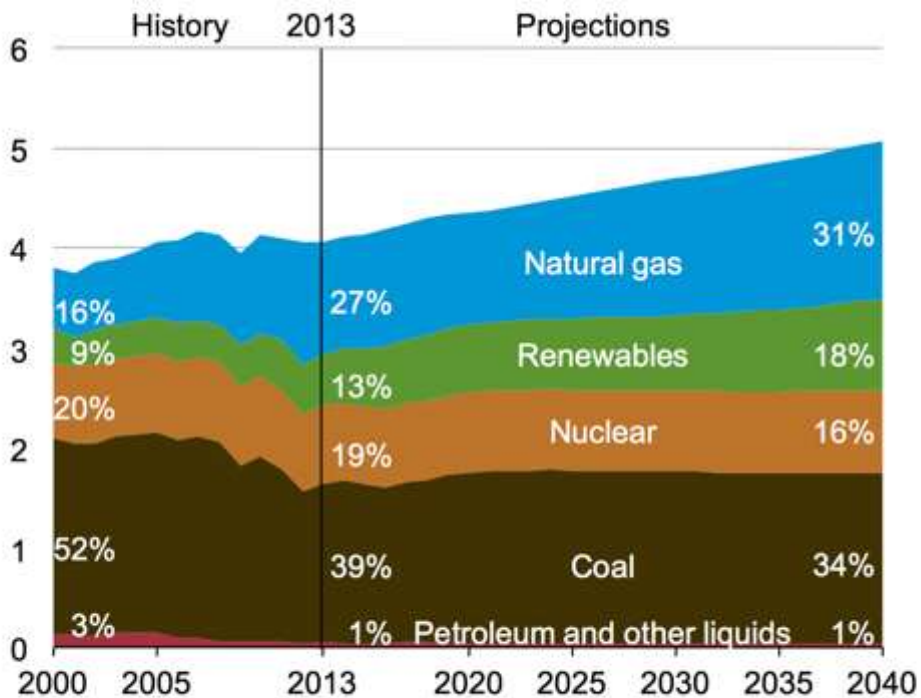
- **Use a sufficient quantity of effective SCM(s)**
  - **fly ash, silica fume, calcined clay, shale, and ground-granulated blast furnace slag**
  - **Class F ash**
- Use of lithium-based compounds
  - Ex) Lithium nitrate ($LiNO_3$) solution
  - a molar ratio of [Li]/[Na+K] = 0.74

ASTM for ASR

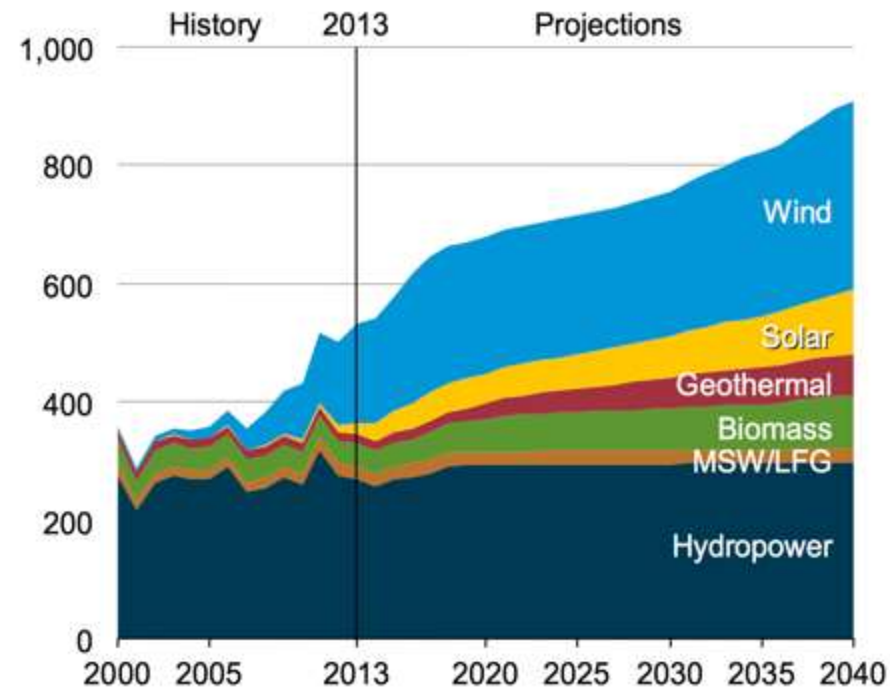
- ASTM C1293 and C1260
  - Recommended for identifying reactive aggregates
    - C1293: Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction
      - Acceptance criteria: 0.04% expansion at **two years**
    - C1260: Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)
- ASTM C1293 and C1567
  - Recommended for evaluating the efficacy of pozzolans and slag for controlling expansion due to ASR
    - C1567: Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)
      - Acceptance criteria: 0.10% expansion at 14 days

Energy generation projection

- Public perception of coal-fueled power
- Environmental regulations
- Cheaper natural gas, greener alternatives



Electricity generation by fuel
in 2000-2040 (trillion kilowatthours)

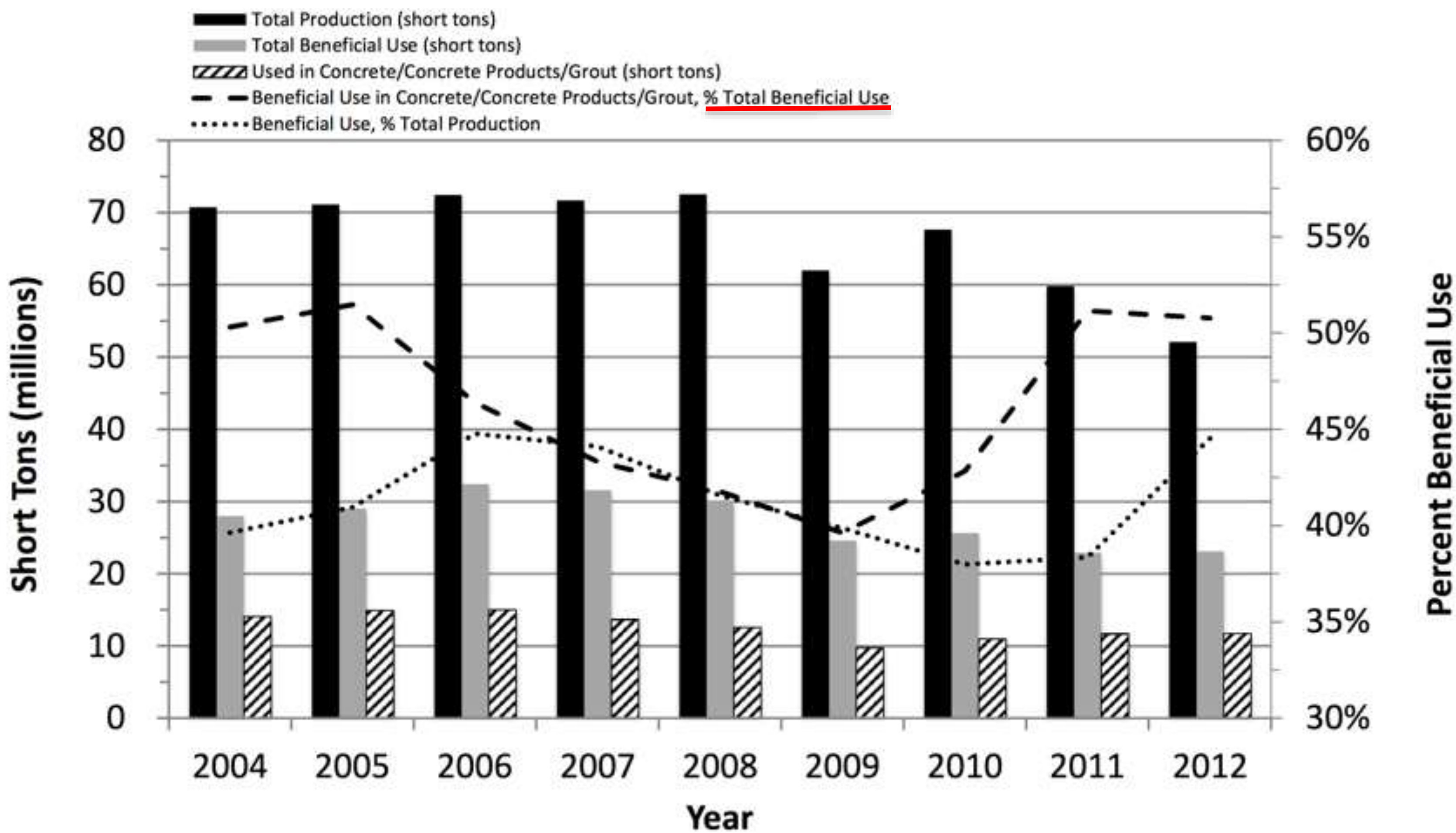


Renewable electricity generation by fuel type
in 2000-2040 (billion kilowatthours)

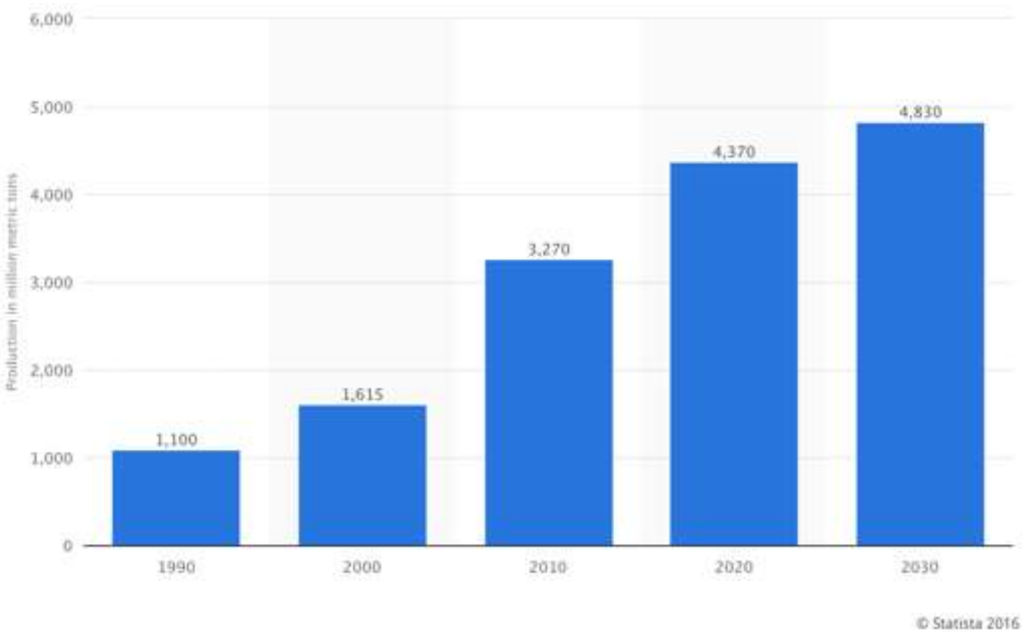
Fly ash production / utilization

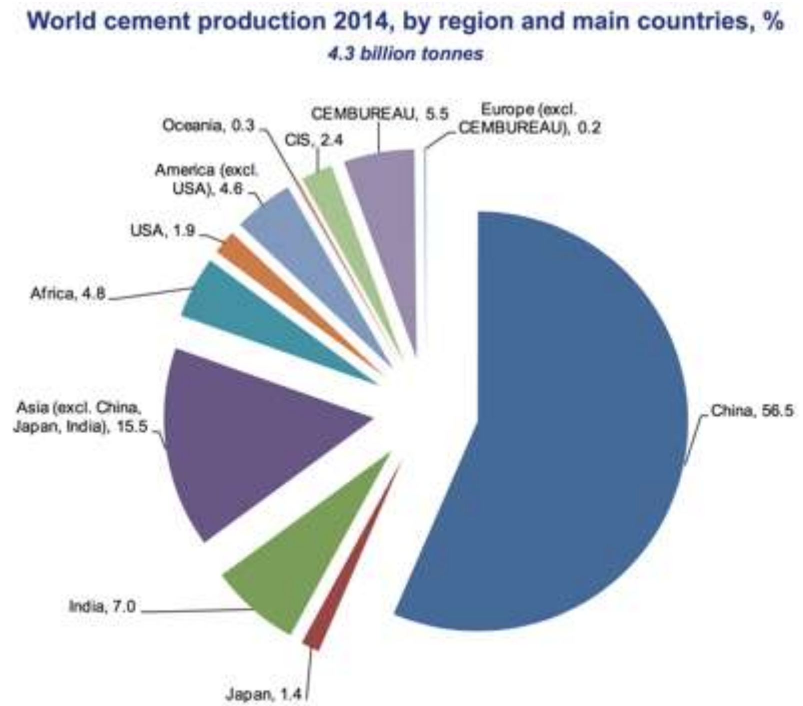
american coal ash association

Fly ash production / utilization in cement & concrete



Cement production





- What can replace fly ash as our go-to tool to mitigate ASR? Or just replace cement?
  - Slag Cement
  - Natural Pozzolans
    - Calcined Clay or Shale, Diatomaceous Earth, Volcanic Materials such as Dacite, Rhyolite
  - Ternary blends of SCMs
    - Cement + fly ash + ???
  - Recovered fly ash from disposal sites
  - Lower quality fly ash
    - Off-spec fly ash

Off-spec fly ash

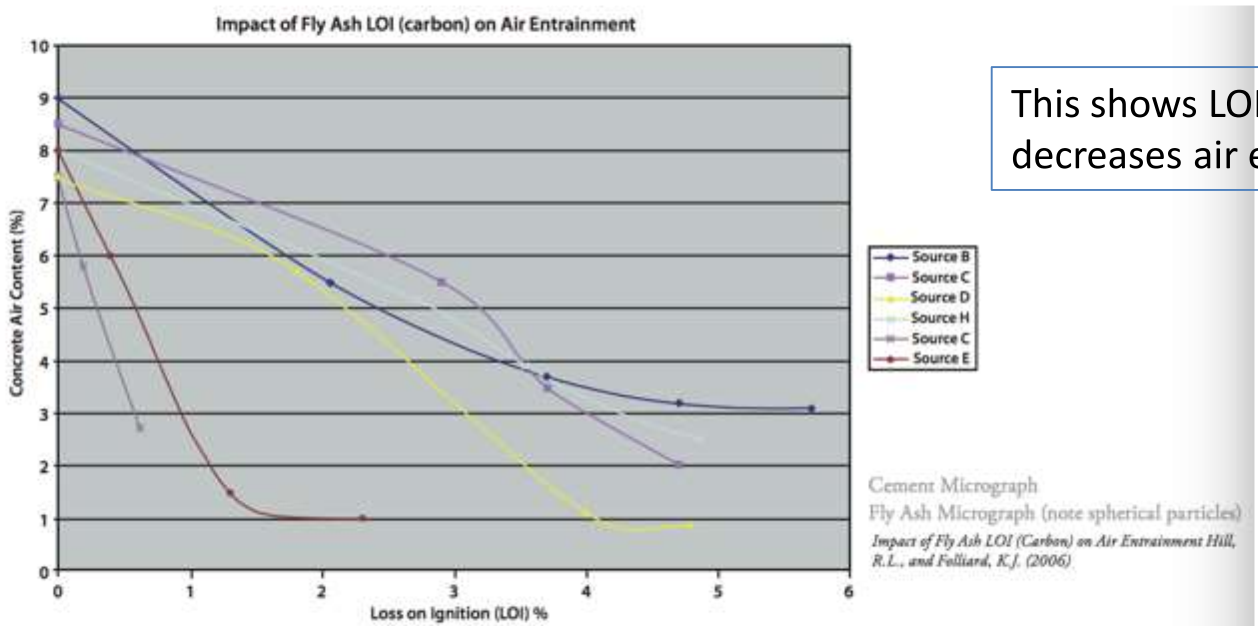
- High-carbon (LOI) fly ash
  - **High carbon content** often eliminates it from being used, because the carbon in fly ash absorbs air-entraining admixture in freshly-mixed concrete, making it very difficult to control entrained air.
  - Concrete generally needs an air-entrainment of 6%
    - **Against freeze & thaw damage**

Microscopic air pockets that relieve internal pressure on the concrete by providing tiny chambers for water to expand into when it freezes

Diameter: 0.0008 to 0.02 inch
(0.02 to 0.5 mm)

cement.org

- Prescriptive limits on fly ash LOI
  - C618: <6%
    - To ensure air entrainment in dense-concrete (not in pervious concrete)
  - Common limitations on LOI of fly ash less than 2 to 4%
    - How many commercially available fly ashes can meet this?
    - “Polished” fly ash?



This shows LOI lower than 2% decreases air entrainment.

PR off-spec fly ash (non-compliant fly ash)

	Oxide content (wt. %)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5
FA	30.84	9.93	5.01	39.61	0.35	11.43	0.9	1.01	0.45	0.11

- $SiO_2 + Al_2O_3 + Fe_2O_3 = 45.78\%$
- $SO_3 = 11.43\%$
- LOI = 7.63%

TABLE 1 Chemical Requirements

	Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min, %	70.0	70.0	50.0
Sulfur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max, %	3.0	3.0	3.0
Loss on ignition, max, %	10.0	6.0[A]	6.0

[A]The use of Class F pozzolan containing up to 12.0 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

PR off-spec fly ash (non-compliant fly ash)

Properties	Portland cement	Fly ash
Mineralogical composition (wt.%)		
SiO_2	27.14	30.84
Al_2O_3	6.68	9.93
Fe_2O_3	3.71	5.01
CaO	55.47	39.61
MgO	1.62	0.35
K_2O	0.48	1.01
Na_2O	0.59	0.90
SO_3	3.48	11.43
TiO_2	0.32	0.45
P_2O_5	0.11	0.11
Lime Saturation Factor (LSF)[a]	0.64	n.a.[e]
Silica Ratio (SR)[b]	2.61	n.a.
Alumina to Iron Ratio (AF)[c]	1.80	n.a.
Loss-on-Ignition (% wt.)	5.52	7.62
Blaine (m^2/kg)	554	441
Fineness (% wt.)[d]	92.6	73.7
Specific gravity	2.86	2.55

[a] $LSF = CaO / (2.8 \cdot SiO_2 + 1.2 \cdot Al_2O_3 + 0.65 \cdot Fe_2O_3)$.

