Permeable Pavement Systems as an Urban BMP for Water Quality And Quantity Control: A Sustainable Concept

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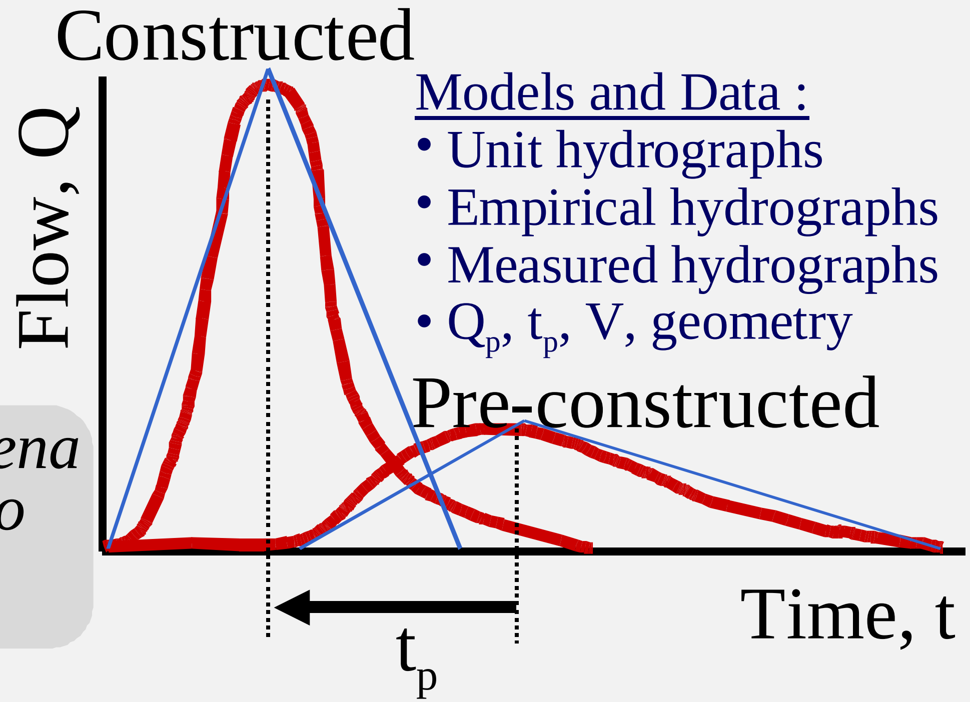
Hydrologic challenges created by urban land use

The urban environment modifies primary hydrologic components (*and therefore quality*) compared to the pre-constructed environment:

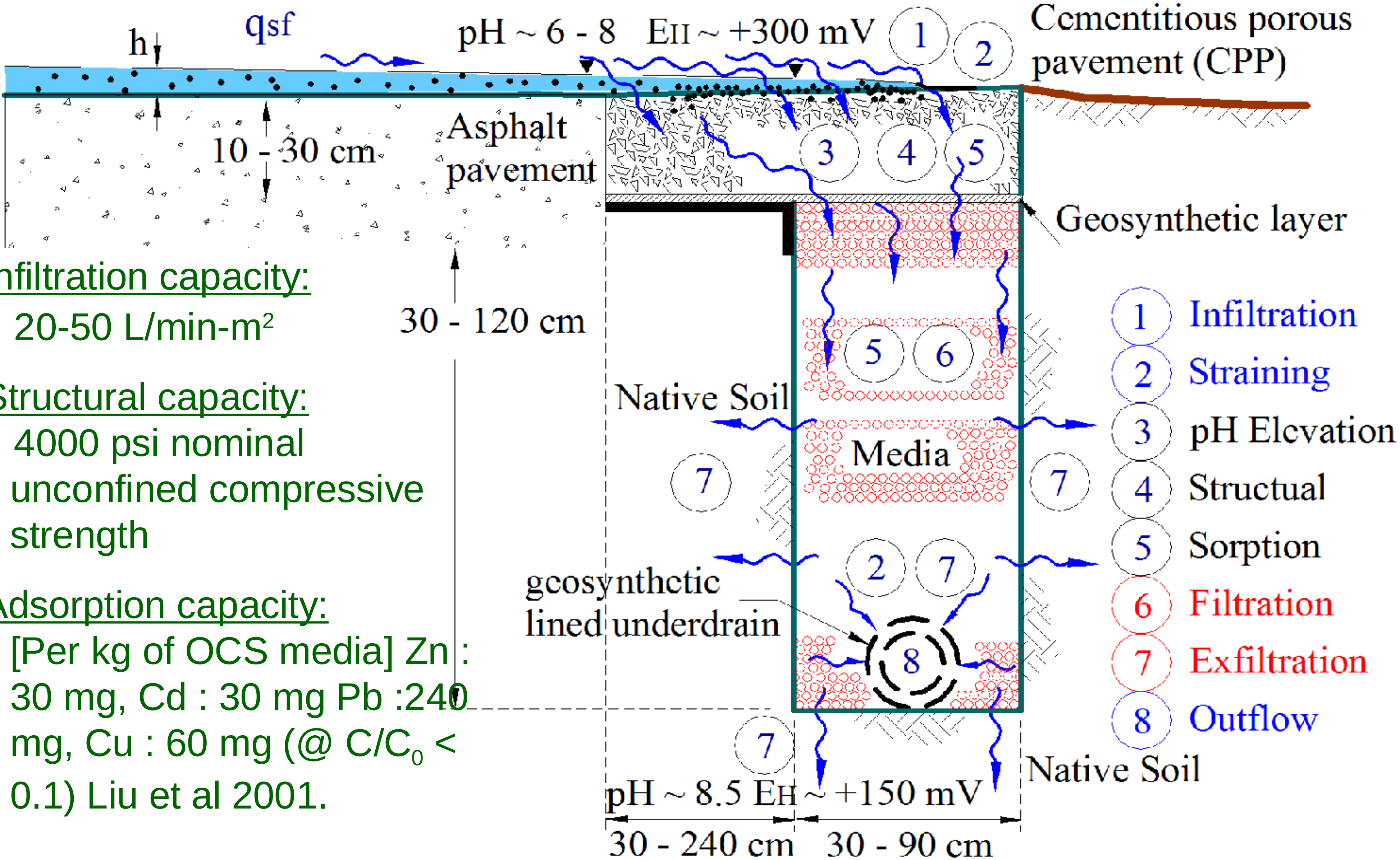
1. **Peak flow, Q_p increases,**
2. **Runoff volume, V increases,**
9. **Lag time, t_p decreases,**
11. **Infiltration decreases,**
5. **Evaporation decreases.**

Quality and quantity are coupled phenomena in urban drainage. Until societies begin to restore the hydrologic cycle; required treatment will be difficult to sustain.