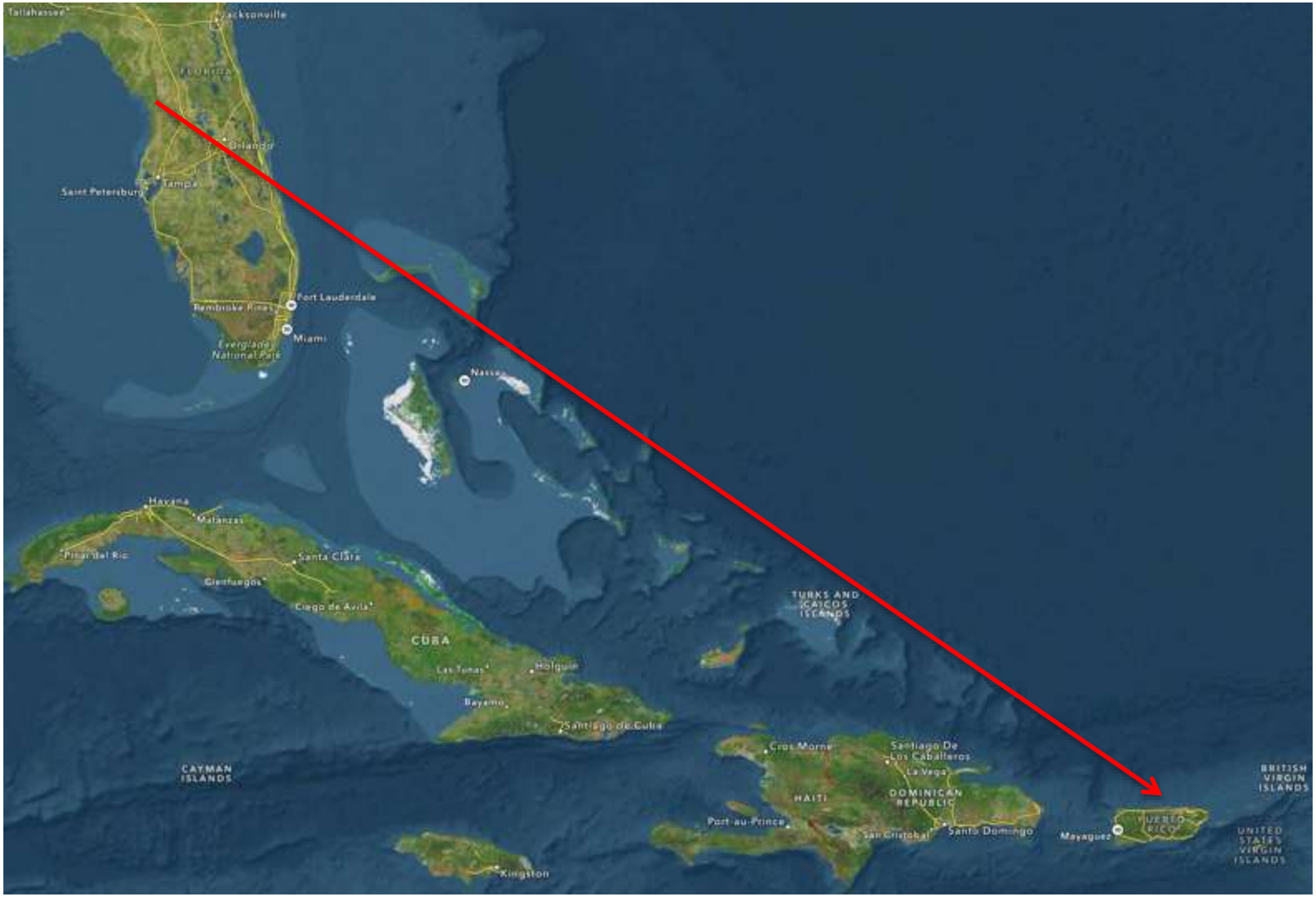
[b] $SR = SiO_2 / (Al_2O_3 + Fe_2O_3)$.

[c] $AF = Al_2O_3 / Fe_2O_3$.

[d] Wet sieve percentage passing the No. 325 (45 μm) sieve (ASTM C430).

[e] n.a.: not applicable.

Fly ash import



Imported fly ash

Chemical Analysis**	Results	Specification (Class F) ASTM C618-08	Specification (Class F) AASHTO M295-07
Silicon Dioxide	**46.89**	----	----
Aluminum Oxide	**19.03**	----	----
Iron Oxide	**18.51**	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide	**84.43**	70 % min.	70 % min.
Calcium Oxide	**6.78**	----	----
Sulfur Trioxide	**2.12**	5 % max.	5 % max.
Loss on Ignition	**1.54**	6 % max.	5 % max.
Moisture Content	**0.23**	3 % max.	3 % max.
Available Alkalies as Na_2O	**0.86**	----	1.5 % max.*
Sodium Oxide	**0.33**	----	----
Potassium Oxide	**0.80**	----	----
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	**14.7%**	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 5090; Test Average, psi: 3820	**75%**	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6170; Test Average, psi: 4920	**80%**	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242; Test, mls: 233	**96%**	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion	**-0.01%**	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	**2.40**	----	----

“Engineering isn’t about perfect solutions; it’s about doing the best you can with limited resources.”

- Prof. Randy Pausch, The Last Lecture -

- Use of recycled materials
  - LEED Credit MR-C4.1 and MR-C4.2
  - Fly ash as a supplementary cementitious material (SCM)
- Use of regional materials
  - LEED Credit MR-C5.1 and MR-C5.2
  - To reduce the environmental impacts resulting from transportation
  - To support the local economy

Questions / comments to myself

- All that glitters is not gold (Shakespeare)
- God has a purpose for everything

- Are you doing your best you can with what you have?
- Are you willing to engineer to make things work?

- Research, Development & Innovation with PR "off-spec" fly ash
  - Non-structural application
  - Encapsulation
  - Environmental engineering
  - Green infrastructure
  - LID
  - LEED credits
  - Sustainability

Pervious concrete!

No pain, no gain

Peer-reviewed journal articles

1. Soto-Pérez L., Hwang S. (2016) “Mix design and pollution control potential of pervious concrete with non-compliant waste fly ash”, Journal of Environmental Management, in press, Mar 2016.
2. Soto-Pérez L., Lopez V., Hwang S. (2015) “Response Surface Methodology to optimize the cement paste mix design: Time-dependent contribution of fly ash and nano-iron oxide as admixtures”, Materials & Design, 86: 22-29.
3. Jo M., Soto L., Arocho M., St John J., Hwang S. (2015) “Optimum mix design of fly ash geopolymer paste and its use in pervious concrete for removal of fecal coliforms and phosphorus in water”, Construction & Building Materials, 93: 1097-1104.
4. Vázquez-Rivera N., Soto-Pérez L., St John J., Molina-Bas O., Hwang S. (2015) “Optimization of pervious concrete containing fly ash and iron oxide nanoparticles and its application for phosphorus removal”, Construction & Building Materials, 93: 22-28.

Oral presentations

1. Masters A., Hwang S. “Stormwater BMP: Pervious concrete pavement and bamboo biofilter.” Junior Technical Meeting (JTM) and the Puerto Rico Interdisciplinary Meeting (PRISM), Ponce, March 5, 2016.
2. Hwang S. “Chemical Durability of Pervious Fly Ash Concrete under Acidic Environments.” Pacifichem 2015, Honolulu, HI, Dec 15-20, 2015.
3. López-Carrasquillo V., Soto-Pérez L., Jo M., St John J., Arocho M., Hwang S. “Comparative quality of water infiltrating through pervious concrete pavements.” AWRA Annual Water Resources Conference, Denver, CO, Nov 16-19, 2015.
4. Hwang S., Soto L. “Pervious concrete for agricultural runoff controls.” StormCon 2015, Austin, TX, Aug 2-6, 2015.
5. Jo M., Lopez V., Soto L., Hwang S. “Delayed Role of Fly ash and Alkali Activation in the Development of Compressive Strength of Geopolymer Paste cured at Ambient Temperature.” World Engineers Summit, Singapore, Jul 21-24, 2015.
6. Jo M., Soto-Pérez L., Hwang S. “Optimization of fly ash geopolymer for early age strength development.” 10th Asia Pacific Conference on Sustainable Energy & Environmental Technologies.” Seoul, Korea, Jun 2-5, 2015.
7. Soto-Pérez L., Vázquez N., Molina O., Jo M., Hwang S. “Effect of Iron-Oxide Nanoparticles on the Durability of Fly Ash Cement Paste.” 5th International Symposium on Nanotechnology in Construction, Chicago, IL, May 24-26, 2015.
8. Soto L., St John J., Suarez C., Jo M., Smith H., Hwang S. “Inactivation of fecal coliforms during rain harvesting with engineered pervious layer.” 23rd Caribbean Water & Wastewater Association Annual Conference, Paradise Island, The Bahamas, Oct 6-9, 2014.
9. Vazquez N., Soto L., Santiago R., Hwang S. “Optimization by Response Surface Methodology of pervious concrete containing fly ash and engineered iron oxide nanoparticles.” International Concrete Sustainability Conference, Boston, MA, May 12-15, 2014.
10. Soto L., Vazquez N., Santiago R., Hwang S. “Characterization of cement paste containing coal fly ash and engineered iron-oxide nanoparticles.” 247th ACS National Meeting, Dallas, TX, Mar 16-20, 2014.

Poster presentations

1. López V., Soto-Pérez L., St John J., Jo M., Arocho M., Hwang S. "Water Quality improvement with pervious pavement.” Caribbean Water & Wastewater Association Annual Conference, Miami, FL, Aug 24-28, 2015.
2. Arocho M., St John J., Soto-Pérez L., Jo M., López V., Hwang S. “Strength, workability and cost of fly ash geopolymer paste. Caribbean Water & Wastewater Association Annual Conference, Miami, FL, Aug 24-28, 2015.
3. Hwang S., Smith H. “Engineered pervious layer for pathogen removal during rainwater harvesting.” ACS Northeast Regional Meeting, Ithaca, NY, Jun 10-13, 2015.
4. St John J., Soto L., Hwang S. “Fecal coliform removal by fly-ash-aided pervious concrete.” XIX Sigma Xi, University of Puerto Rico, PR, April 3, 2014.
5. Torres, I., Santiago R., Vazquez N., Hwang S. “Bioclogging and Fenton regeneration of pervious concrete pavements.” XIX Sigma Xi, University of Puerto Rico, PR, April 3, 2014.
6. Soto L., Rivera K., Conde M., Hwang S. “Structural and hydrological properties of pervious fly ash concrete.” Puerto Rico Water & Environmental Association Annual Convention, San Juan, PR, May 22-24, 2013.
7. Soto L., Rivera K., Conde M., Hwang S. “Structural properties of fly ash-aided pervious composite.” XVIII Sigma Xi, University of Puerto Rico, PR, April 25, 2013.

HEDGE

Hwang Eco-friendly Development for Green Environment

Chapter 3

Pervious Concrete Mix Design & Testing

- The rate and extent of cement hydration are governed mainly by the length of curing time, the type of cementitious materials, the presence of admixtures and mixture proportions.

- Designed mixes
  - Any efficient engineering ways?
    - Perhaps, a statistical optimization of mix design

Response Surface Methodology (RSM)

- Example of **4-factor, 2-level, face-centered, central composite design with RSM** for cement paste
  - Independent variables
    - Percentages of water-to-binder (W/B, 35–37, X1), fly ash-to-binder (FA/B, 20–40, X2) and nanoFe_3O_4-to-binder (NI/B, 0.5–3.0, X3)
  - Dependent response variables
    - Spread percentage (Y1) of the fresh pastes and compressive strength (Y2) of the hardened pastes
  - Binder: the total amount of Portland cement and FA
  - RSM was utilized to optimize the mix design in order to obtain a time-dependent maximum Y2 cured for 3, 28 and 90 days and achieve the desired Y1 simultaneously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Response Surface Methodology to optimize the cement paste mix design: Time-dependent contribution of fly ash and nano-iron oxide as admixtures

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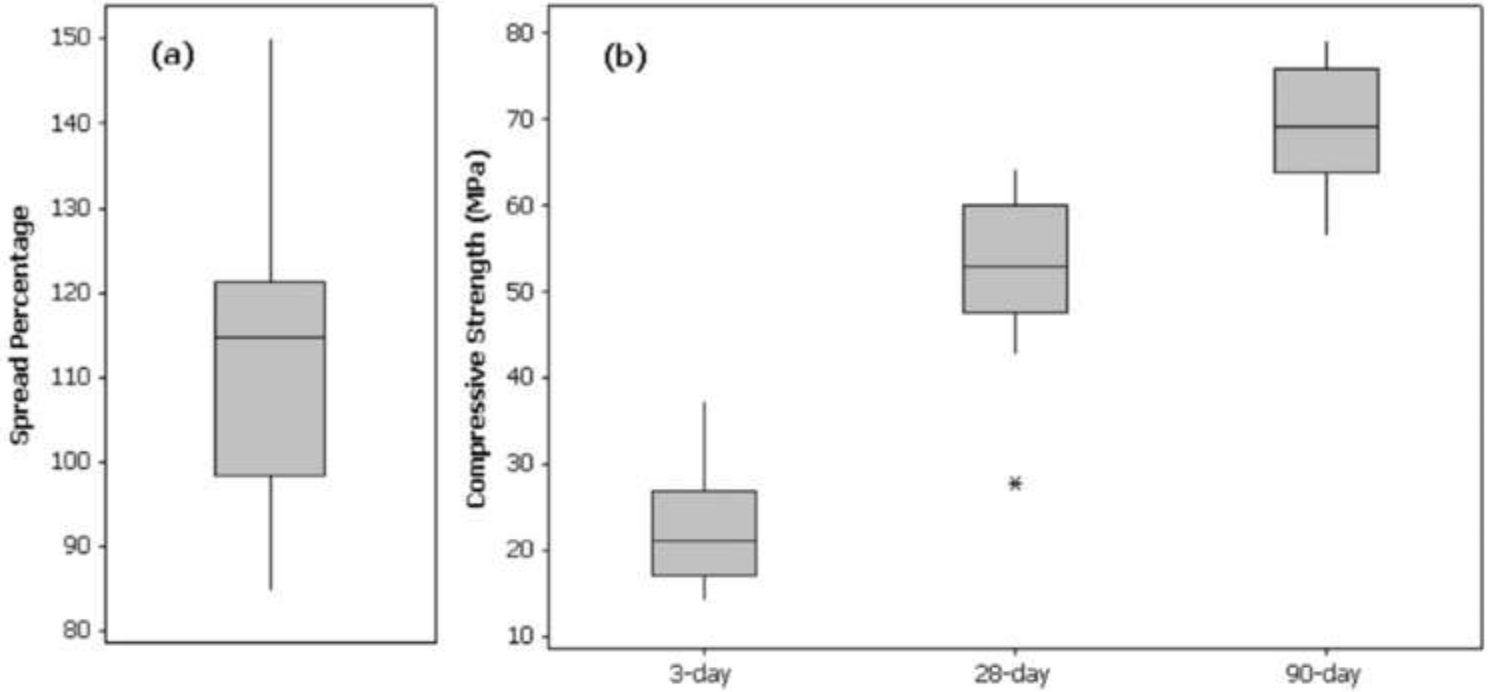
Matrix of 2^3 face centered central composite design and the measured dependent variables.

Run	Point[a]	Mix design of independent variables[b]						Measured dependent variables[c]			
		Coded			Uncoded (% wt.)			Y_1 (%)	$Y_{2,3d}$ (MPa)	$Y_{2,28d}$ (MPa)	$Y_{2,90d}$ (MPa)
		X_1	X_2	X_3	X_1	X_2	X_3				
1	F	−1	−1	−1	35	20	0.5	89.5	20.6 ± 0.5	59.6 ± 1.4	78.8 ± 1.6
2	F	1	−1	−1	37	20	0.5	110.0	21.1 ± 1.0	47.5 ± 6.3	69.2 ± 2.4
3	F	−1	1	−1	35	40	0.5	84.8	17.8 ± 0.3	49.3 ± 14.8	64.6 ± 3.5
4	F	1	1	−1	37	40	0.5	97.3	14.2 ± 0.9	46.6 ± 6.6	69.0 ± 3.7
5	F	−1	−1	1	35	20	3.0	137.3	18.9 ± 0.8	54.6 ± 0.8	72.1 ± 2.9
6	F	1	−1	1	37	20	3.0	135.5	22.8 ± 0.3	27.9 ± 2.2	56.5 ± 3.2
7	F	−1	1	1	35	40	3.0	106.8	19.5 ± 2.1	55.0 ± 1.7	64.8 ± 21.4
8	F	1	1	1	37	40	3.0	115.8	16.3 ± 2.3	47.8 ± 7.9	60.1 ± 4.7
9	A	−1	0	0	35	30	1.75	97.0	26.4 ± 2.4	59.5 ± 9.0	72.6 ± 5.2
10	A	1	0	0	37	30	1.75	120.3	27.1 ± 1.1	51.1 ± 11.8	63.7 ± 7.7
11	A	0	−1	0	36	20	1.75	126.8	37.4 ± 1.9	46.1 ± 7.9	57.8 ± 6.5
12	A	0	1	0	36	40	1.75	101.8	21.3 ± 1.1	49.3 ± 8.1	64.1 ± 2.0
13	A	0	0	−1	36	30	0.5	97.3	26.8 ± 1.3	60.3 ± 14.9	79.1 ± 5.8
14	A	0	0	1	36	30	3.0	121.5	31.2 ± 0.7	52.3 ± 23.9	79.3 ± 2.6
15	C	0	0	0	36	30	1.75	113.5	17.0 ± 1.0	60.8 ± 2.5	60.6 ± 16.2
16	C	0	0	0	36	30	1.75	115.8	16.5 ± 0.3	62.4 ± 5.8	75.5 ± 2.7
17	C	0	0	0	36	30	1.75	150.0	16.7 ± 1.1	60.5 ± 7.0	76.1 ± 3.7
18	C	0	0	0	36	30	1.75	119.0	26.7 ± 0.9	64.3 ± 2.8	76.8 ± 3.2
19	C	0	0	0	36	30	1.75	114.0	27.9 ± 0.6	42.8 ± 29.7	72.2 ± 3.9
20	C	0	0	0	36	30	1.75	115.3	27.8 ± 0.5	53.4 ± 14.6	74.7 ± 5.9

[a] F: factorial point, A: axial point, C: center point.

[b] X_1: W/B, X_2: FA/B, X_3: NI/B.

[c] Y_1: spread % (single measurement), Y_2: 3-, 28-, and 90-day compressive strengths (mean ± standard deviations, $n = 3$).



(a)
Spread Percentage
150
140
130
120
110
100
90
80
(b)
Compressive Strength (MPa)
80
70
60
50
40
30
20
10
3-day
28-day
90-day

Prediction models

$$Y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i<j}^{k} \beta_{ii} x_i x_j + \varepsilon$$

$$Y_1 = 122.1 - 0.928X_2 + 11.04X_3$$

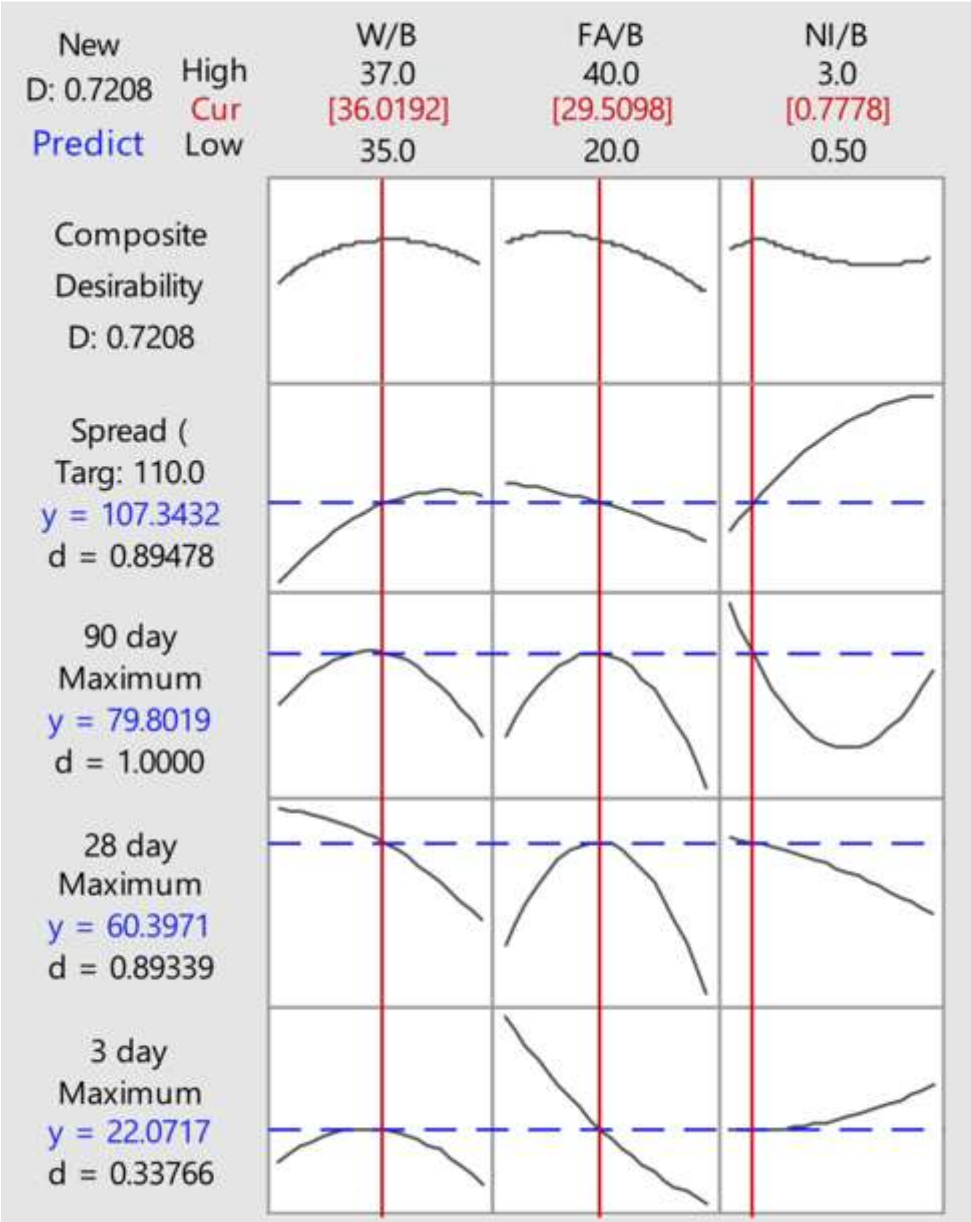
$$Y_{2,3d} = 31.58 - 0.316X_2$$

$$Y_{2,28d} = 164.8 - 5.71X_1 + 6.48X_2 - 0.1059X_2^2$$

$$Y_{2,90d} = -8.3 + 6.60X_2 - 18.10X_3 - 0.1119X_2^2 + 4.530_3^2.$$

Optimization criteria for each dependent variable.

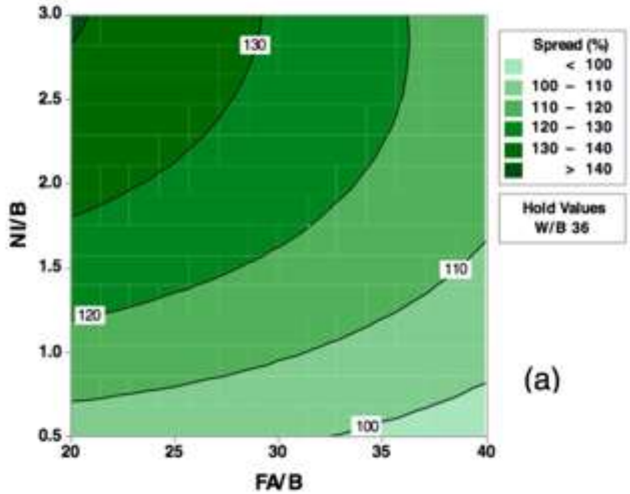
Dependent variable	Measured Y's		Optimization	
	Lower	Upper	Goal	Target
Y_1: spread (%)	84.75	150	Target	110
Y_2: compressive strength (MPa)				
3 day	14.24	37.44	Maximum	37.44
28 day	27.93	64.27	Maximum	64.27
90 day	56.48	79.30	Maximum	79.30

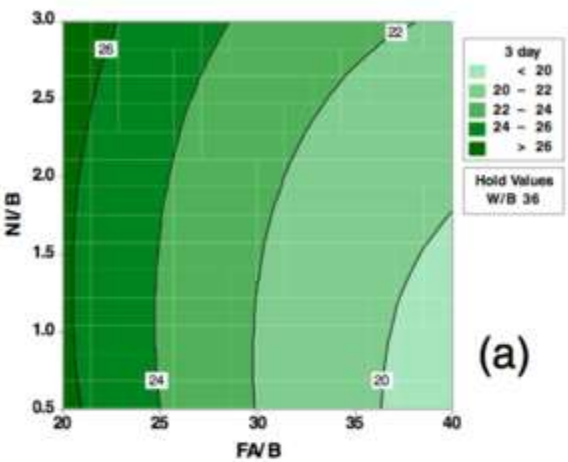


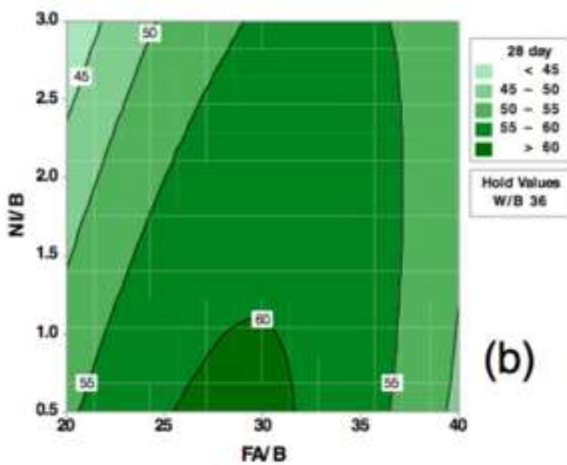
Minitab

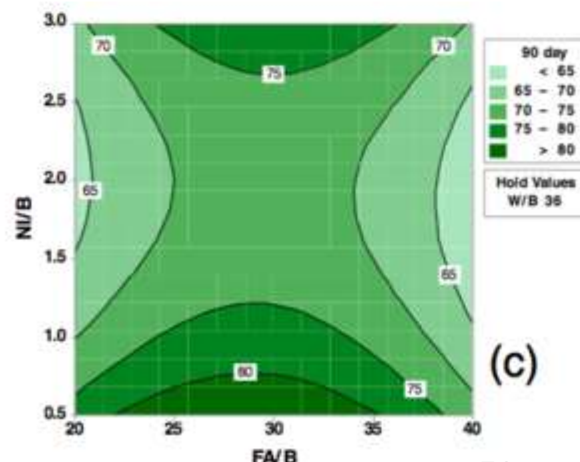
Design-Expert

RSM contour plots









RSM validation

Validation results of the optimum independent variable settings for the dependent variables.

Optimum mix (wt.%)			Y_1: spread (%)[a]			Y_2: compressive strength (MPa)[a]								
X_1: W/B	X_2: FA/B	X_3: NI/B	Pred.	Meas.	PE[b]	3-day			28-day			90-day		
						Pred.	Meas.	PE	Pred.	Meas.	PE	Pred.	Meas.	PE
36.0	29.5	0.78	107.3 (95.8–118.9)[c]	102.5 (±2.3)[d]	4.7	22.1 (17.1–27.0)[c]	20.7 (±6.5)[d]	6.8	60.4 (54.3–66.5)[c]	60.7 (±3.3)[d]	0.5	79.8 (72.9–86.7)[c]	68.1 (±0.6)[d]	17.3

[a] Data are the average of triplicate samples.
[b] Absolute relative percent error = $\left|1-\frac{\text{Value}_{\text{predicted}}}{\text{Value}_{\text{measured}}}\right| \times 100\%$.
[c] 95% confidence interval.
[d] Standard deviations ($n = 3$).

What? Come on!

- Any simple ways?
  - 1:4 mix
    - 1 part cement and 4 part coarse aggregate

Typical ranges of material proportions in pervious concrete (NRMCA, PCA)	
	Proportions, lb/yd^3 (kg/m^3)
Cementitious materials	450 to 700 (270 to 420)
Aggregate	2000 to 2700 (1200 to 1600)
w/cm, by mass	0.27 to 0.34
Water	16 to 25 gal (80 to 150 L)
Aggregate : cement, by mass	4 to 4.5 : 1
Fine : coarse aggregate, by mass	0 to 1 : 1

NRMCA mix design

1. Determine the dry-rodded unit weight (density) of the aggregate and calculate the void content (V.C.) of the aggregate

2. Estimate the % of paste volume (Vol_{paste})

Vol_{paste} (%) = $V.C._{agg}$ (%) + compaction index (%) – $V.C._{PC}$

Compaction index: 1 to 10%, typ. 5%

Vol_{paste} (%): typ. 17 to 25%

$V.C._{pc}$ (%): typically targeting 20%

3. Vol_{paste} (ft^3) = (Vol_{paste} (%)/100) x 27

27? → **designed to yield PC for 1 yd^3 (1 yd^3 = 27 ft^3)**

4. Select w/c ratio (0.25 to 0.36)

5. Cement volume, $Vol_{cement}\ (ft^3) = \dfrac{Vol_{paste}(ft^3)}{[1+({}^{w}/_{c} \times s.g._{cement})]}$

s.g.: specific gravity of cement (typ. 3.15)

6. Volume of water

$$Vol_{water}\ (ft^3) = Vol_{paste}\ (ft^3) - Vol_{cement}\ (ft^3)$$

7. Volume of saturated-surface-dry (SSD) aggregate

$$Vol_{agg}\ (ft^3) = 27 - (Vol_{paste} + V.C._{pc}/100)$$

8. Express each ingredients in lb/yd^3

Cement (lb/yd^3) $= Vol_{cement} \times s.g._{cement} \times 62.4$

Water (lb/yd^3) $= Vol_{water} \times 62.4$

SSD coarse aggregate (lb/yd^3) $= Vol_{agg} \times s.g._{agg} \times 62.4$

Water density = 62.4 lb/ft^3

STEPS		VALUE		REMARKS			
1	Aggregate density	125	lb/ft3	need to be measured			
2	Aggregate specific gravity	2.00		water density		62.4	lb/ft3
3	Aggregate void content	38	%	need to be measured			
4	compaction index	5	%	Select b/w 1% to 10%			
5	design PC voild content	20	%	Unless otherwise specified			
6	Paste volume	23	%				
7	Paste volume	6.21	ft3	Produce 1 yd3 of fresh PC mixture (1 yd3 = 27 ft3)			
8	w/c ratio	0.3		Select b/w 0.25 and 0.36			
9	Cement specific gravity	3.15		This can be varied dependsing on the type of cement.			
10	Cement volume	3.2	ft3				
11	Water volume	3.0	ft3	=	22.6	gallons	(1 ft3 = 7.48052 gallons)
12	SSD aggregate volume	20.59	ft3				
13	Cement	627.6	lb/yd3				
	Water	188.3	lb/yd3				
	SSD coarse aggregate	2573.75	lb/yd3				
14	cement:aggregate ?	1:	4.1				
	w/c ratio ?	0.3					
15	It is better to make enough PC, so consider 10 to 15% increase on the calculated values.						

Typical ranges of material proportions in pervious concrete (NRMCA, PCA)	
	Proportions, lb/yd^3 (kg/m^3)
Cementitious materials	450 to 700 (270 to 420)
Aggregate	2000 to 2700 (1200 to 1600)
w/cm, by mass	0.27 to 0.34
Water	16 to 25 gal (80 to 150 L)
Aggregate : cement, by mass	4 to 4.5 : 1
Fine : coarse aggregate, by mass	0 to 1 : 1

Compressive strength

- ASTM C192 / C192M: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
- ASTM C39 / C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- ASTM C1231 / C1231M: Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders


1 psi = 6.895 x 10^{-3} MPa
(1 MPa = 145 psi)

Permeability

- "Modified" ASTM D2434-68: Standard Test Method for Permeability of Granular Soils (Constant Head)

$$k = \frac{V \cdot L}{A \cdot h \cdot t}$$

Durability

- Physical durability
  - ASTM C1747 / C1747M: Standard Test Method for Determining Potential Resistance to Degradation of **Pervious Concrete** by Impact and Abrasion

- Chemical durability
  - “Modified” ASTM C267: Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes

- Because of its porous nature, pervious concrete cannot be tested using standards developed for traditional concrete.

- In order to fill this need, ASTM International Committee C09 on Concrete and Concrete Aggregates has developed and is developing a series of proposed test methods specific to pervious concrete.

- Field infiltration rate
  - ASTM C1701 / C1701M: Standard Test Method for Infiltration Rate of In Place **Pervious Concrete**

- Density and Void content
  - ASTM C1688 / C1688M: Standard Test Method for Density and Void Content of Freshly Mixed **Pervious Concrete**

  - ASTM C1754 / C1754M: Standard Test Method for Density and Void Content of Hardened **Pervious Concrete**

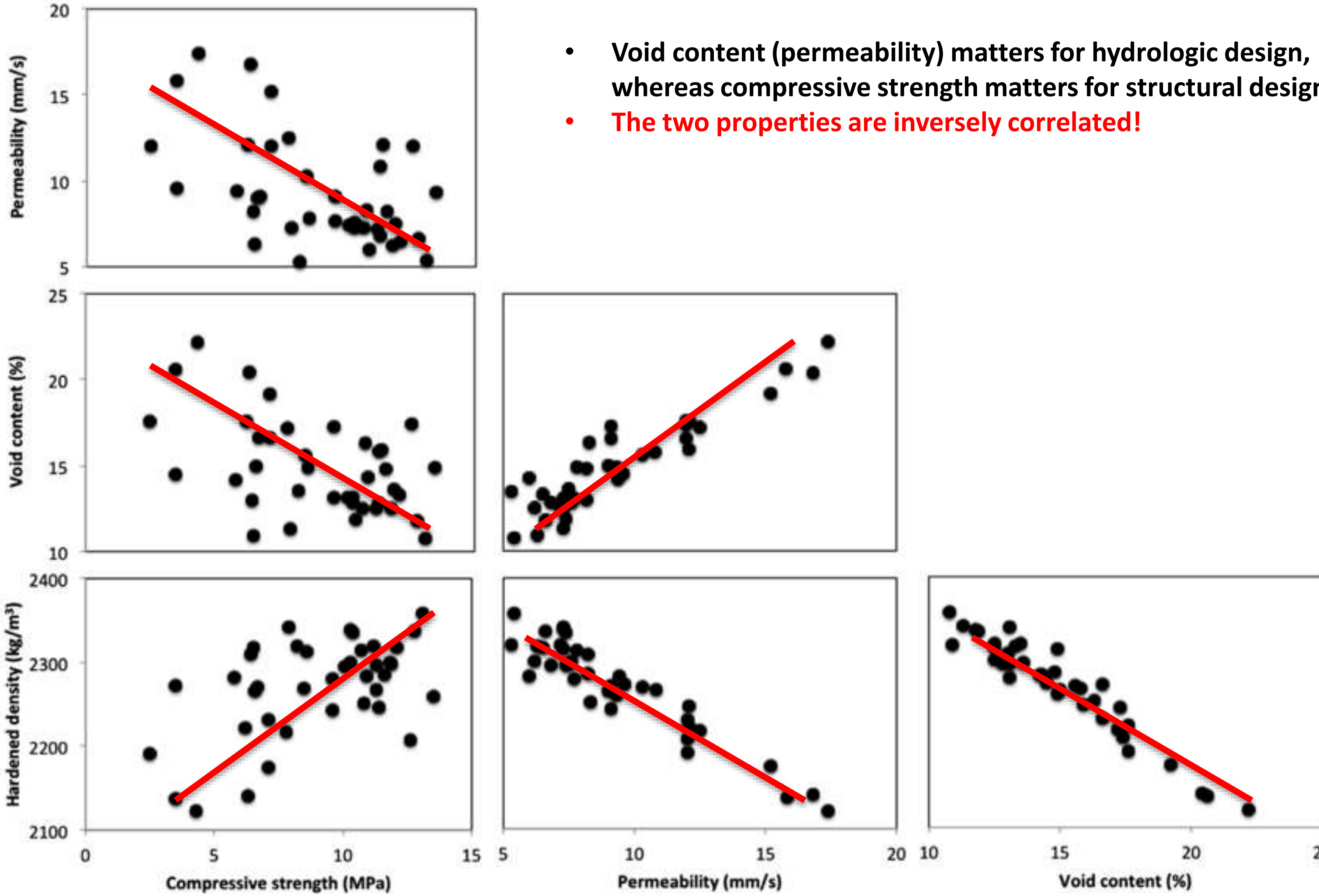
ASTM Draft: Standard Test Method for Compressive Strength of Pervious Concrete (Proposed)

- High variability of compressive strength testing of pervious concrete compared to conventional concrete.

- 4x8 cylinder mold & collar
- Standard Proctor Hammer

- Fill in 2 layers, approximately equal thickness
- 20 hammer drops per layer
- Use collar for 2nd layer

- Initial curing similar to C31
  - ASTM C31 / C31M: Standard Practice for Making and Curing Concrete Test Specimens in the Field
- Do not remove molds in fewer than 6 days
- Laboratory curing in moist room
- Allow cylinder to drain 5 minutes
- Remove surface water
- Weigh and measure
- Cap – ASTM C617 (sulfur or gypsum – no pad caps)
  - ASTM C617 / C617M: Standard Practice for Capping Cylindrical Concrete Specimens
- Test – ASTM C39
  - ASTM C39 / C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

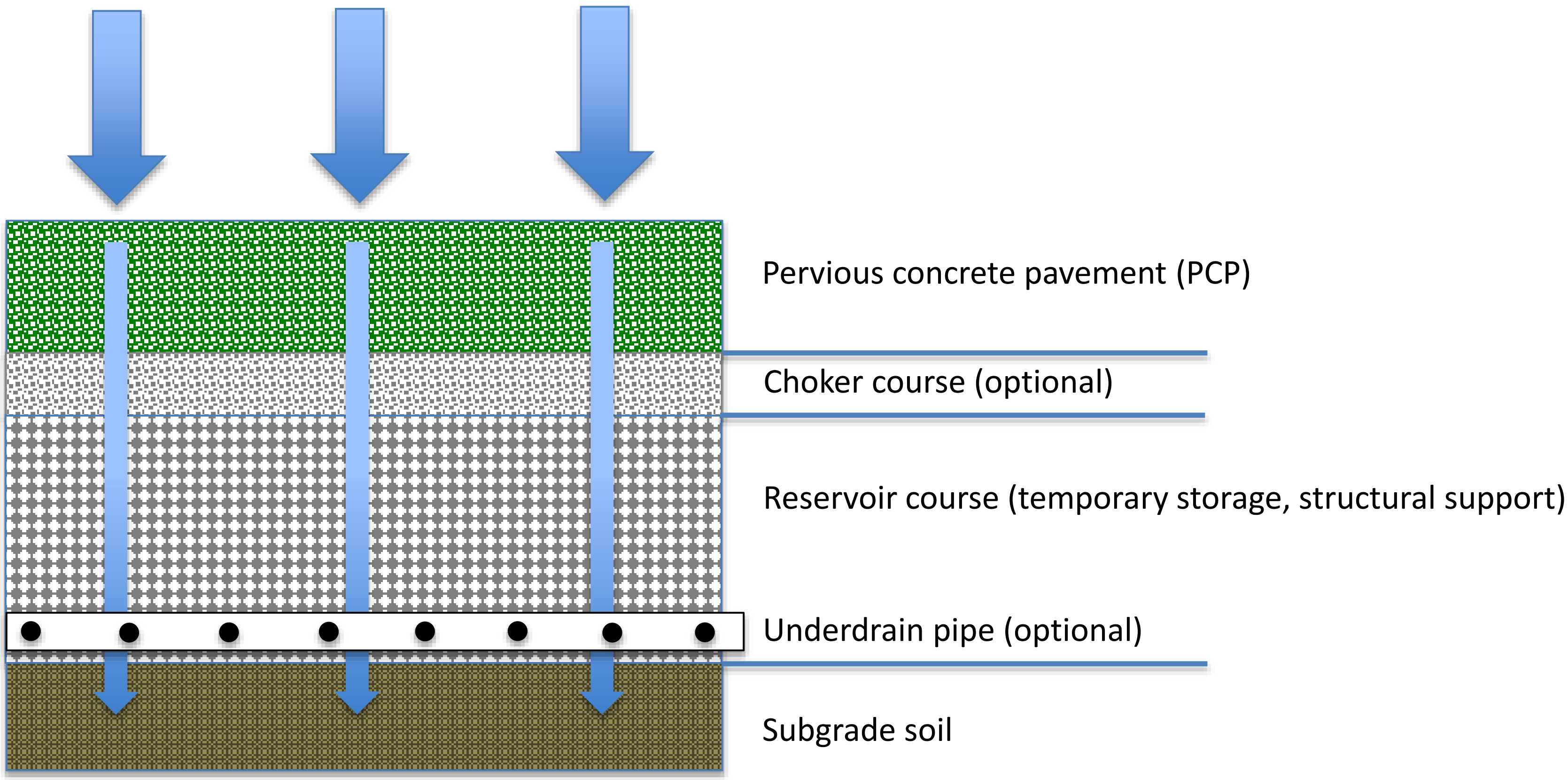


- **Void content (permeability) matters for hydrologic design, whereas compressive strength matters for structural design.**
- **The two properties are inversely correlated!**