- Example: A rainfall event generating 3 inches (7.6 cm) of runoff over a 200-acre urban catchment can generate over 16 million gallon of runoff volume. Consider the treatment infrastructure required to "control" and "treat" such volumes intermittently, ***if there is not some level of hydrologic restoration***.

A Partial Exfiltration Reactor (PER) with CPP



Infiltration capacity:

20-50 L/min-m²

Structural capacity:

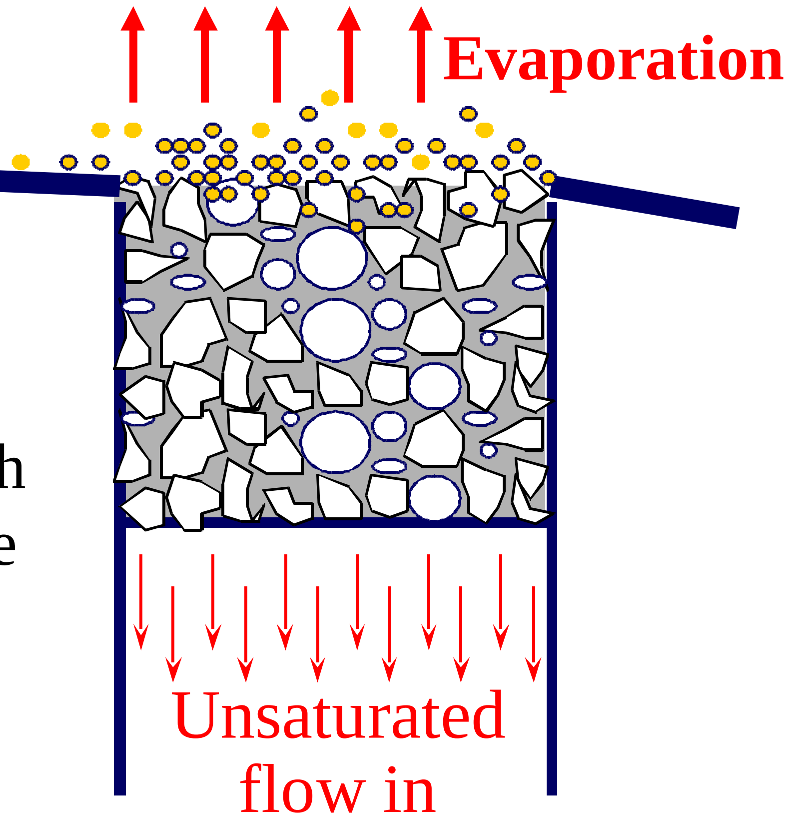
4000 psi nominal unconfined compressive strength

Adsorption capacity:

[Per kg of OCS media] Zn : 30 mg, Cd : 30 mg Pb :240 mg, Cu : 60 mg (@ $C/C_0 < 0.1$) Liu et al 2001.

Cementitious permeable pavement (CPP), as an in-situ material with behavior that can be measured/modeled

Lateral Sheet Flow, q_{sf}



CPP adsorptive-filter design:

• 11 - 15 kN/m^3	Unit weight
• 0.1- 0.005 cm/s	$K_{saturated}$ (clean bed)
• 25,000 – 30,000 Kpa	Unconfined strength
• 20 - 50 L/min-m^2	Surface loading rate

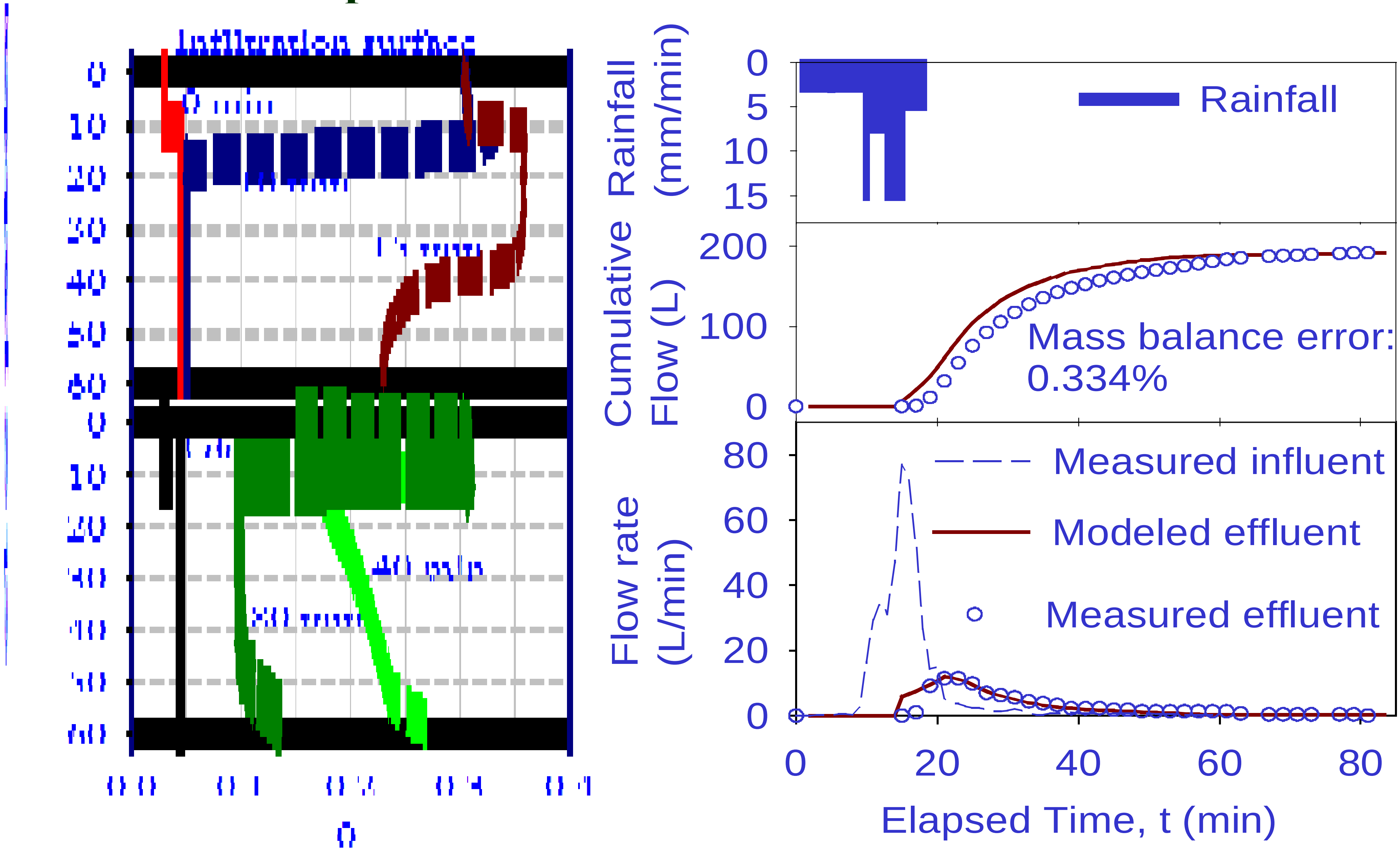
Mix Design Proportions:

• varies	Type II Cement
• varies kg	Sand
• varies kg	Gravel
• varies	Water
• 10 – 30 %	Total porosity
• varies	Amphoterics

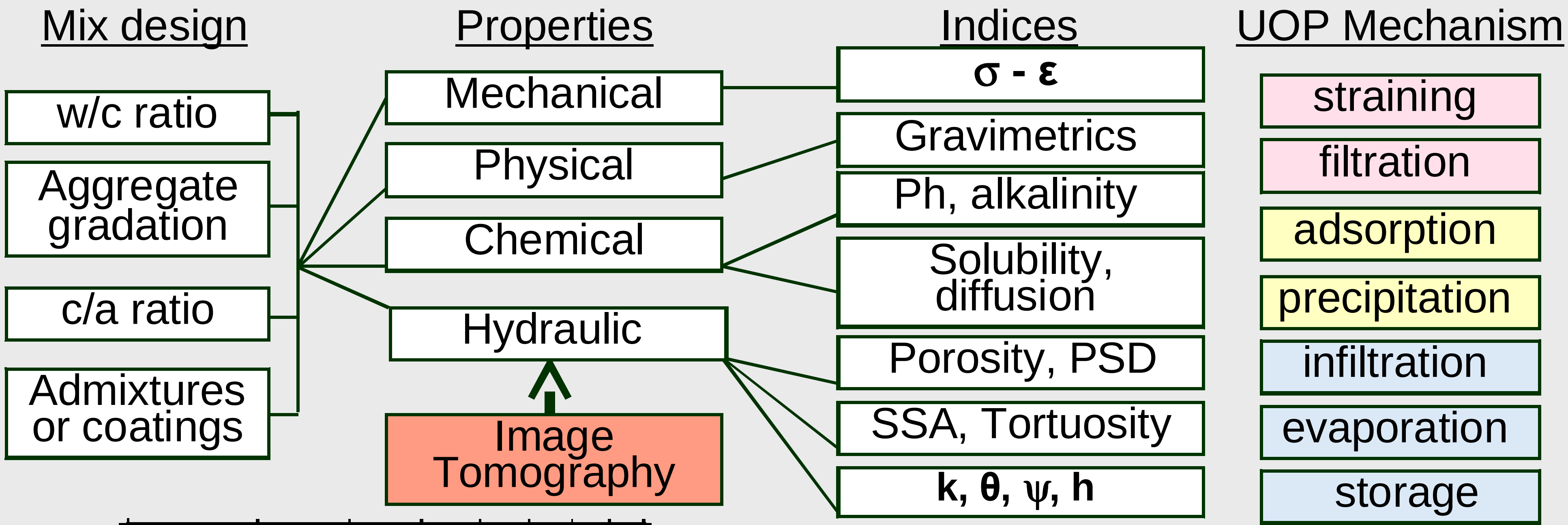
$K_{sat.}$ for media: 0.01 cm/s

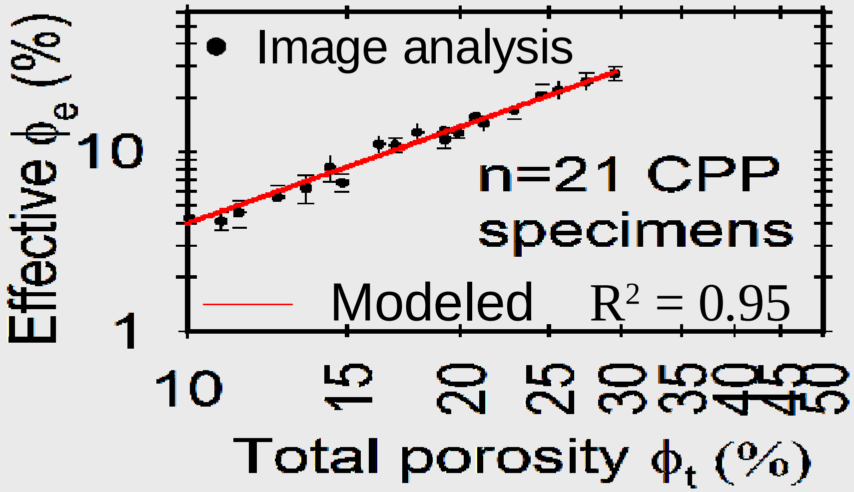
Solids & particulates

Water content profile and mass balance for 12 June 1997 event

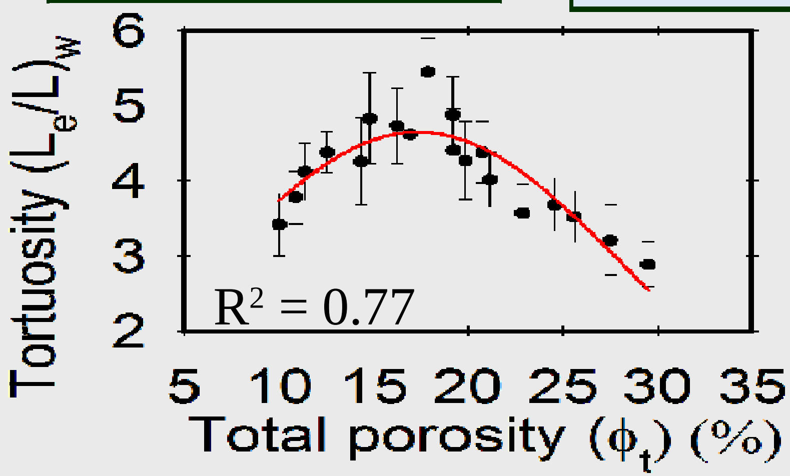


Permeable Pavement: A Multi-Purpose In-situ Material





$$\phi_e=(0.0642)(\phi_t)^{1.7929}$$

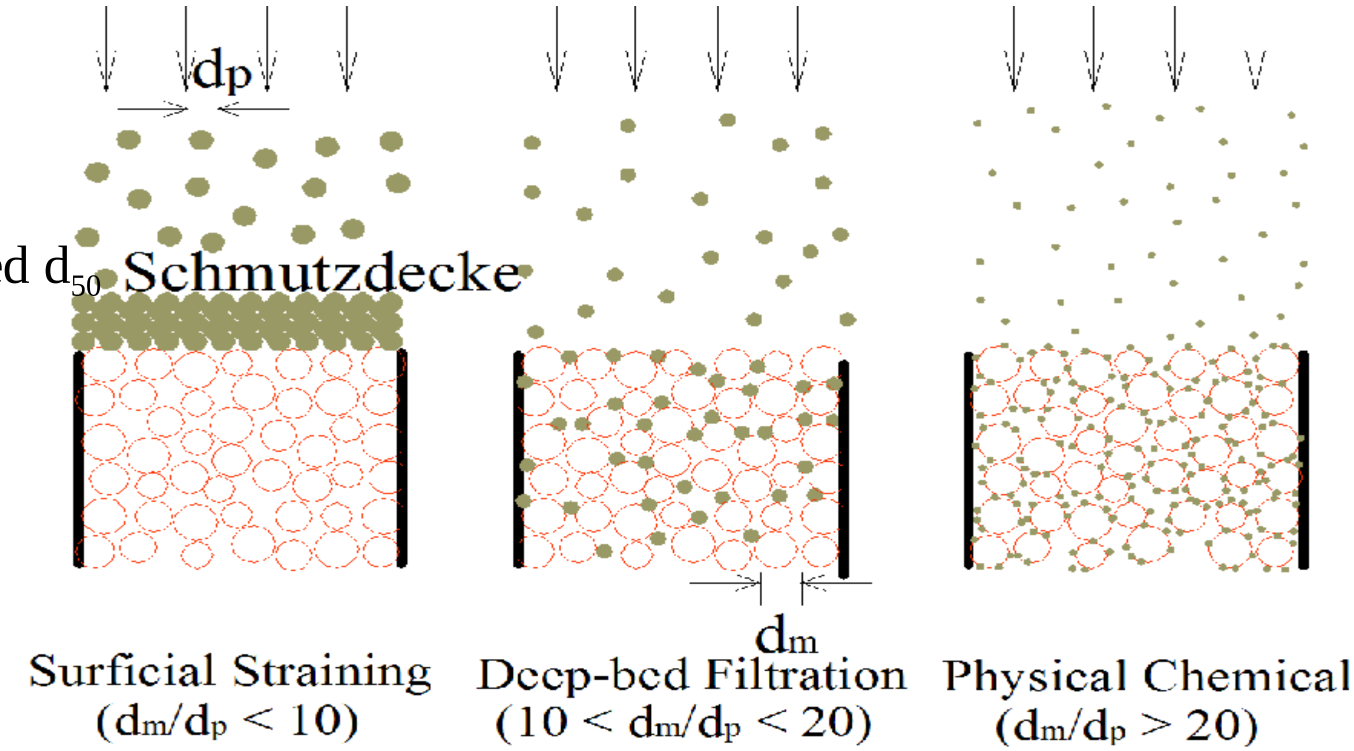