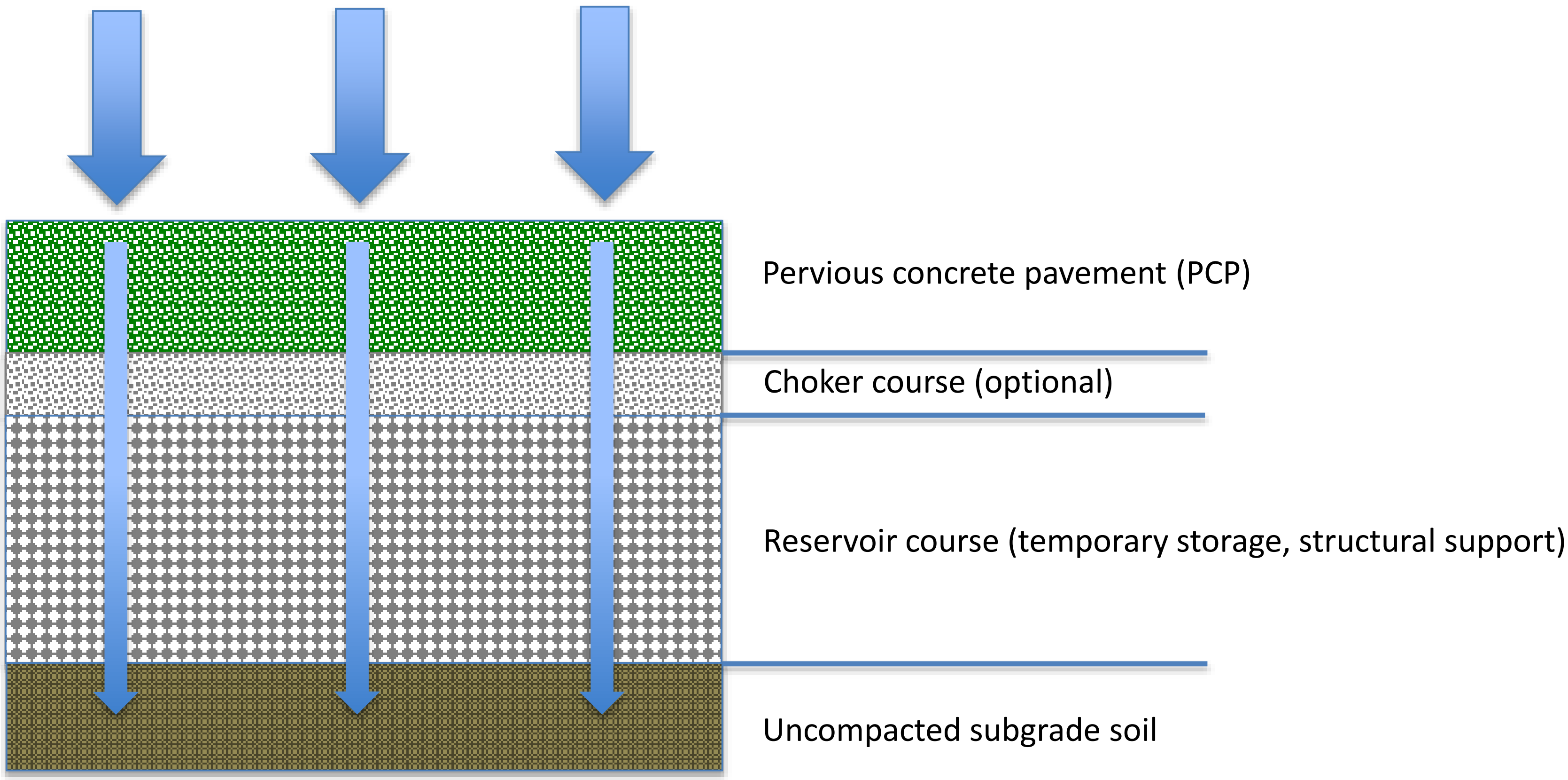
Chapter 4

Pervious Concrete Pavement: Design

Typical PCP construction

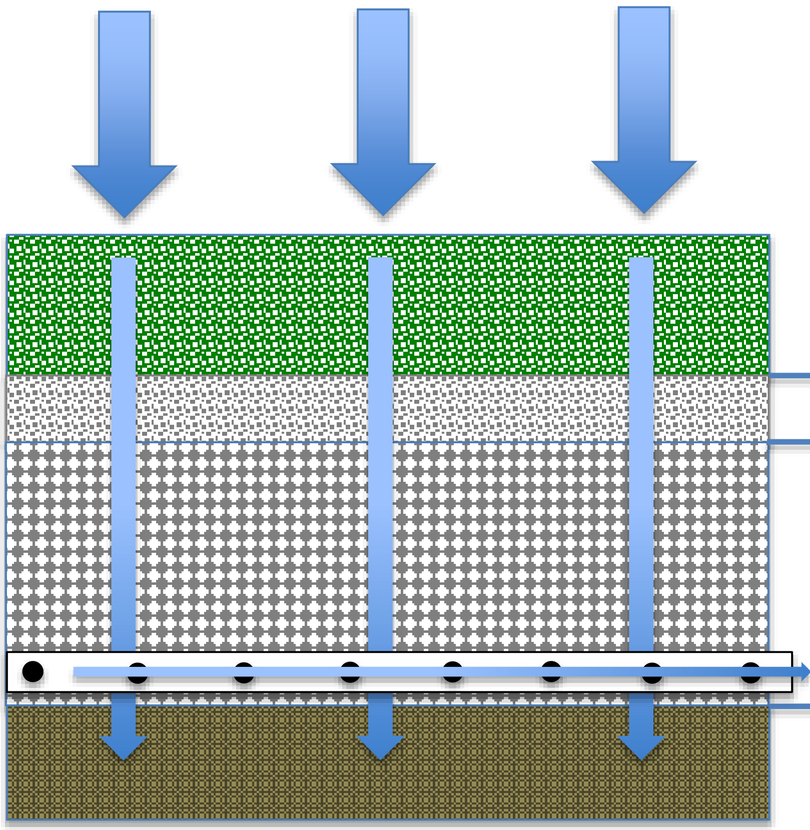


"Full-infiltration" PCP construction



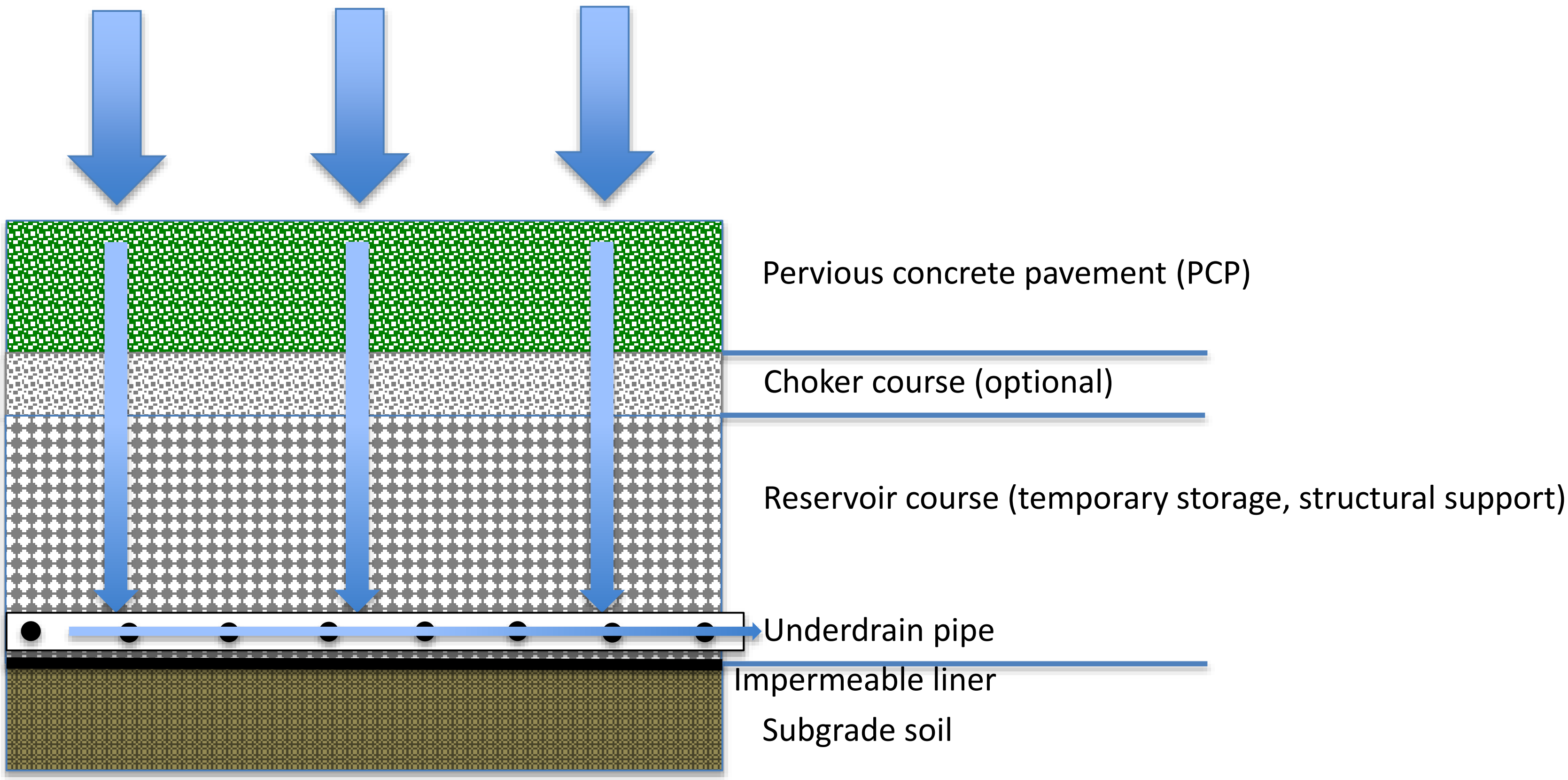
Where underlying soil is highly permeable
When ensuring quality of infiltrating water

"Partial-infiltration" PCP construction



When underlying soil is less permeable, infiltration within 48-72 hours

“No-infiltration” PCP construction



When preventing infiltration into soil
When not sure of quality of infiltrating water
Depending on the location of the underdrain pipe, volume reduction can be determined

No-infiltration design

- In close proximity to building foundation, basements, water supply wells
- Within 2’ of high GWT
- Located in karst topography
- Over expansive or unstable soils

- Geotextiles (filter fabrics)
  - Holes in size of 0.002 to 0.02 inch (0.05 to 0.5 mm)
  - 10 to 1000 in/hr (250 to 25000 mm/hr)

- Geogrids

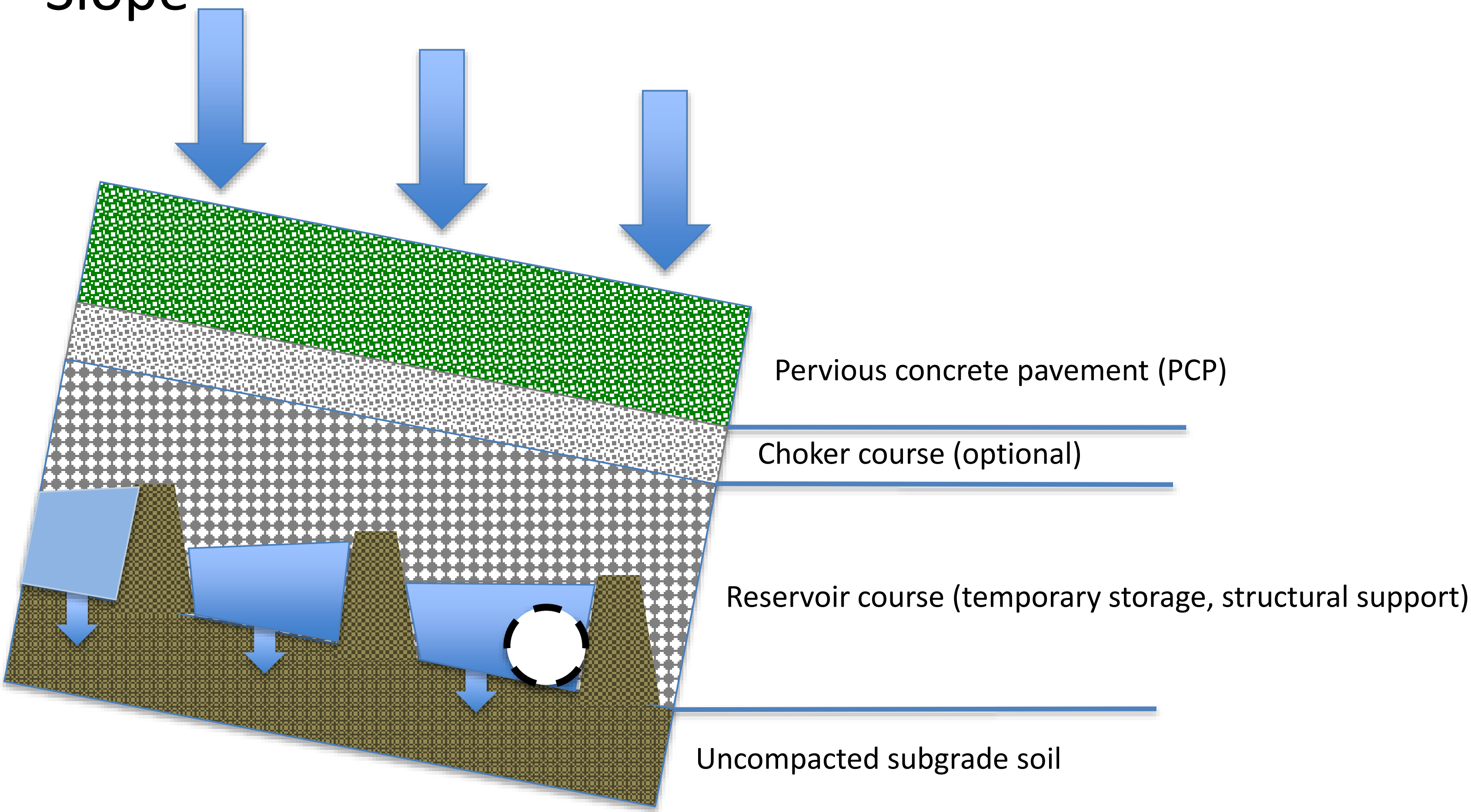
- Geomembranes (liners)
  - Impervious
  - No-infiltration design
    - Brownfield sites with contaminated soil
    - Pavement where water is harvested for use
    - Live-stock-handling facilities

Site design considerations

- Underlying soils
  - Determines which design should be
    - Ex) karst, Expandable clay, unstable soil, or low permeable soil → no-infiltration design
- Groundwater
  - Generally, a minimum 2’ separation recommended
  - Otherwise consider use of impermeable liner
- Contributing area run-on and surrounding land use
  - Only run-on free from sediment
    - Berm or curb
  - Pervious concrete surface needs to be increased by ~2 to 5 times
- Edge/perimeter design
- Other constraints
  - Utilities
  - Foundations
  - Private wells
  - Septic systems

Site design considerations

- Slope



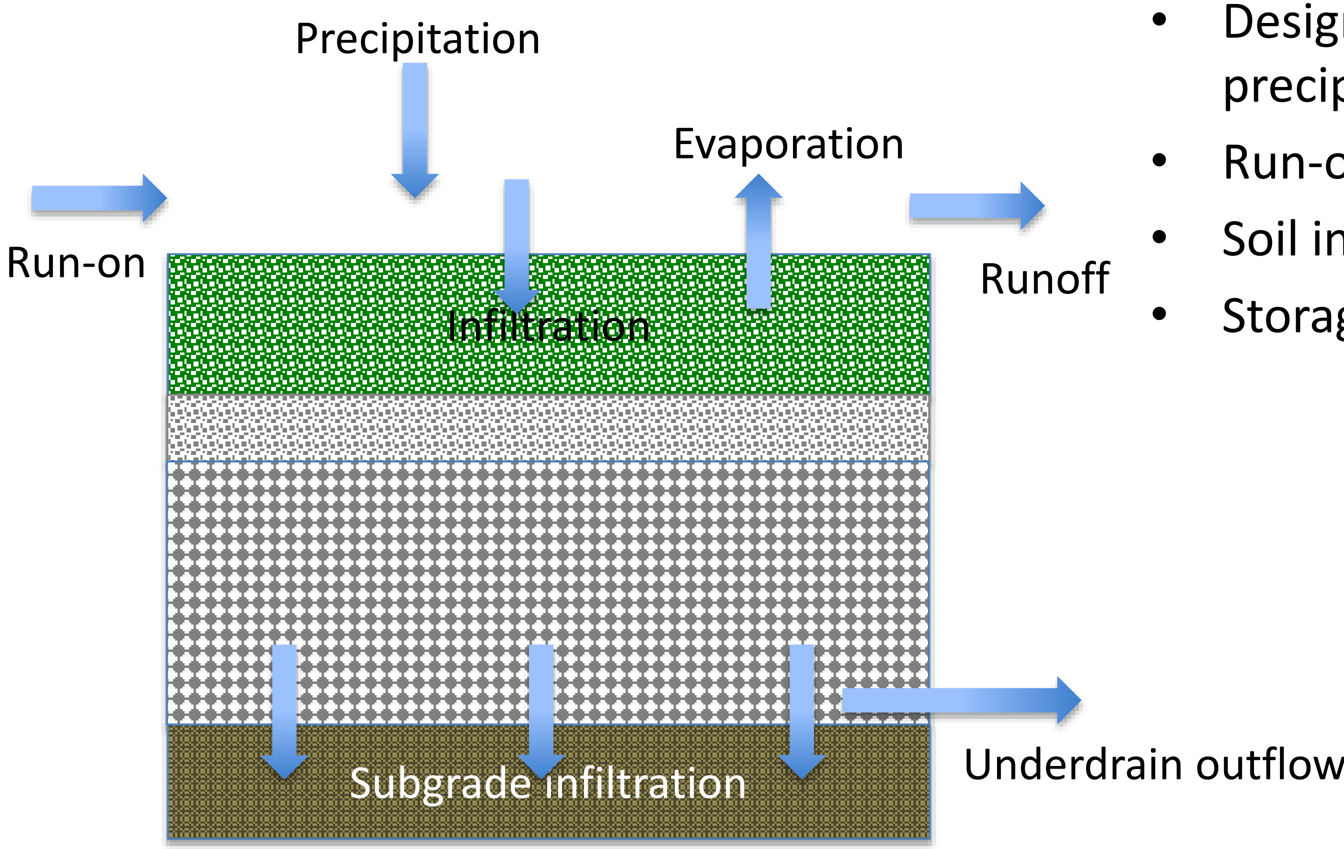
Terracing, check dams, baffles or berms

Geotechnical considerations

- Soil?
  - USCS soil classification (ASTM D2487)
  - Depth of GWT
  - Soil infiltration test (ASTM D3385)
    - ASTM D5093 is only appropriate for soils with an infiltration of 10^{-7} to 10^{-10} m/sec
    - At proposed system bottom elevation
    - A safety factor of 0.5 for design calculations to account for subgrade compaction during construction

- Consult Geotechnical Engineers

Hydrologic design considerations



- Design storm, precipitation depth
- Run-on
- Soil infiltration
- Storage capacity