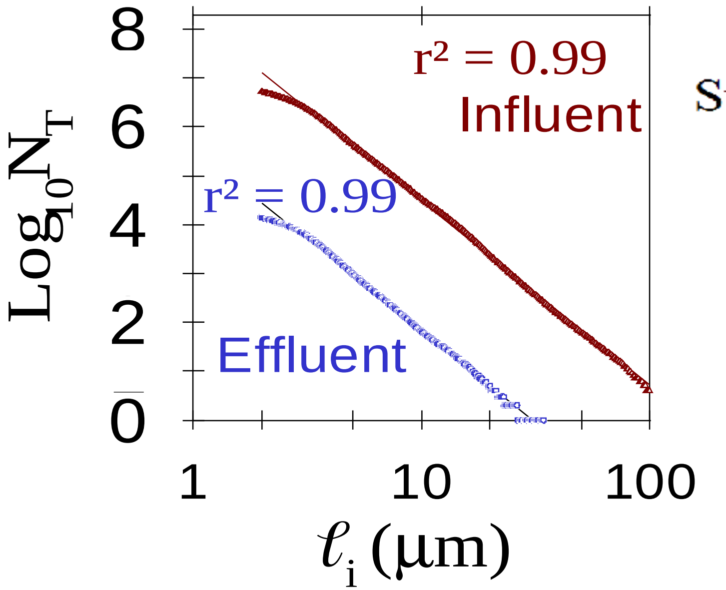
$$\left(\frac{L_e}{L}\right)_w=(4.65)e^{\left[-0.5\left(\frac{\phi_t-17.36}{11.09}\right)^2\right]}$$

Filtration mechanisms of the CPP layer at PER surface
(a pre- & primary treatment, protects media, can be maintained)

Filtration mechanism

d_m/d_p ratio using mass based d_{50} of media and particulates





The power law function uses cumulative particle number density (PND) of all particles larger than the reference value R (i.e. 1 μm).

$$N_T = \alpha\left(\frac{l_i}{R}\right)^{-\beta}$$

XRT imaging and image processing

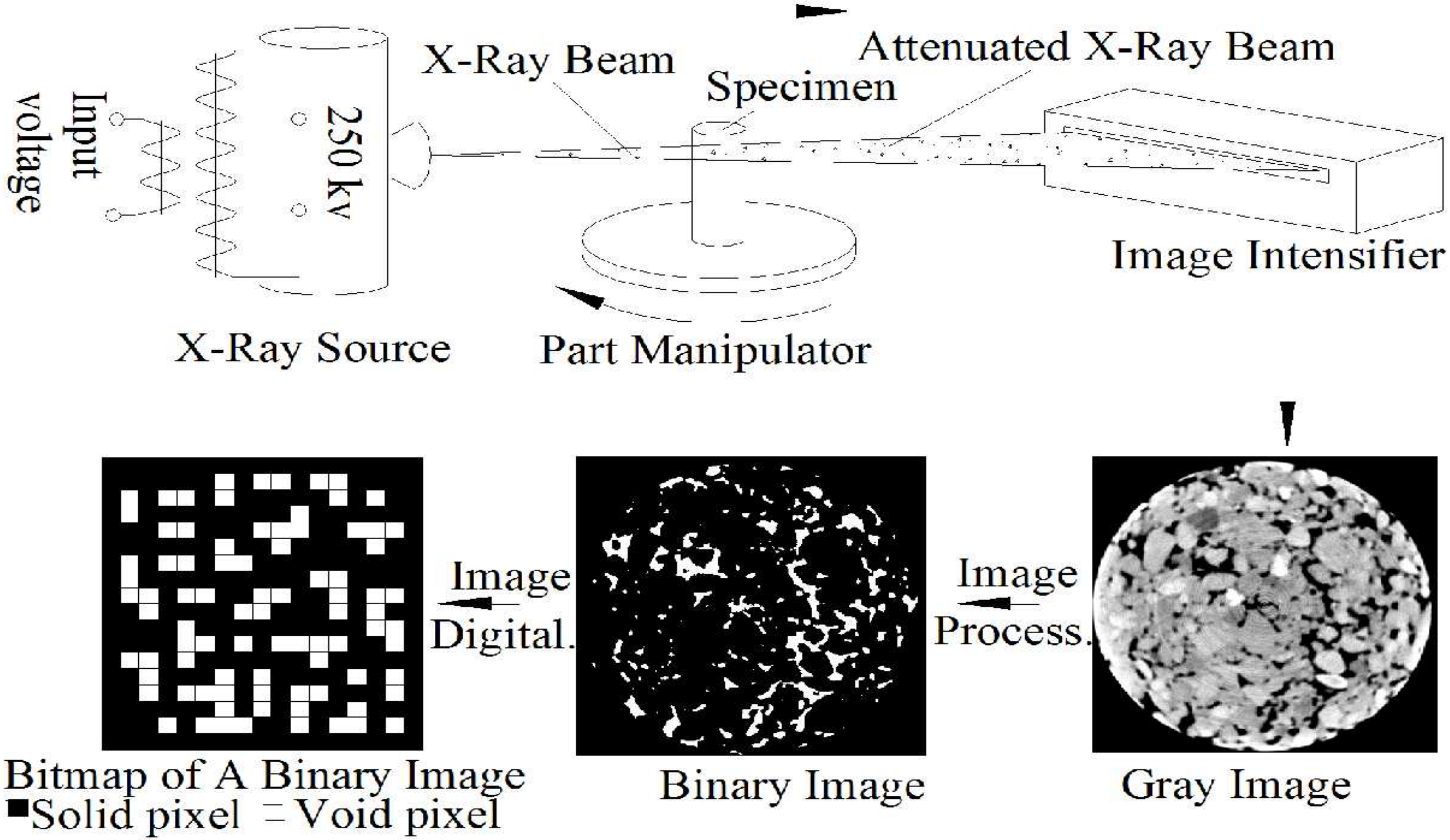


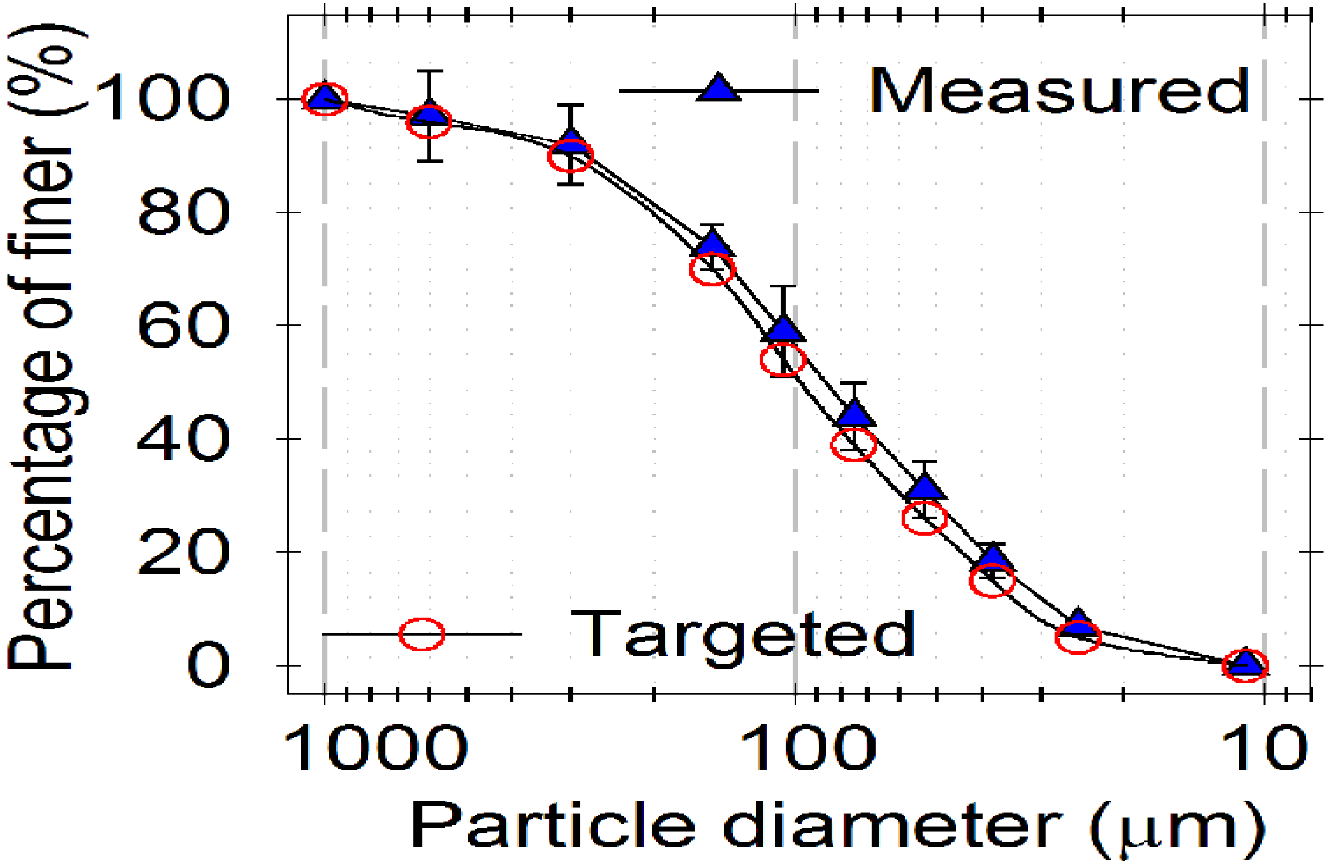
Image resolution R_r = 30 μm, 200 image slices were acquired along the height evenly with a spacing ≈ 0.5 mm