- Consult Environmental / Water Resources Engineers

NOAA's National Weather Service

Hydrometeorological Design Studies Center

Precipitation Frequency Data Server (PFDS)

http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_pr.html

POINT PRECIPITATION FREQUENCY (PF) ESTIMATES

WITH 90% CONFIDENCE INTERVALS AND SUPPLEMENTARY INFORMATION

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PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.491 (0.465-0.517)	0.596 (0.562-0.626)	0.654 (0.614-0.693)	0.711 (0.665-0.759)	0.791 (0.734-0.851)	0.856 (0.790-0.927)	0.921 (0.841-1.01)	0.988 (0.895-1.09)	1.08 (0.966-1.21)	1.15 (1.02-1.31)
10-min	0.671 (0.635-0.707)	0.814 (0.768-0.855)	0.893 (0.839-0.947)	0.972 (0.908-1.04)	1.08 (1.00-1.16)	1.17 (1.08-1.27)	1.26 (1.15-1.38)	1.35 (1.22-1.49)	1.48 (1.32-1.66)	1.58 (1.40-1.79)
15-min	0.861 (0.815-0.908)	1.04 (0.986-1.10)	1.15 (1.08-1.22)	1.25 (1.17-1.33)	1.39 (1.29-1.49)	1.50 (1.39-1.63)	1.61 (1.48-1.77)	1.73 (1.57-1.92)	1.90 (1.70-2.13)	2.02 (1.79-2.29)
30-min	1.38 (1.31-1.45)	1.67 (1.58-1.76)	1.84 (1.72-1.95)	2.00 (1.87-2.13)	2.22 (2.06-2.39)	2.40 (2.22-2.60)	2.59 (2.36-2.83)	2.78 (2.51-3.07)	3.04 (2.71-3.41)	3.24 (2.87-3.67)
60-min	2.05 (1.94-2.16)	2.48 (2.34-2.61)	2.72 (2.56-2.89)	2.96 (2.77-3.16)	3.29 (3.06-3.55)	3.56 (3.29-3.86)	3.84 (3.50-4.20)	4.12 (3.73-4.55)	4.50 (4.03-5.05)	4.81 (4.25-5.45)
2-hr	2.56 (2.40-2.69)	3.11 (2.92-3.28)	3.50 (3.27-3.71)	3.85 (3.58-4.11)	4.39 (4.04-4.74)	4.81 (4.39-5.25)	5.25 (4.73-5.80)	5.70 (5.09-6.38)	6.31 (5.55-7.17)	6.78 (5.91-7.82)
3-hr	2.65 (2.50-2.83)	3.25 (3.04-3.45)	3.73 (3.47-4.00)	4.18 (3.86-4.51)	4.87 (4.42-5.32)	5.42 (4.86-5.99)	5.99 (5.30-6.73)	6.58 (5.74-7.53)	7.42 (6.34-8.68)	8.09 (6.81-9.60)
6-hr	2.93 (2.71-3.19)	3.65 (3.36-3.97)	4.43 (4.03-4.85)	5.14 (4.62-5.65)	6.18 (5.45-6.91)	7.04 (6.09-7.98)	7.95 (6.73-9.19)	8.94 (7.43-10.5)	10.3 (8.38-12.5)	11.5 (9.12-14.2)
12-hr	3.16 (2.84-3.54)	4.01 (3.60-4.49)	5.18 (4.60-5.83)	6.29 (5.49-7.12)	7.99 (6.79-9.21)	9.47 (7.86-11.1)	11.1 (8.98-13.3)	12.9 (10.2-15.9)	15.7 (11.9-19.7)	17.9 (13.3-23.1)
24-hr	3.51 (3.16-3.96)	4.53 (4.07-5.10)	6.16 (5.48-6.95)	7.67 (6.75-8.68)	10.0	12.1	14.5	17.1	21.1	24.4
2-day	4.33 (3.95-4.80)	5.53 (5.02-6.12)	7.27 (6.55-8.08)	8.91 (7.93-9.96)						
3-day	4.61 (4.22-5.08)	5.86 (5.36-6.47)	7.65 (6.94-8.47)	9.30 (8.35-10.3)						
4-day	4.88 (4.49-5.35)	6.20 (5.70-6.82)	8.04 (7.34-8.86)	9.70 (8.77-10.7)						
7-day	6.07 (5.64-6.57)	7.64 (7.10-8.32)	9.59 (8.86-10.5)	11.3 (10.3-12.4)						
10-day	7.14 (6.67-7.70)	8.97 (8.36-9.72)	11.1 (10.3-12.0)	12.9 (11.9-14.0)						
20-day	10.2 (9.54-10.9)	12.7 (11.9-13.6)	15.2 (14.2-16.3)	17.2 (16.0-18.5)						
30-day	12.9 (12.1-13.7)	16.0 (15.0-17.1)	18.9 (17.7-20.3)	21.4 (19.9-22.9)						
45-day	16.9 (15.9-17.9)	20.9 (19.7-22.3)	24.2 (22.8-25.8)	26.9 (25.2-28.7)						
60-day	20.6 (19.5-21.9)	25.5 (24.1-27.1)	29.3 (27.6-31.1)	32.2 (30.3-34.3)						

- Rainfall at a depth of >1.04 inches and a duration of 15 minutes occurs once every 2 years on average in Mayaguez
    - Annual average probability of occurrence = 1/2 = 50%
- We can also say, there is 50% possibility that we have rain of >1.04 inches for 15 minutes in a year in Mayaguez

POINT PRECIPITATION FREQUENCY (PF) ESTIMATES

WITH 90% CONFIDENCE INTERVALS AND SUPPLEMENTARY INFORMATION

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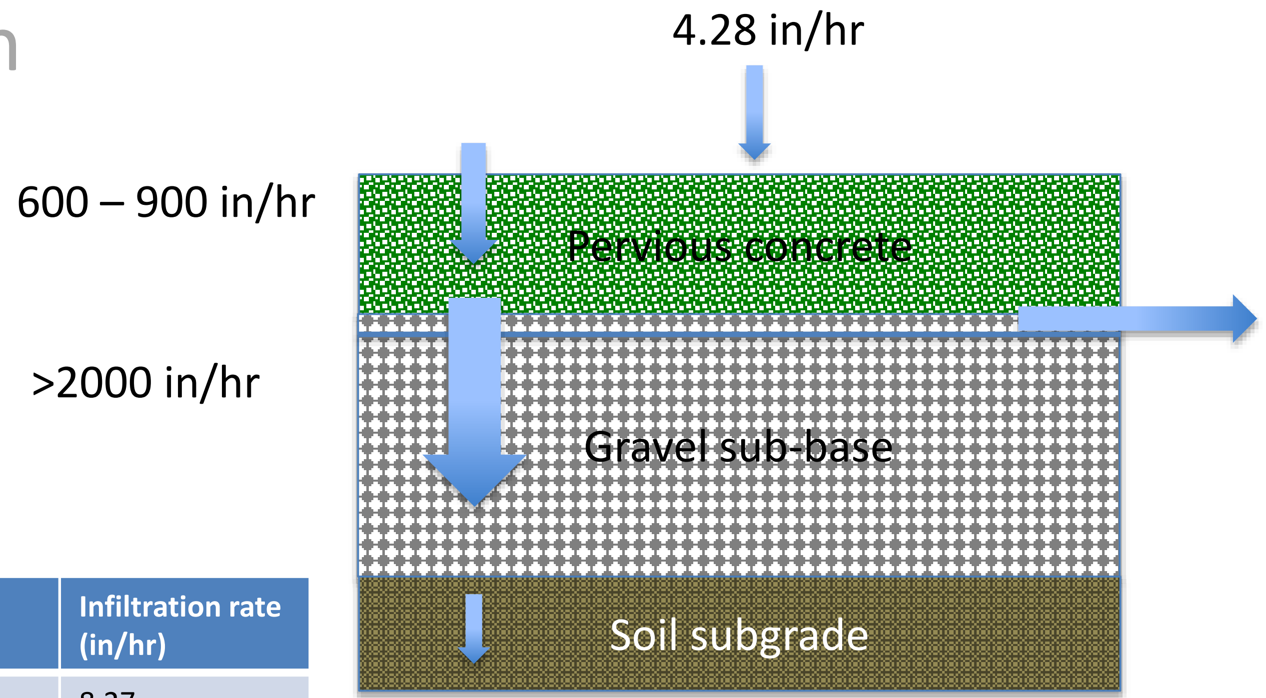
PDS-based precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]										
Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	6.06 (5.72-6.34)	7.32 (6.91-7.66)	8.00 (7.51-8.48)	8.71 (8.12-9.31)	9.71 (8.99-10.5)	10.5 (9.67-11.4)	11.4 (10.3-12.5)	[illegible] (11.0-13.6)	13.4 (11.9-15.2)	14.4 (12.6-16.4)
10-min	4.15 (3.91-4.33)	5.00 (4.72-5.23)	5.47 (5.13-5.80)	5.96 (5.56-6.36)	6.63 (6.14-7.16)	7.19 (6.61-7.82)	7.77 (7.05-8.55)	8.35 (7.52-9.29)	9.17 (8.14-10.4)	9.82 (8.62-11.2)
15-min	3.55 (3.35-3.70)	4.28 (4.04-4.48)	4.68 (4.39-4.96)	5.10 (4.75-5.44)	5.68 (5.26-6.13)	6.16 (5.66-6.70)	6.65 (6.03-7.32)	7.15 (6.44-7.95)	7.85 (6.97-8.87)	8.40 (7.37-9.58)
30-min	2.84 (2.68-2.97)	3.42 (3.23-3.58)	3.74 (3.51-3.97)	4.08 (3.80-4.36)	4.54 (4.21-4.91)	4.93 (4.53-5.36)	5.32 (4.83-5.86)	5.72 (5.15-6.37)	6.28 (5.58-7.10)	6.72 (5.90-7.67)
60-min	2.11 (1.99-2.20)	2.54 (2.40-2.66)	2.78 (2.61-2.94)	3.03 (2.82-3.23)	3.37 (3.12-3.64)	3.66 (3.36-3.98)	3.95 (3.58-4.34)	4.25 (3.82-4.72)	4.66 (4.14-5.26)	4.99 (4.38-5.69)
2-hr	1.32 (1.24-1.38)	1.59 (1.50-1.67)	1.79 (1.67-1.90)	1.97 (1.83-2.10)	2.25 (2.06-2.43)	2.47 (2.24-2.71)	2.70 (2.42-3.00)	2.94 (2.61-3.31)	3.27 (2.85-3.74)	3.52 (3.04-4.08)
3-hr	0.905 (0.855-0.963)	1.11 (1.04-1.18)	1.27 (1.18-1.36)	1.43 (1.31-1.54)	1.67 (1.50-1.83)	1.86 (1.66-2.06)	2.06 (1.81-2.33)	2.27 (1.97-2.62)	2.57 (2.18-3.02)	2.81 (2.34-3.35)
6-hr	0.500 (0.464-0.544)	0.624 (0.574-0.676)	0.757 (0.687-0.830)	0.881 (0.787-0.972)	1.06 (0.929-1.19)	1.21 (1.04-1.39)	1.37 (1.15-1.60)	1.55 (1.28-1.84)	1.80 (1.44-2.19)	2.00 (1.57-2.49)
12-hr	0.267 (0.241-0.299)	0.340 (0.305-0.380)	0.440 (0.389-0.495)	0.535 (0.464-0.607)	0.681 (0.575-0.789)	0.809 (0.666-0.952)	0.951 (0.762-1.15)	1.11 (0.867-1.37)	1.34 (1.01-1.71)	1.54 (1.13-2.00)
24-hr	0.149 (0.134-0.168)	0.192 (0.173-0.216)	0.262 (0.232-0.296)	0.327 (0.286-0.371)	0.429 (0.366-0.492)	0.519 (0.434-0.602)	0.620 (0.507-0.728)	0.734 (0.589-0.875)	0.905 (0.706-1.10)	1.05 (0.802-1.29)
2-day	0.091 (0.083-0.101)	0.116 (0.106-0.129)	0.154 (0.138-0.171)	0.189 (0.167-0.211)	0.243 (0.210-0.277)	0.291 (0.246-0.337)	0.344 (0.284-0.406)	0.404 (0.326-0.486)	0.494 (0.386-0.608)	0.571 (0.436-0.715)
3-day	0.065 (0.059-0.071)	0.083 (0.076-0.091)	0.108 (0.098-0.120)	0.131 (0.118-0.147)	0.167 (0.146-0.189)	0.198 (0.170-0.228)	0.233 (0.195-0.273)	0.272 (0.223-0.326)	0.331 (0.263-0.407)	0.382 (0.295-0.479)
4-day	0.052 (0.048-0.056)	0.066 (0.060-0.072)	0.085 (0.078-0.094)	0.103 (0.093-0.114)	0.129 (0.114-0.145)	0.152 (0.132-0.174)	0.177 (0.151-0.205)	0.205 (0.171-0.245)	0.250 (0.201-0.307)	0.288 (0.224-0.361)
7-day	0.037 (0.034-0.040)	0.046 (0.043-0.050)	0.058 (0.054-0.063)	0.068 (0.063-0.075)	0.084 (0.075-0.092)	0.097 (0.086-0.108)	0.110 (0.096-0.125)	0.125 (0.108-0.144)	0.147 (0.124-0.177)	0.166 (0.137-0.208)
10-day	0.030 (0.029-0.033)	0.038 (0.036-0.041)	0.047 (0.044-0.051)	0.055 (0.051-0.060)	0.066 (0.060-0.072)	0.075 (0.068-0.083)	0.085 (0.075-0.095)	0.095 (0.083-0.107)	0.110 (0.095-0.127)	0.123 (0.104-0.147)
20-day	0.022 (0.021-0.023)	0.027 (0.026-0.029)	0.033 (0.031-0.035)	0.037 (0.035-0.040)	0.043 (0.040-0.047)	0.048 (0.044-0.052)	0.053 (0.048-0.058)	0.058 (0.052-0.064)	0.065 (0.057-0.073)	0.070 (0.061-0.080)
30-day	0.019 (0.018-0.020)	0.023 (0.022-0.025)	0.027 (0.026-0.029)	0.031 (0.029-0.033)	0.036 (0.033-0.038)	0.040 (0.036-0.043)	0.043 (0.039-0.047)	0.047 (0.043-0.052)	0.053 (0.047-0.059)	0.057 (0.050-0.064)
45-day	0.017 (0.016-0.017)	0.020 (0.019-0.022)	0.024 (0.022-0.025)	0.026 (0.025-0.028)	0.030 (0.028-0.032)	0.032 (0.030-0.035)	0.035 (0.032-0.038)	0.037 (0.034-0.041)	0.041 (0.037-0.045)	0.043 (0.039-0.048)
60-day	0.015 (0.015-0.016)	0.019 (0.018-0.020)	0.022 (0.021-0.023)	0.024 (0.022-0.025)	0.027 (0.025-0.028)	0.029 (0.027-0.031)	0.031 (0.029-0.033)	0.033 (0.030-0.036)	0.036 (0.032-0.039)	0.038 (0.034-0.041)

Water retention



Generally suitable for use with pervious concrete

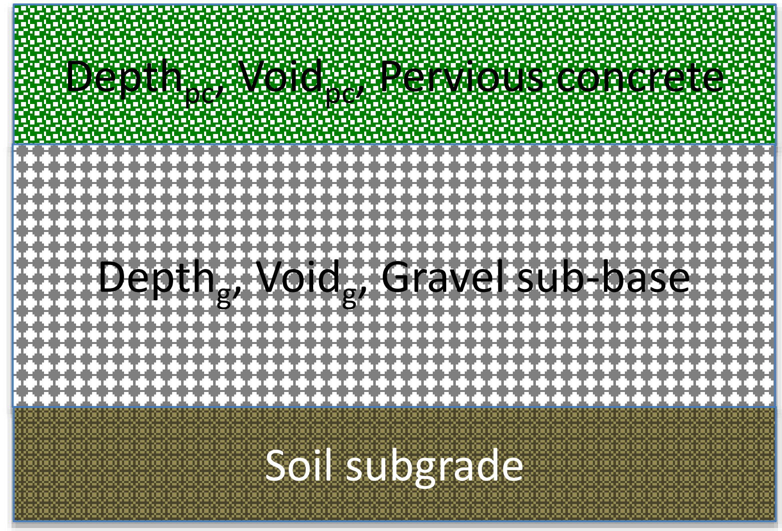
	Infiltration rate (in/hr)
Sand	8.27
Loamy sand	2.41
Sandy loam	1.02
Loam	0.52
Silty loam	0.27
Sandy clay loam	0.17
Clay loam	0.09
Silty clay loam	0.06
Sandy clay	0.05
Silty clay	0.04
clay	0.02

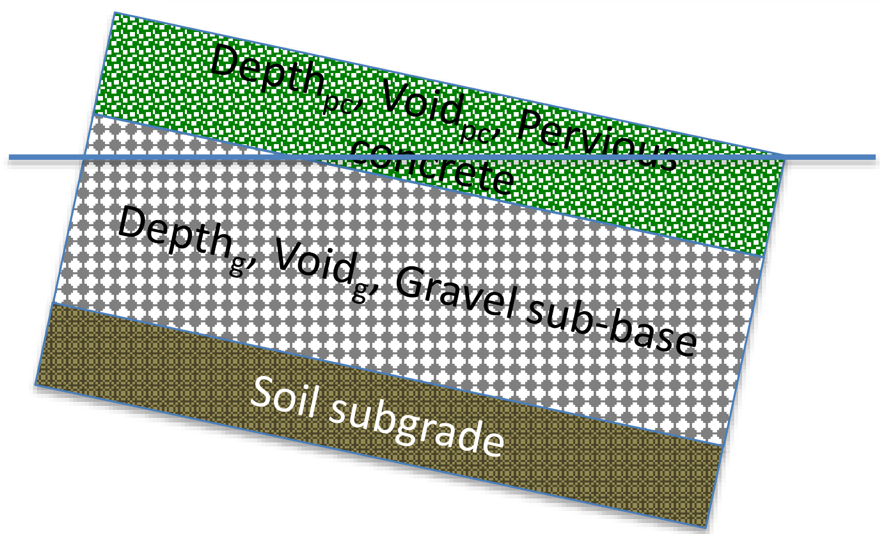
Reservoir capacity

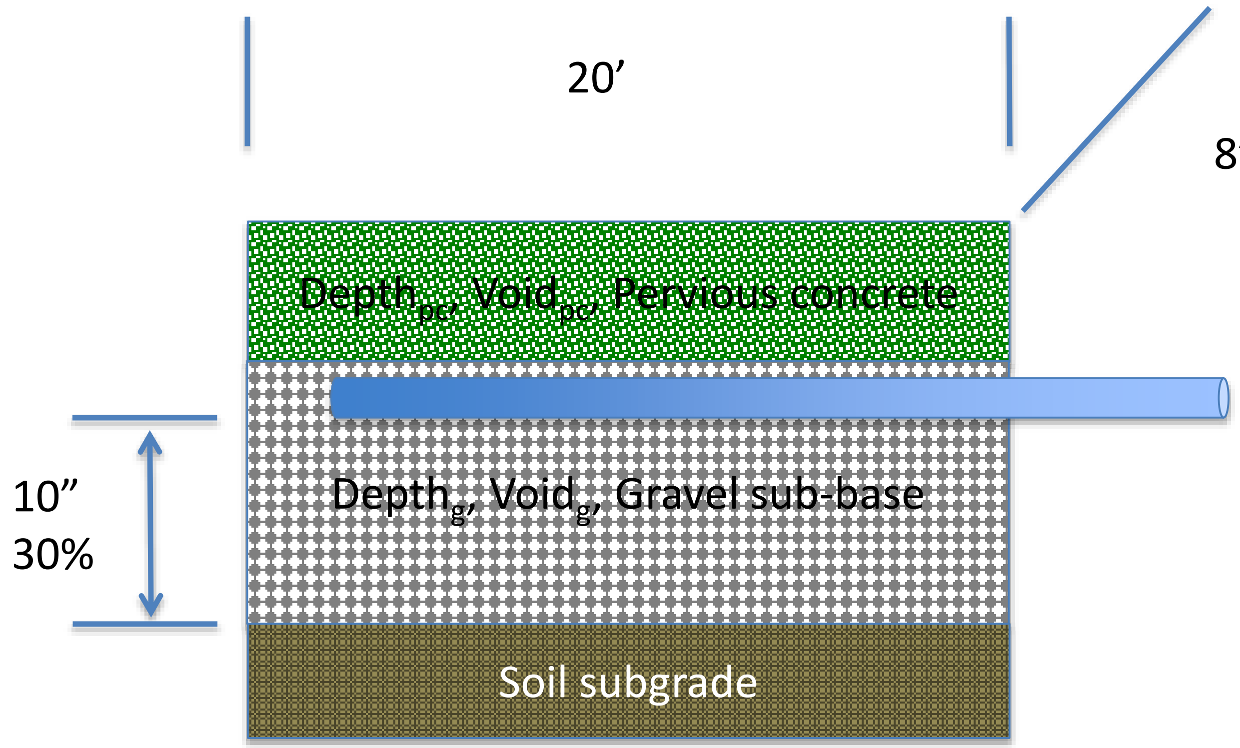
- Reservoir capacity

  $$R = (D_{pc}V_{pc} + D_g V_g) / 100$$

  If D_{pc} 6”, V_{pc} 20%, D_g 12” and V_g 30%, then R = 4.8”

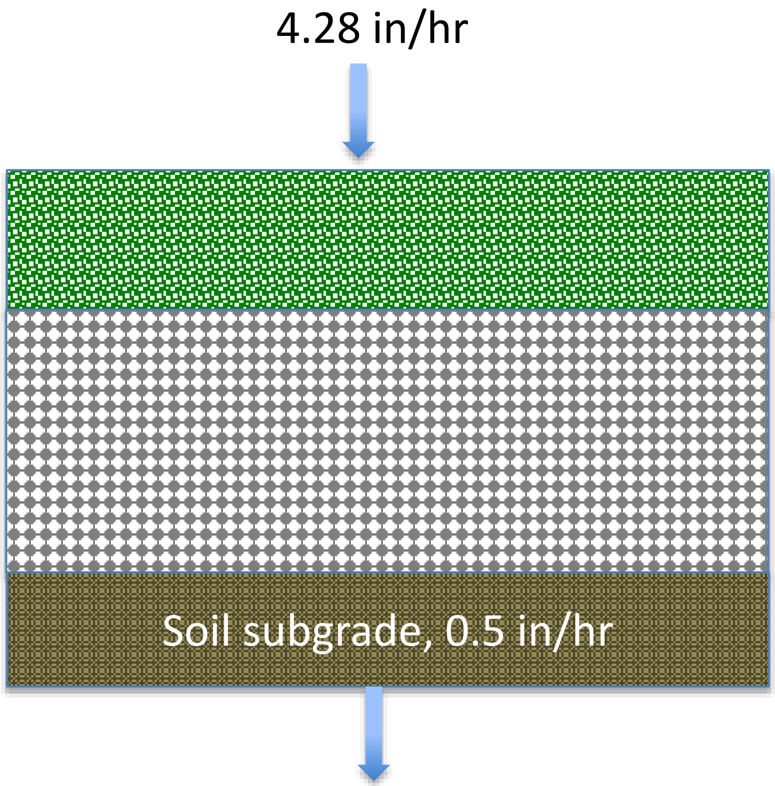






$20 \times 8 \times 10/12 \times 30/100 = 40\ ft^3$ water retention

Drawtime



- 4.28 in/hr x 15 mins = 0.5 in/hr x ? mins

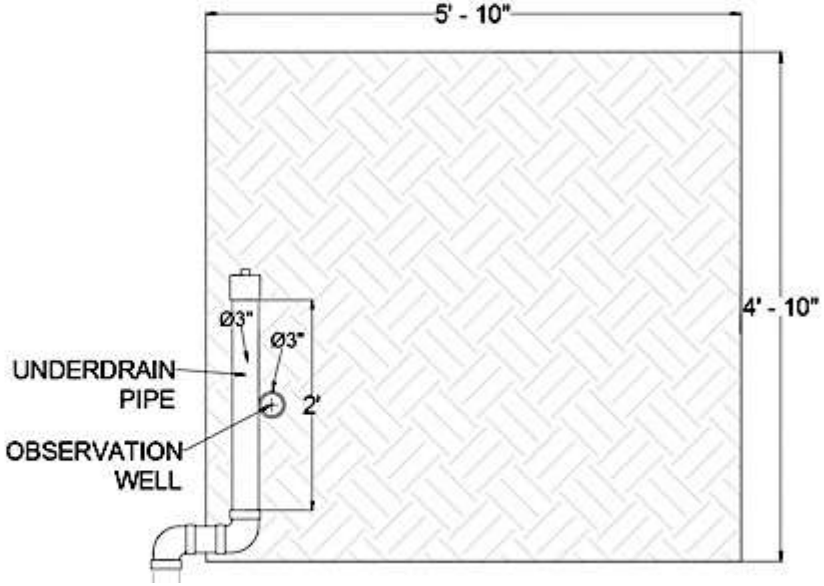
➔ 128.4 mins = 2.1 hours

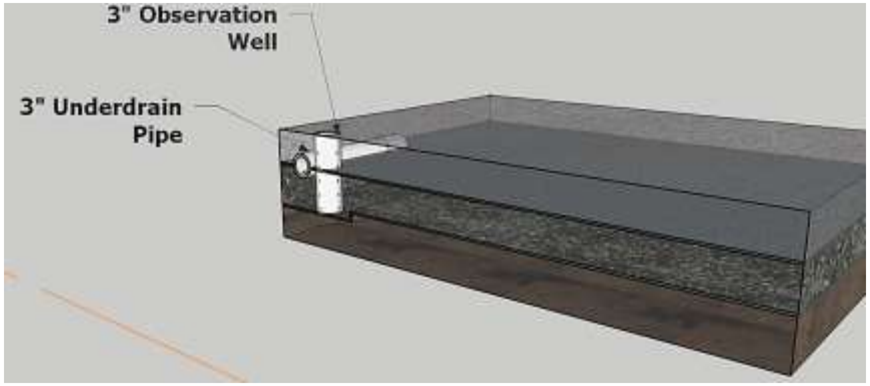
- Water retention capacity of sub-base gravel reservoir

  $= 70'' \times 58'' \times 4'' \times 30\%/100 = 4872\ in^3 = 2.82\ ft^3$
- Let’s consider 2-year storm at 4.28 in/hr for 15 mins
  - Precipitation volume on the surface of pervious concrete

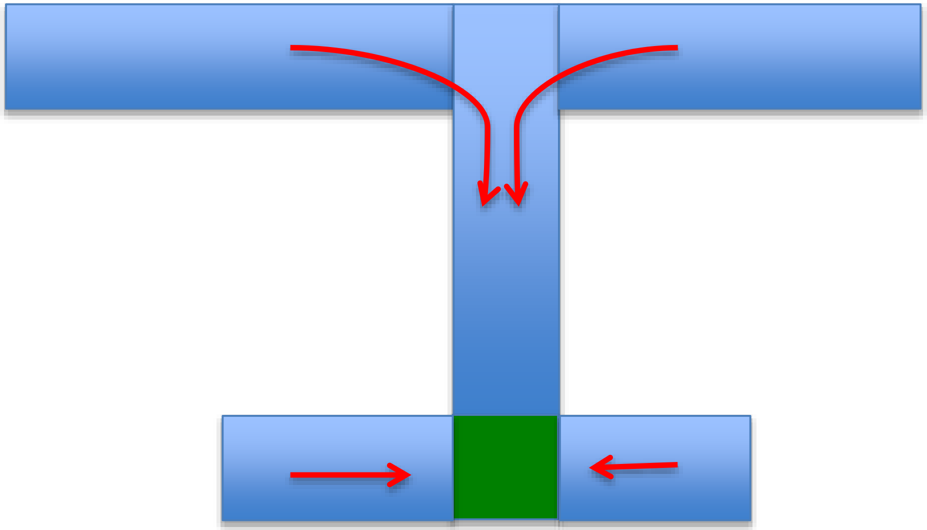
    4.28 in/hr x 15/60 hrs x 70” x 58” = 4344 in3

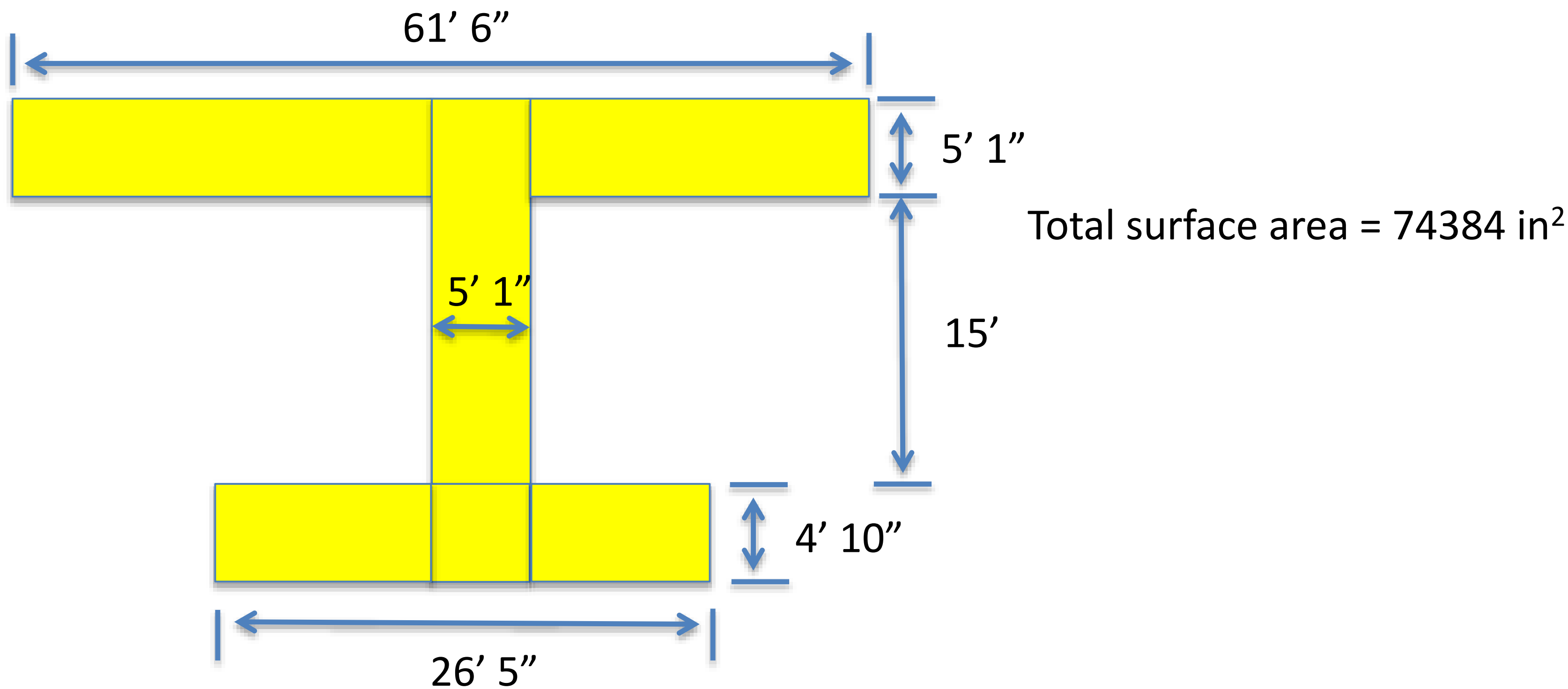
    So, reservoir retention volume > precipitation volume → no underdrain discharge and all the retained water will infiltrate into soil subgrade after 2.1 hours





- But, there are run-on’s!





Precipitation volume on the surface of pervious concrete for 15 mins (assuming all precipitation make run-on)

4.28 in/hr x 15/60 hrs x 74384 in^2 = 79591 in^3

Soil subgrade infiltration rate = 0.5 in/hr

Infiltration volume for 15mins to the subsoil beneath pervious concrete area

= 0.5 in/hr x 15/60 hrs x 70” x 58” = 507 in^3

Gravel sub-base reservoir retention volume beneath pervious concrete area = 70” x 58” x 4” x 30%/100 = 4872 in^3

So, there will be a total of 79591 – 507 – 4872 = 74212 in^3 that needs to be discharged through underdrain pipe

Structural design considerations

- Often based on 1993 AASHTO Guide for Design of Pavement Structures (Flexible Pavement Design)
- Calculate the design structural number (SN)
  - Anticipated traffic load/type
  - Soil properties
  - Environmental/climatic factors
- Determine materials/thickness of surface and reservoir layers needed to meet or exceed SN

- Consult Pavement Engineers

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Chapter 5

Pervious Concrete Pavement: Construction / Maintenance

- Admixture:
  - Air voids: 18-20%
  - Water to cement ratio: 0.27-0.34
  - Polypropylene or cellulose fibers may be added to improve durability and workability
  - Test pour highly recommended for quality control
- Surface thickness
  - Typically, 4-8 inches

- Installation
  - Place within 30-60 minutes of mix time
  - Place over moist subgrade and subbase layers
  - Install forms
  - Deposit pervious concrete, cut to a rough elevation with a rake or other hand tools
  - Compaction
    - For hand compaction, riser strips (3/8 to 3/4 inch thick) may be used on top of the forms
    - For larger jobs, weighted spinning-tube screed followed by cross rolling (no need of riser strips)

- Compaction / consolidation roller
  - 500 lb / 12 ft width (227 kg / 3.7 m width)
- Cross roller

70 lb, 42”x10”

Contraction joints

72 lb, 42” x 12”

- Contraction joint cutter
  - A depth of 1/3 to 1/4 of the thickness of the pavement
- Contraction joint spacing
  - Traditional way for dense concrete pavement
    - Joint spacing should be <24 to 35 times the pavement thickness
    - For a 4” slab, the maximum joint spacing = 8 to 12 ft
  - For pervious concrete that shrinks only about half dense concrete
    - 35 times the pavement thickness
    - For a 4” slab, the joints up to 12 ft
    - Some cases, 50 to 60 times the pavement thickness
      - For a 4” slab, 16 to 20 ft
- Other joints (isolation and expansion joints)
  - Seldom used

- Curing
  - Cover pavement with heavy duty polyethylene sheeting to retain moisture no later than 20 minutes of concrete placement

  - Curing time
    - >7 days for plain pervious concrete
    - >10 days for SCM-amended pervious concrete

Shown here is a motorized roller screed
(Star Ready Mix)

HDPE curing sheet
(Star Ready Mix)

Joint Cutting
(www.ptolomeo.unam.mx)

NRMCA Certification for Pervious Concrete Contractors

- Technician
- Installer
- Craftsman

- Re-Certification
  - Every five years
  - A written examination.

NRMCA Certification for Pervious Concrete Contractors

- Technician Certification
  - Pass the NRMCA Pervious Concrete Contractor Certification Written Examination with a score of 75% or greater administered by a Local Sponsoring Group approved by NRMCA

Puerto Rico

Concrete Producers Association of Puerto Rico
Primary Contact: Thomas E. Kierce, tkierce@cmc-pr.com
Phone: (787) 274-0259

NRMCA Certification for Pervious Concrete Contractors

- Installer Certification
  - Pass the NRMCA Pervious Concrete Contractor Certification Written Examination with a score of 75% or greater administered by a Local Sponsoring Group approved by NRMCA
  - Complete a Performance Evaluation (Form PCC10) administered by a Local Sponsoring Group approved by NRMCA.
  - Provide project experience documentation (Form PCC8) of successful construction of a minimum of 3 projects with a total area exceeding 10,000 square feet (1000 m^2).

- Craftsman Certification
  - Pass the NRMCA Pervious Concrete Contractor Certification Written Examination with a score of 75% or greater administered by a Local Sponsoring Group approved by NRMCA
  - Possess a current ACI Flatwork Finisher Technician or Craftsman certification at the time of application
  - Work Experience:
    - OPTION A: Complete a Performance Evaluation administered by a Local Sponsoring Group approved by NRMCA and document work experience constructing pervious concrete pavement exceeding 1500 hours – Forms PCC10, PCC9 and Experienced Worksheet, respectively.

      or
    - OPTION B: Provide documentation of work experience constructing pervious concrete pavements exceeding 3000 hours – Form PCC9 and Work Experience Worksheet, respectively.
  - Work experience shall be documented in hours and square footage on a standard spreadsheet. Documentation shall include project and contact, preferable an owner, who can verify the conduct of the work.
  - The craftsman applicant shall document a minimum of 3 problems they have had on pervious concrete jobs and how they resolved these problems. The craftsman application shall be reviewed and approved by a minimum of 3 member certification committee established by the Local Sponsoring Group.

Certification in PR (as of March 13, 2016)

FIRST NAME	M INTIAL	LAST NAME	SUFFIX	COMPANY	CITY	STATE	ZIP	CERT TYPE	EXPIRATION DATE
Victor	M.	Morales		Morales Construction Corp Morales Construction Corp.	Cagnas	PR	00726	Pervious Concrete Technician	08/26/2020
Ruben		Segarra		Essroc San Juan	Rio Grande	PR	00745	Pervious Concrete Technician	08/26/2020
Angel		Ramos		Grupo Titan AE Corp	Guaywabo	PR	00970	Pervious Concrete Technician	08/26/2020
Victor	M.	Diaz		Star Ready Mix	Caguas	PR	00726	Pervious Concrete Technician	08/26/2020

FIRST NAME	M INTIAL	LAST NAME	SUFFIX	COMPANY	CITY	STATE	ZIP	CERT TYPE	EXPIRATION DATE
Leonardo		Ramos		Grupo Titan AE Corp	Guaywabo	PR	00970	Pervious Concrete Installer	08/26/2020
Edgardo		Ramos		Grupo Titan AE Corp	Guaywabo	PR	00970	Pervious Concrete Installer	08/26/2020
Angel		Ramos		Grupo Titan AE Corp.	Guaywabo	PR	00970	Pervious Concrete Installer	01/24/2017

Cost

- Pervious concrete (6")
  - Materials alone = $2 - 6/ft^2 ($22 - 65/m^2)
  - Installed coats = $6 - 10/ft^2

POROUS PAVEMENT TYPE	TYPICAL INSTALLED COST ($/SF)	TYPICAL COST RANGE ($/SF)
Porous Asphalt (5 cm [2 in.] surface course, 7.62 cm [3 in.] ATPB)	$6.00	$4.00 – $8.00
Pervious Concrete (6 in.)	$8.00*	$6.00 – $10.00
Interlocking Permeable Pavers & Rigid Open Cell Pavers (including 5 cm [2 in.] bedding layer)	(small hand installation) $13.00	$10.00 – $20.00
	(large mechanical installation) $6.50	$5.00 – $10.00
Open Cell/Grid Paving Systems	$7.00	$5.00 – $9.00
Proprietary Porous Pavement Products	Vary by manufacturer	

Note: Based on 17 actual bids with unit materials costs for permeable pavements (excluding open celled/grid lattice) from projects 2011–2013. General Estimates for installed permeable pavement surfaces with no sub-surface storage. Prices vary greatly with pavement depth, base/subbase and drainage variations.
*Estimate provided by National Ready Mix Concrete Association 2013
Source: CH2M Hill, 2013

Typical costs for 2" asphalt ($2 to 4/ft^2), concrete ($3 to 5/ft^2)

Potential problems

- Draindown
- Raveling
- Cold joints
- Cracking
- Sealing
- Clogging
- High hills?

greengirlpdx.com

visualphotos.com

Draindown

- Two bad sequences
  - Starving top
    - Weak, raveling
  - Tight bottom
    - Reduced infiltration

- Water amount!
- Viscosity modifier
- Raining, no pouring

Raveling

- Coarse aggregates set free
- Mostly, traffic-related
  - Heavy
  - Sharp turn
  - Snowplow
- Poor compaction
- Frost damage? No, unlikely.

- Good compaction
- Avoid draindown
- Immediate curing
- Reducing abrasive traffic
  - This is mission impractical
- Patching does not work, generally speaking.