Experimental matrix summary with mass balance for CPP

Particle loading $[m]_i$, (mg/L)	50	100	200
Hydraulic loading rate, Q_i (L/m^2-min)	22.28	22.17	22.35
Initial, k_i (10^{-2} cm/s)	3.23	3.04	3.24
Final, k_f (10^{-5} cm/s)	6.97	6.29	5.58
Elapsed time, t_e (hour)	252	197	136
Particles in influent particles, M_i (g)	60.9	92.7	131.6
Particles in overflow, M_o (g)	43.7	74.3	111.6
Particles in effluent, M_e (g)	2.1	2.0	1.5
Particles strained on surface, M_s (g)	14.0531	15.2368	16.8598
Strained particle thickness, h_{st} (mm)	1.5	1.6	1.8

Mass balance error for each experiment < 10%

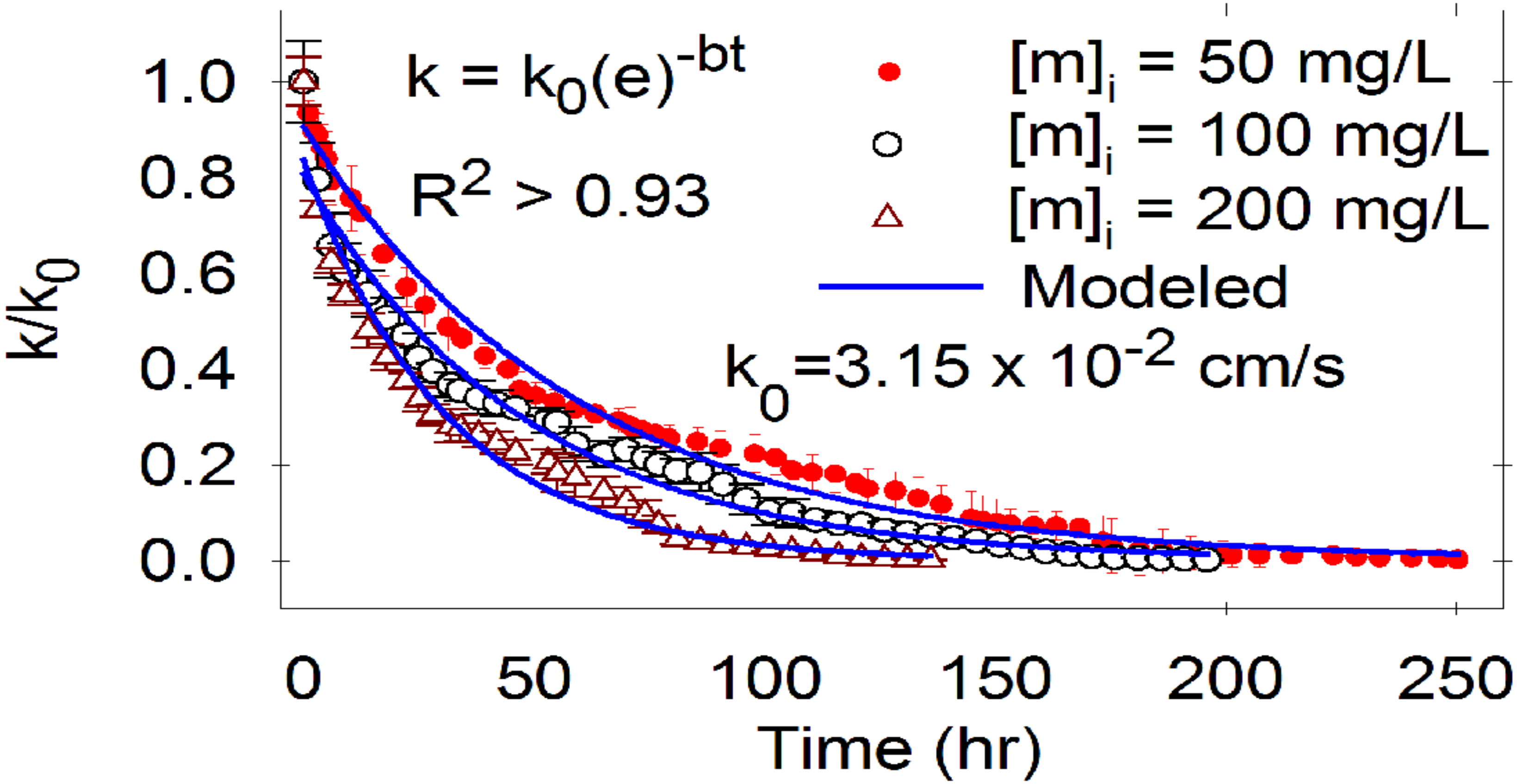
Methodology: Particle Loading Size Gradation



d_{90}	300 μm
d_{50}	75 μm
d_{10}	25 μm

Particles: sandy silt
Loading concentration: 50, 100, and 200 mg/L
CPP pore characteristics: $\phi_t > 27\%$ and $\phi_e \geq 23\%$

CPP hydraulic conductivity (k) functions for typical highway pavement particulate (SSC) loadings