Cold joints

- Due to discontinuity and/or change in the concrete mix from batch to batch
- Cold joints mostly occur in hot weather

- Scheduled delivery of ready mix truck
- Set retarders, set stabilizers

cement.org

Cracking

- Plastic-shrinkage cracks
  - Rapid drying of slab surface
  - Hot weather, windy
  - More frequent with pervious concrete
    - Low w/cm, open texture, no bleed water

> - Place night or early morning
> - Spray evaporation retardant
> - Mist spray (no hose directly)
> - Immediate curing

- Drying-shrinkage cracks
  - Later time
  - Fewer occurrence with pervious concrete
    - Only shrink only about half as much as it dries

> - Contraction joints
>   - (+) or (-)

- Structural cracks
  - Overloading, subgrade settlement/heaving

> - Mix design
> - Slab thickness
> - Subgrade, sub-base

Sealing

- Impervious layer on and/or within the slab surface
- Watery paste
- Overcompaction
- Paint

pinterest.com

Clogging

- Debris filling in the pores
  - Inorganic, organic
- Prevention
- Maintenance

Maintenance

- Routine maintenance
  - Blowing
  - Vacuum sweeping
- Periodic maintenance
  - Pressure washing
  - High pressure washing?
    - How high is high?

perviouspavement.org

www.ldaengineering.com

- Deep cleaning/unclogging
  - Typically, an average infiltration rate decrease of 25% from the initial value, or an infiltration rate less than 100 in/hr, triggers the need for deep cleaning/unclogging.
  - Simultaneous pressure washing and vacuuming
  - Use of chemicals to clean pervious concrete should be done with extreme caution to prevent damage to the aquifer, the biological organisms within the pervious system, or the pervious concrete pavement itself.

perviouspavement.org

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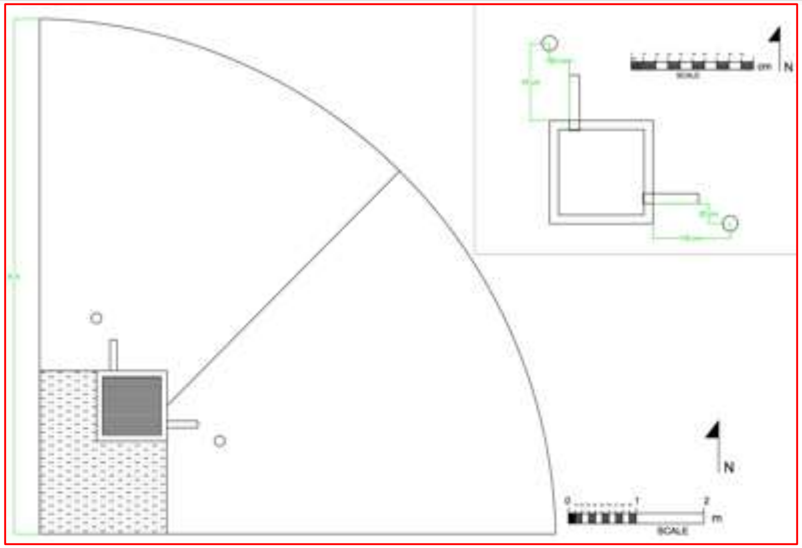
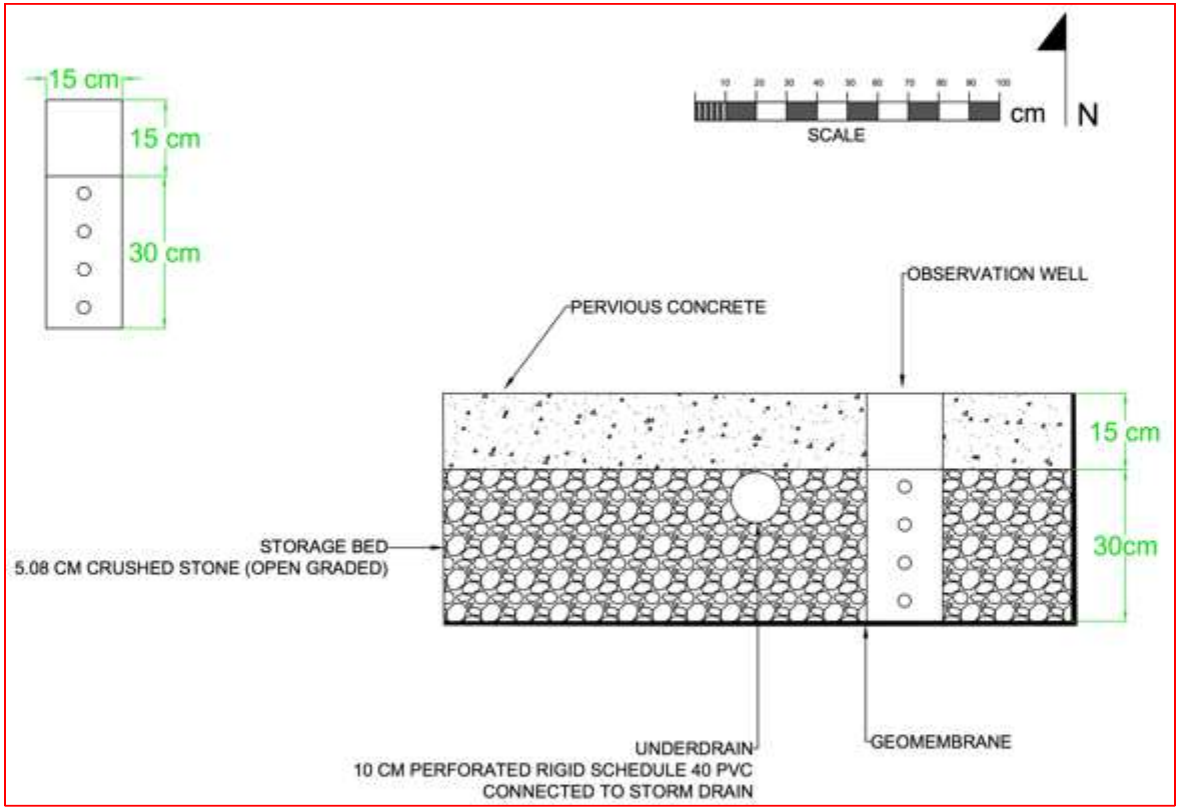
Chapter 6

Pervious Concrete Areas at UPR-Mayagüez

Pervious Concrete Area 1 (PCA1)

490 ft²





No-infiltration design

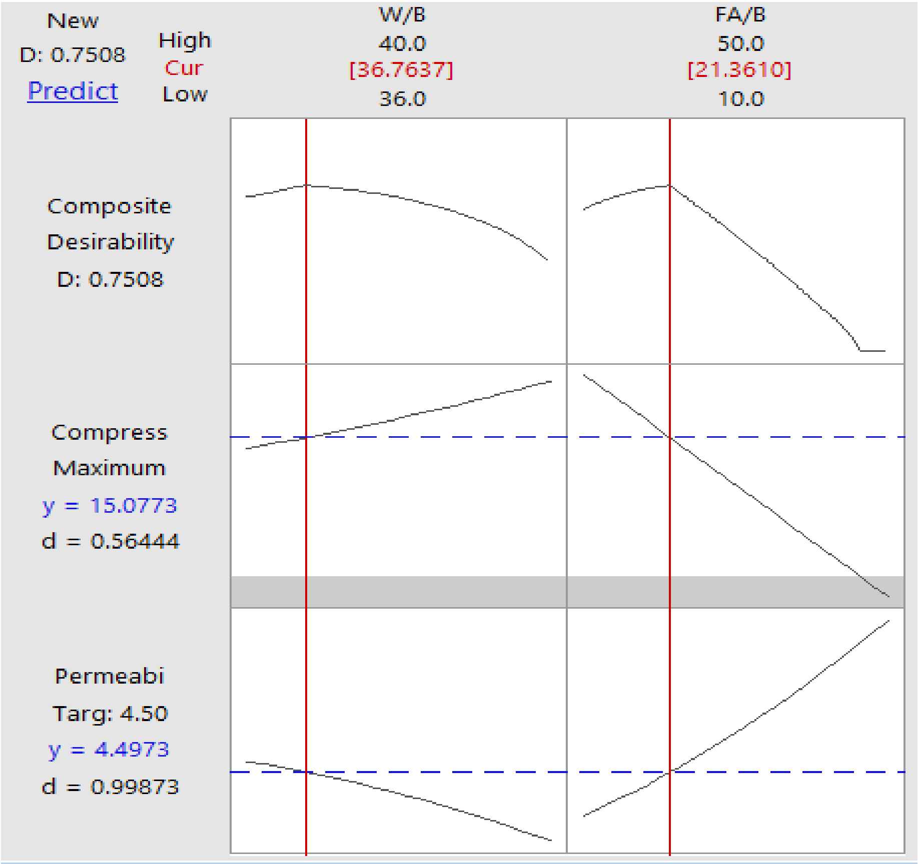
Lab-scale feasibility study

A thesis work by Marleisa Arocho

- Two-factor, two-level, central composite design with Response Surface Methodology

Factors	Levels (% wt.)				
	(-)axial	low	center	high	(+)axial
Water/B	36	36.6	38	39.4	40
FA/B	10	15.9	30	44.1	50

A thesis work by Valerie Lopez

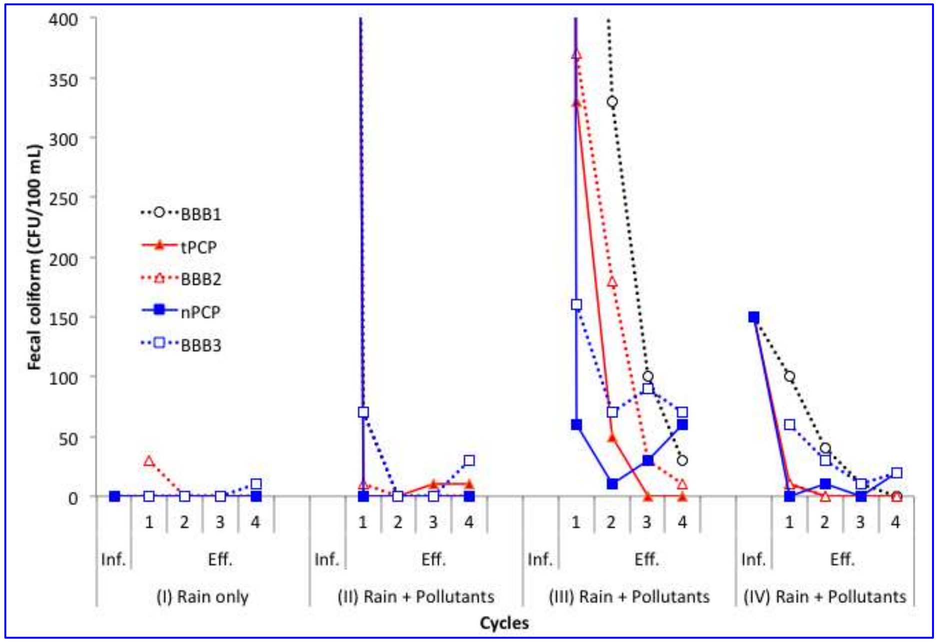


<u>Optimized Mix</u>
FA/B 21.4%
W/B 36.8%

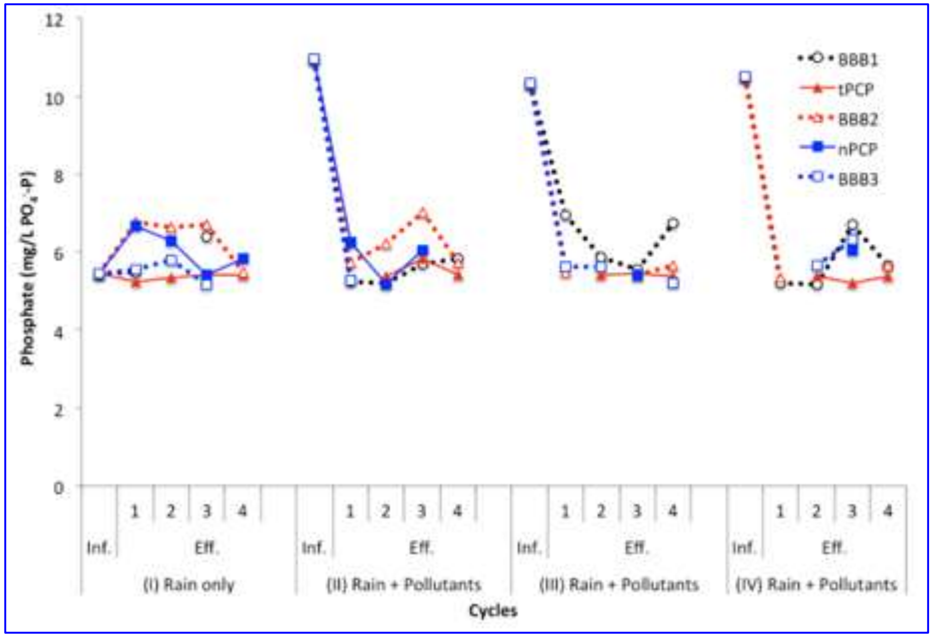
- **Compressive strength 15.1 MPa (~2190 psi)**
- **Permeability 4.5 mm/s (~635 in/hr)**

Water quality and phyto-viability performance

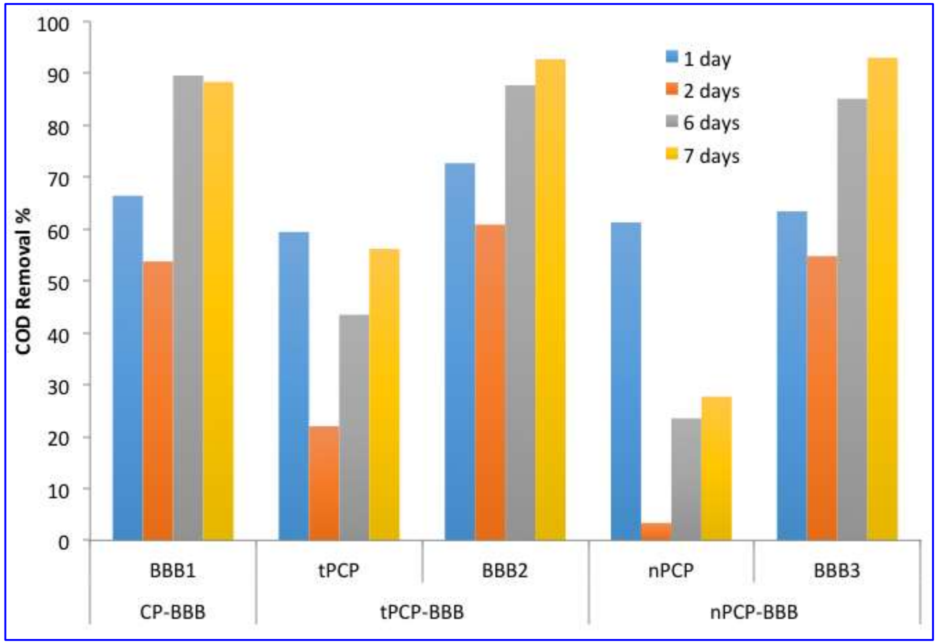
PR-LSAMP Fellowship project by Amber Masters (INCI undergrad.)
Science fair project by Vincent Hwang (11th grade)



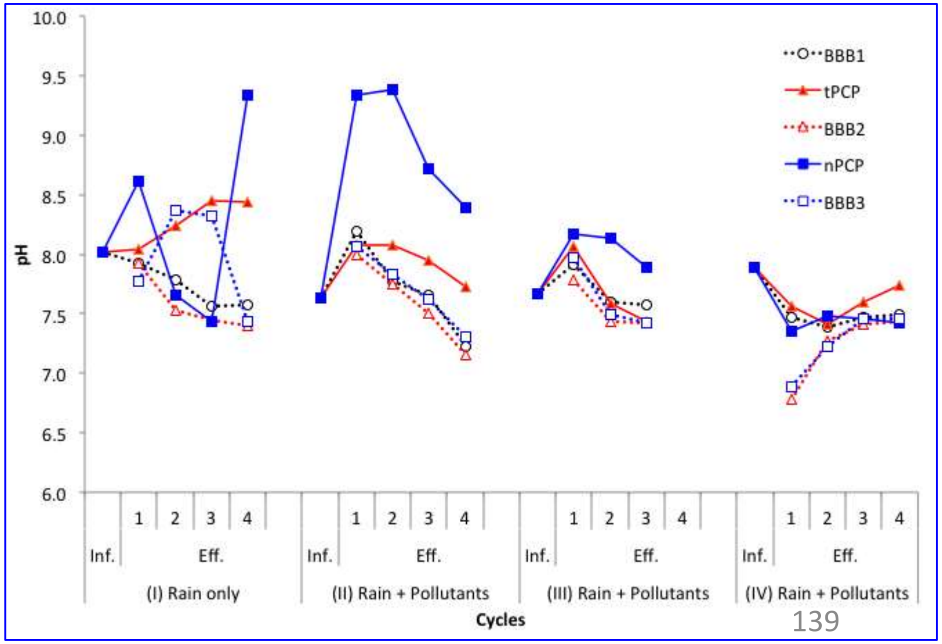
Fecal coliform (CFU/100 mL)
BBB1
tPCP
BBB2
nPCP
BBB3
Inf.
Eff.
(I) Rain only
(II) Rain + Pollutants
(III) Rain + Pollutants
(IV) Rain + Pollutants
Cycles



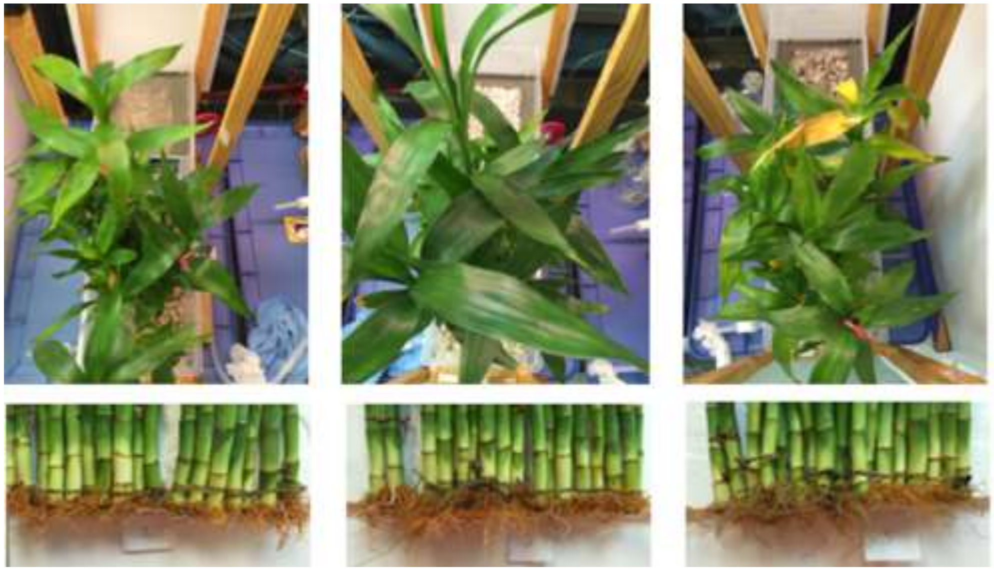
Phosphate (mg/L PO_4-P)
BBB1
tPCP
BBB2
nPCP
BBB3
Inf.
Eff.
(I) Rain only
(II) Rain + Pollutants
(III) Rain + Pollutants
(IV) Rain + Pollutants
Cycles



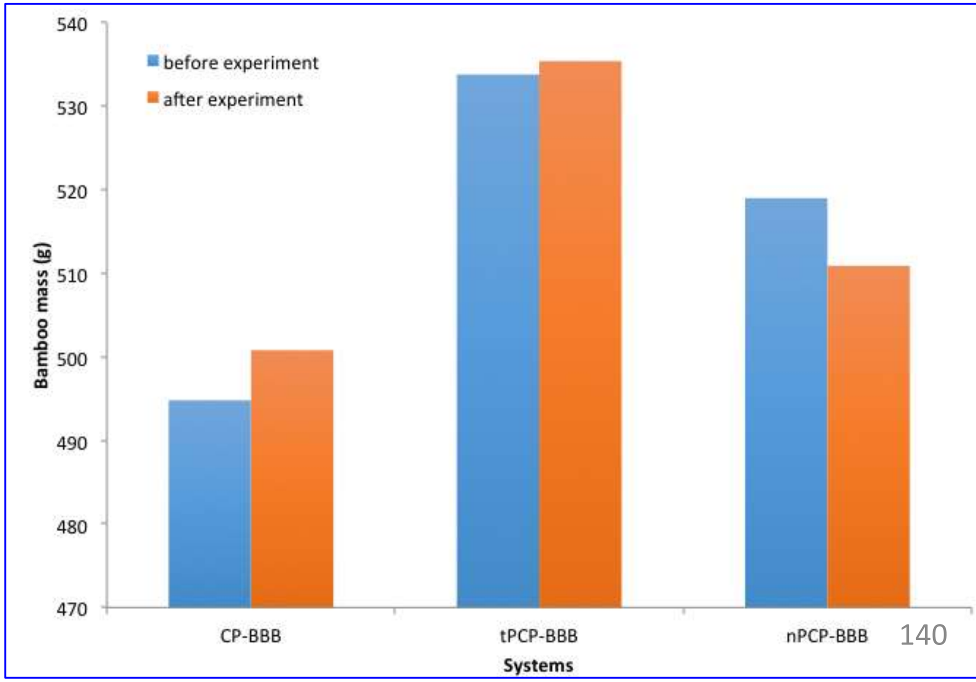
COD Removal %
1 day
2 days
6 days
7 days
BBB1
tPCP
BBB2
nPCP
BBB3
CP-BBB
tPCP-BBB
nPCP-BBB



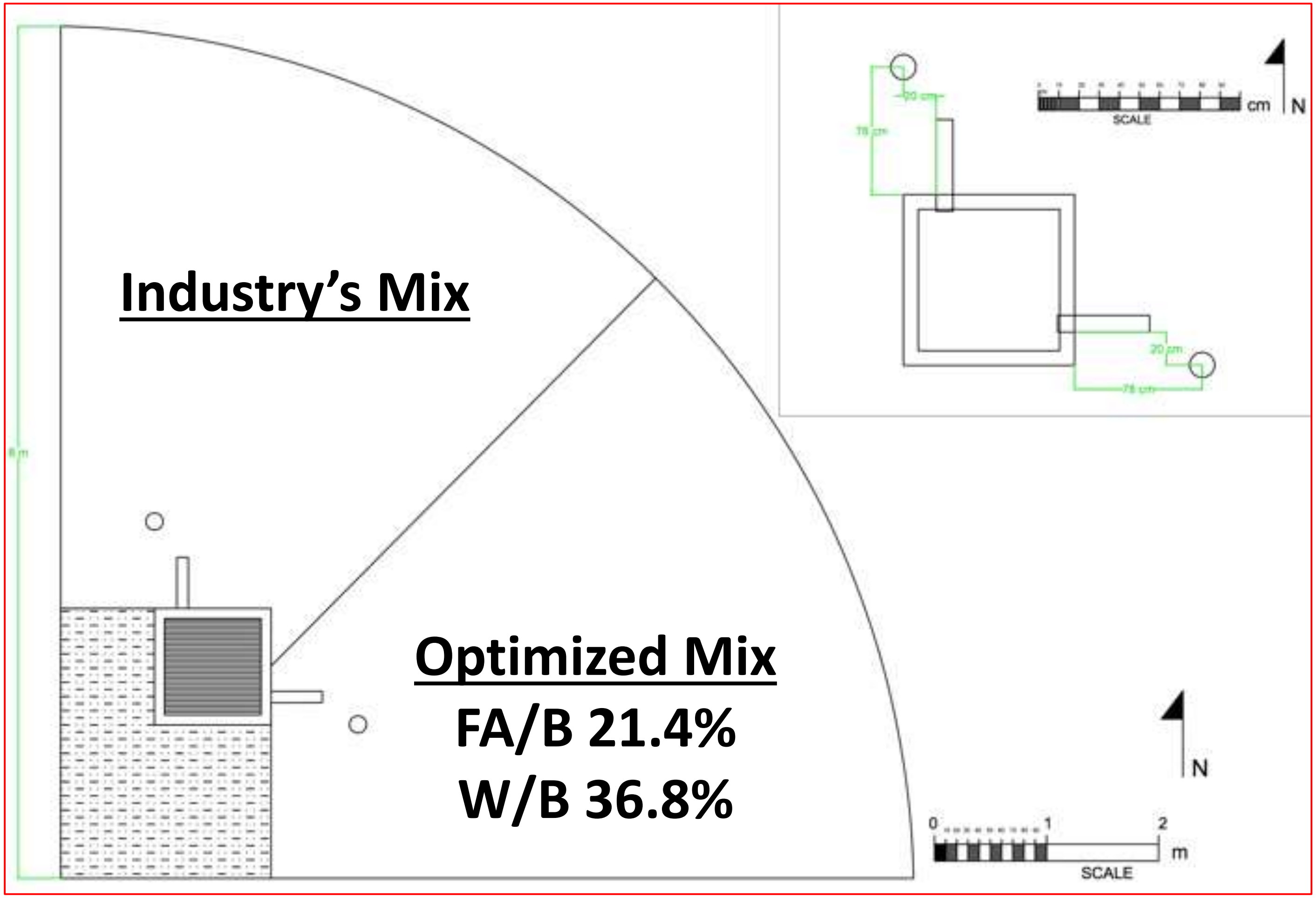
pH
BBB1
tPCP
BBB2
nPCP
BBB3
Inf.
Eff.
(I) Rain only
(II) Rain + Pollutants
(III) Rain + Pollutants
(IV) Rain + Pollutants
Cycles



CP bamboos tPCP bamboos nPCP bamboos

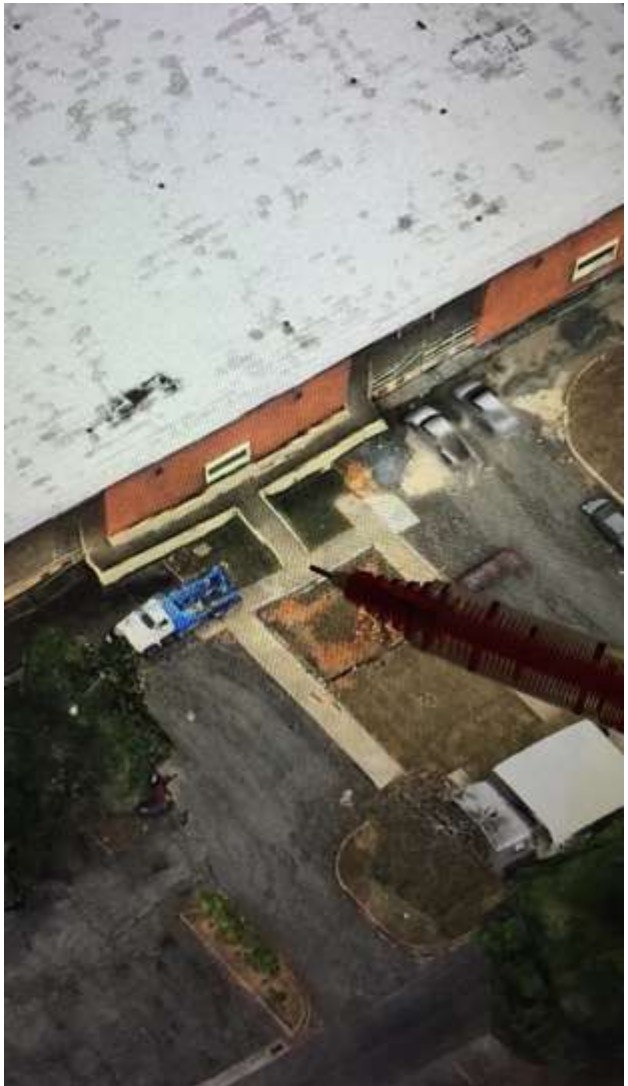


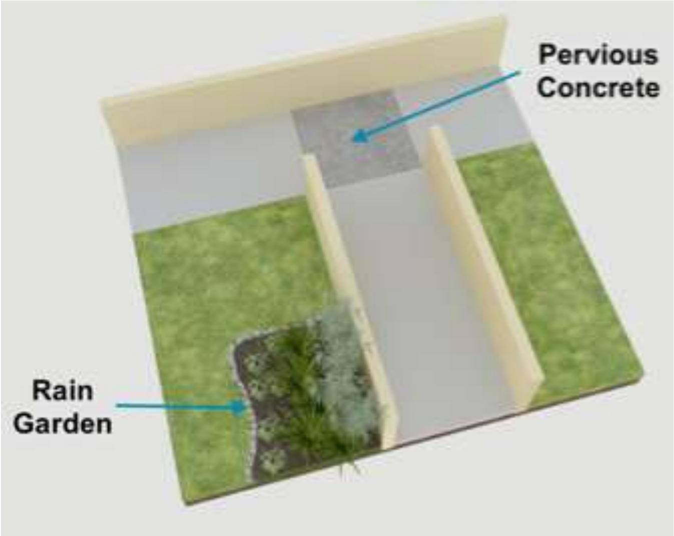
To-do (March 22, 2016)

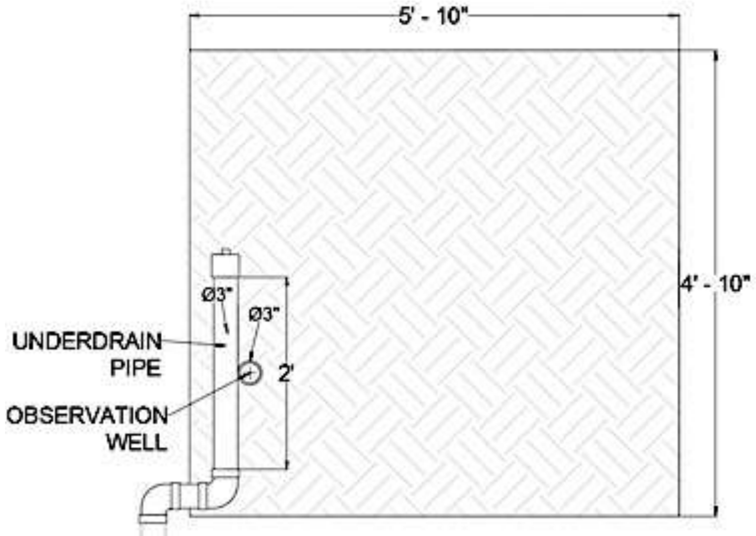


PCA1 Implementation

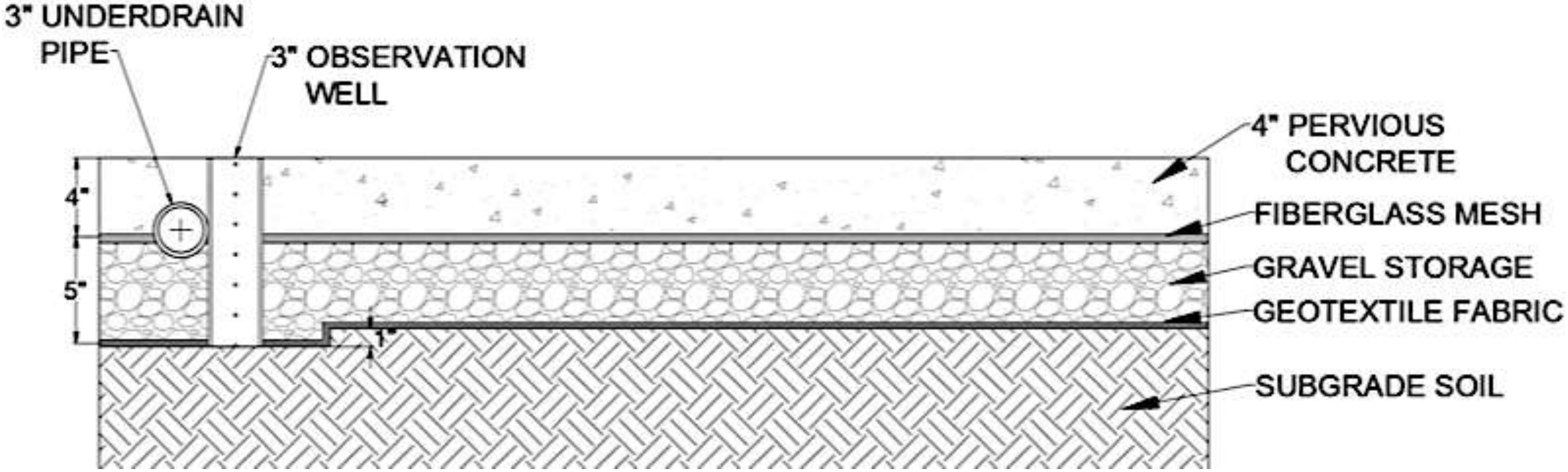
Pervious Concrete Area 2 (PCA2)







28 ft^2



Partial-infiltration Design

Lab-scale feasibility study

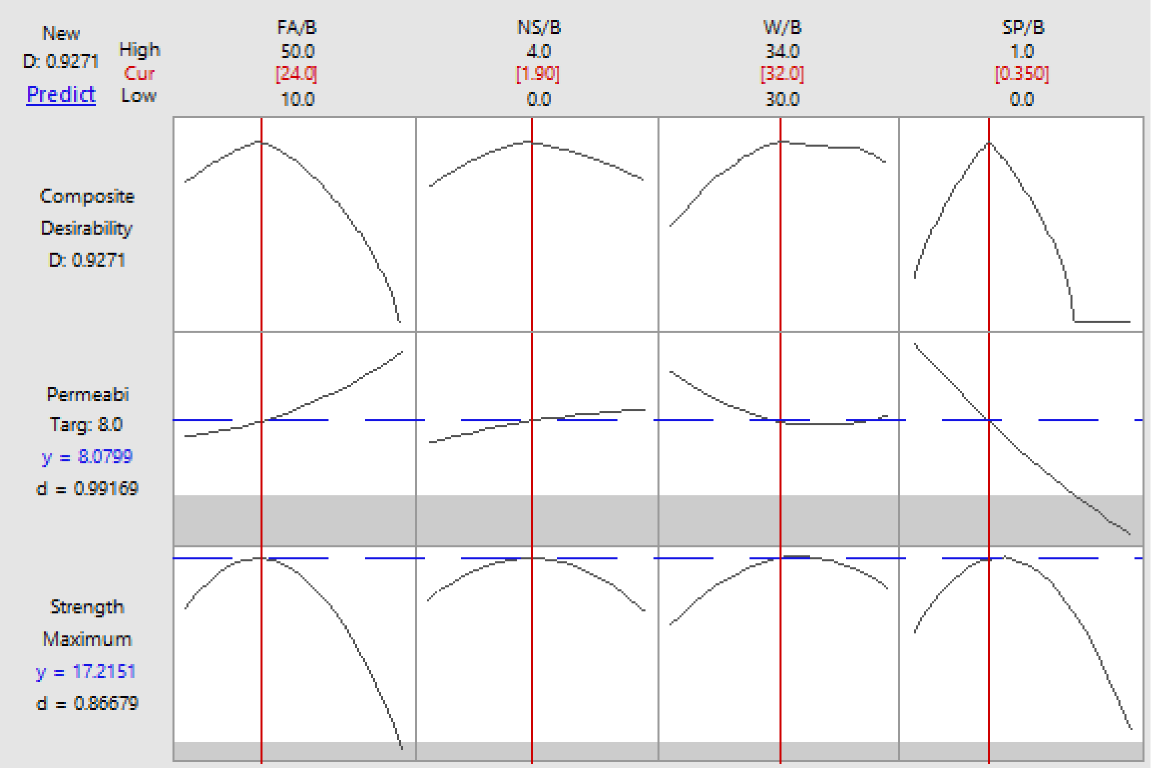
A thesis work by Valerie Lopez

- $NanoSiO_2$, fly ash and water reducer
- 4-factor, 2-level, Central Composite Design with Response Surface Methodology

FACTORS	LEVELS				
	-α	-1	Center	+1	+α
Fly Ash (FA/B)	10	20	30	40	50
$NanoSiO_2$ (NS/FA)	0	1	2	3	4
Water (W/B)	30	31	32	33	34
Water Reducer (SP/B)	0	0.25	0.5	0.75	1

A thesis work by Valerie Lopez

- Optimization



Optimized Mix

FA/B 24%

NS/FA 1.9%

W/B 32%

WR/B 0.35%

- **Compressive strength 17.2 MPa (~2500 psi)**
- **Permeability 8.1 mm/s (~1150 in/hr)**

Water quality performance

A thesis work by Valerie Lopez

pH <8
Turbidity <2 NTU
100% PO_4^--P removal
99% fecal coliform removal

$10.6/ft²

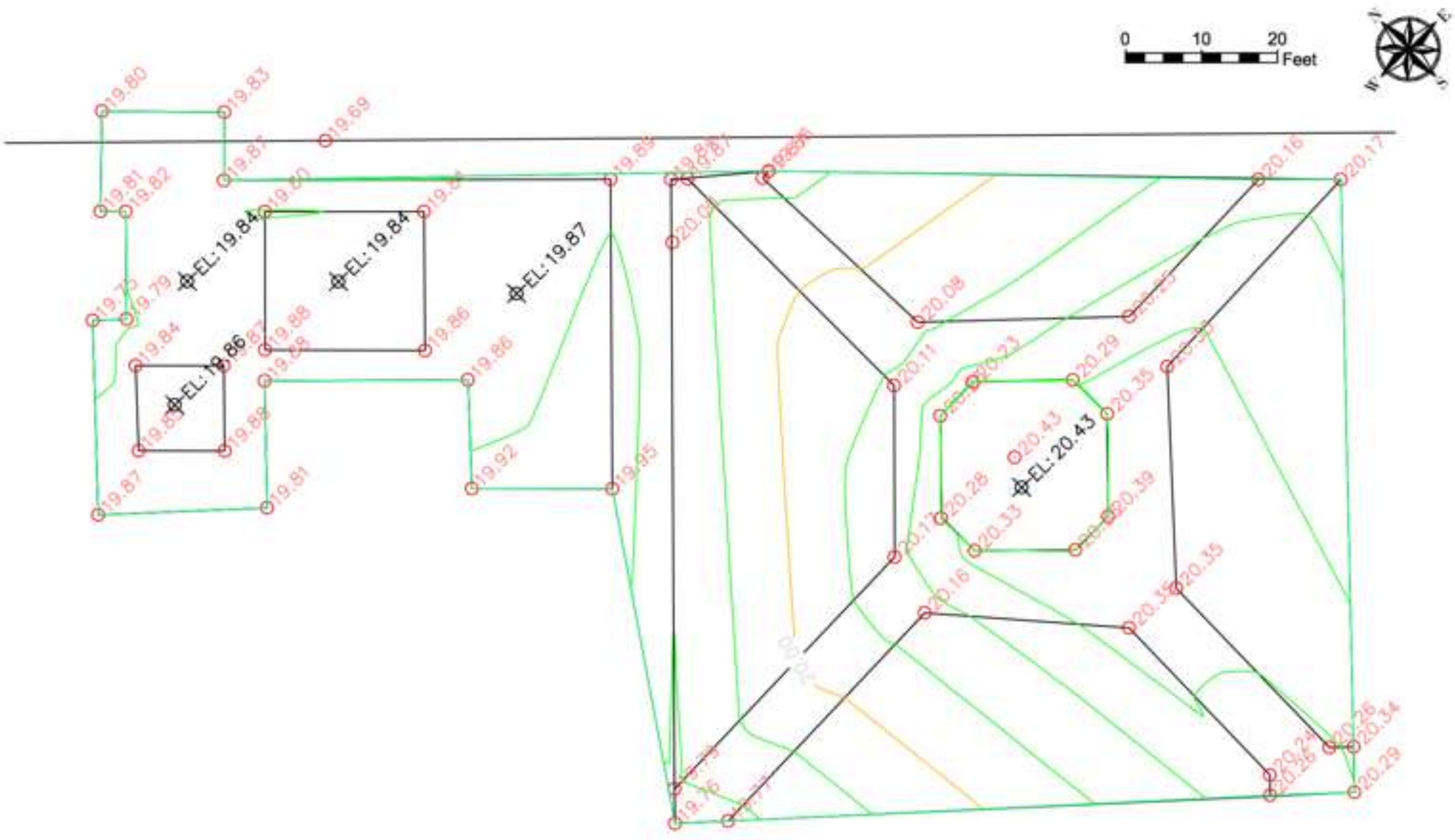
(6 inch thick)

Materials	Amount
Gravel	$0.059/lb
Superplasticizer	$0.13/mL
$NanoSiO_2$	$0.16/g
Water	$0.028/gal
GU cement	$0.08/lb
FA	$0 (Free)

PCA2 Implementation (January 2016)

Pervious Concrete Area 3 (PCA3)

Surveyed by Prof. Jose Flores, Valerie Lopez, and Rafael Terán



1260 ft^2

Partial-infiltration Design

Students







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Chapter 7

Mini Workshop

Assistant instructors

- Sionel Arocho
  - A recipient of the 2015-2016 Dwight David Eisenhower Transportation Fellowship
- Marleisa Arocho
  - A HEDGE graduate student in charge of the PCA1 site

Chapter 8.

Seminar Review: Hype, Hope and Nope


Pervious concrete
Hype
Hope
Nope

Contact

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Professor

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Thank You!

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