$[m]_i$ = 50 mg/L

b = 0.0218

$[m]_i$ = 100 mg/L

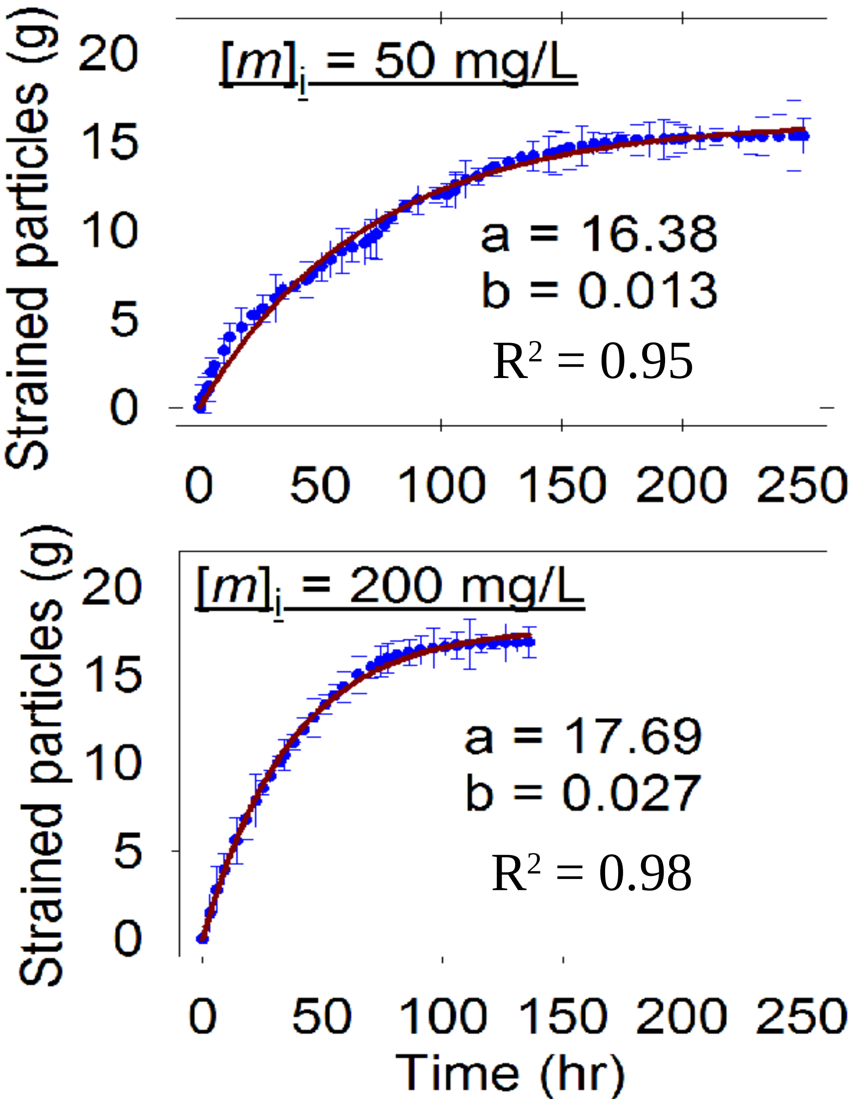
b = 0.0245

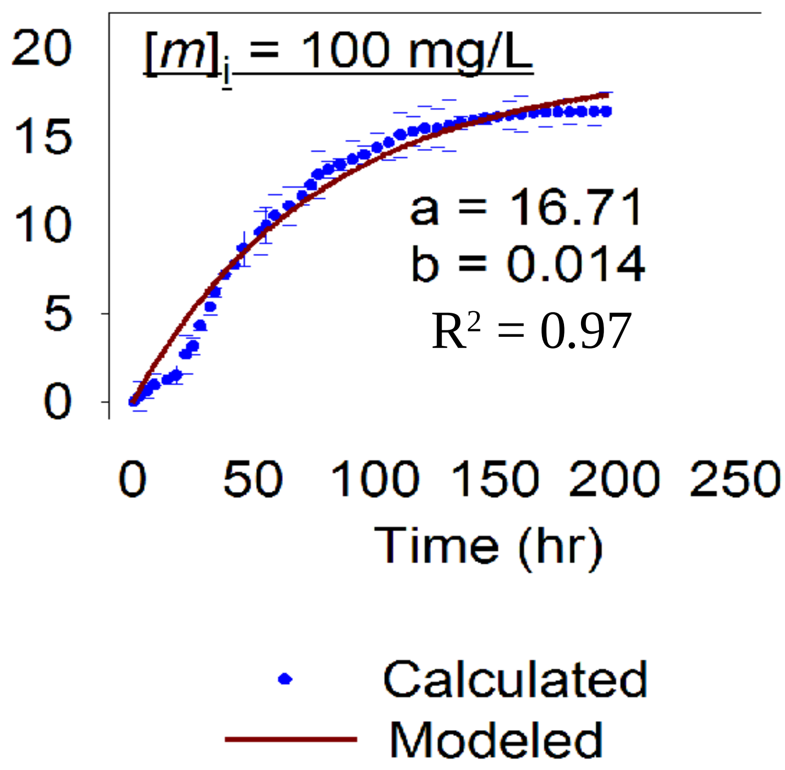
$[m]_i$ = 200 mg/L

b = 0.0356

k_0: the initial hydraulic conductivity with normalized k(t) data modeled using a 1st order exponential function that can be a model input in SWMM

Results: cumulative strained particles on the CPP surface

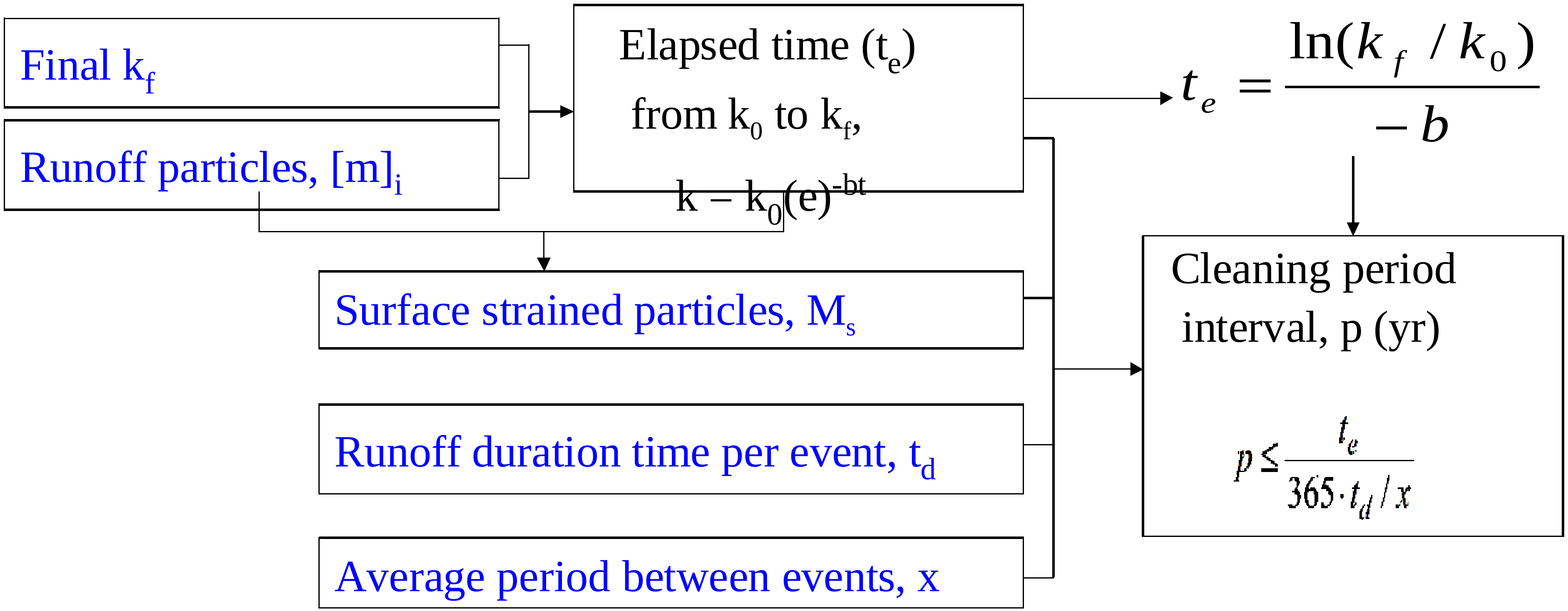




$$M_s = a(1-e^{-bt})$$

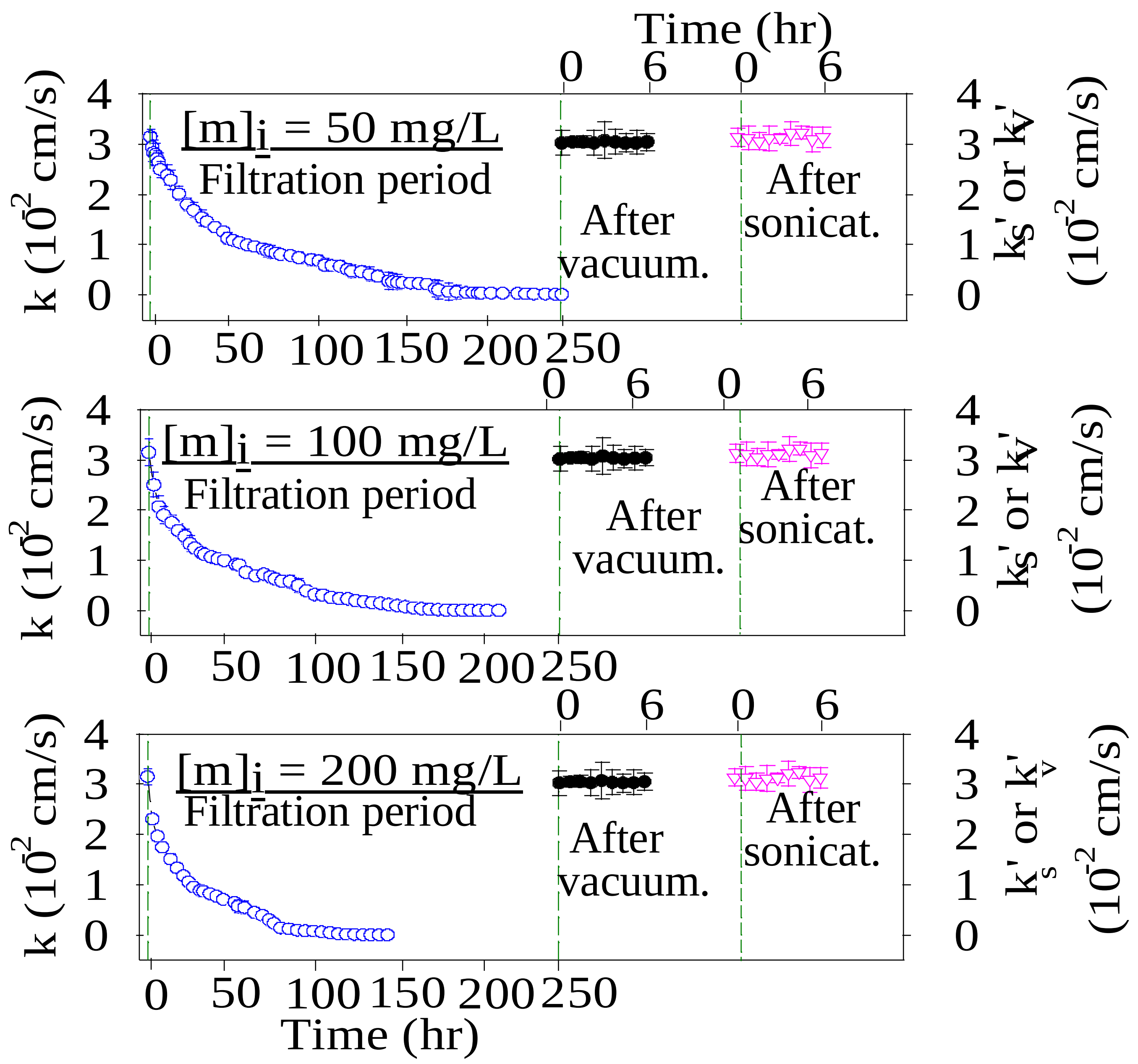
Again, another model that can be used as input into SWMM

Maintenance cycle determination on k_f basis



Runoff duration (t_d) per event:	3 hours (total duration of 156 hours)
Average period (x) between events:	4 days
Minimum hydraulic conductivity (K_f):	10^{-3} cm/s
Mass concentration $[m]_i$ loading:	100 mg/L at Q_i for sandy silt gradation
Maintenance cycle (P):	**0.57 years for this simple example**

K restored by surface cleaning: Vacuuming or Sonicating



After vacuuming

k_v/k_0 = 97.3%

After sonicating

k_s/k_0 = 99.6%

After vacuuming

k_v/k_0 = 96.1%

After sonicating

k_s/k_0 = 99.8%

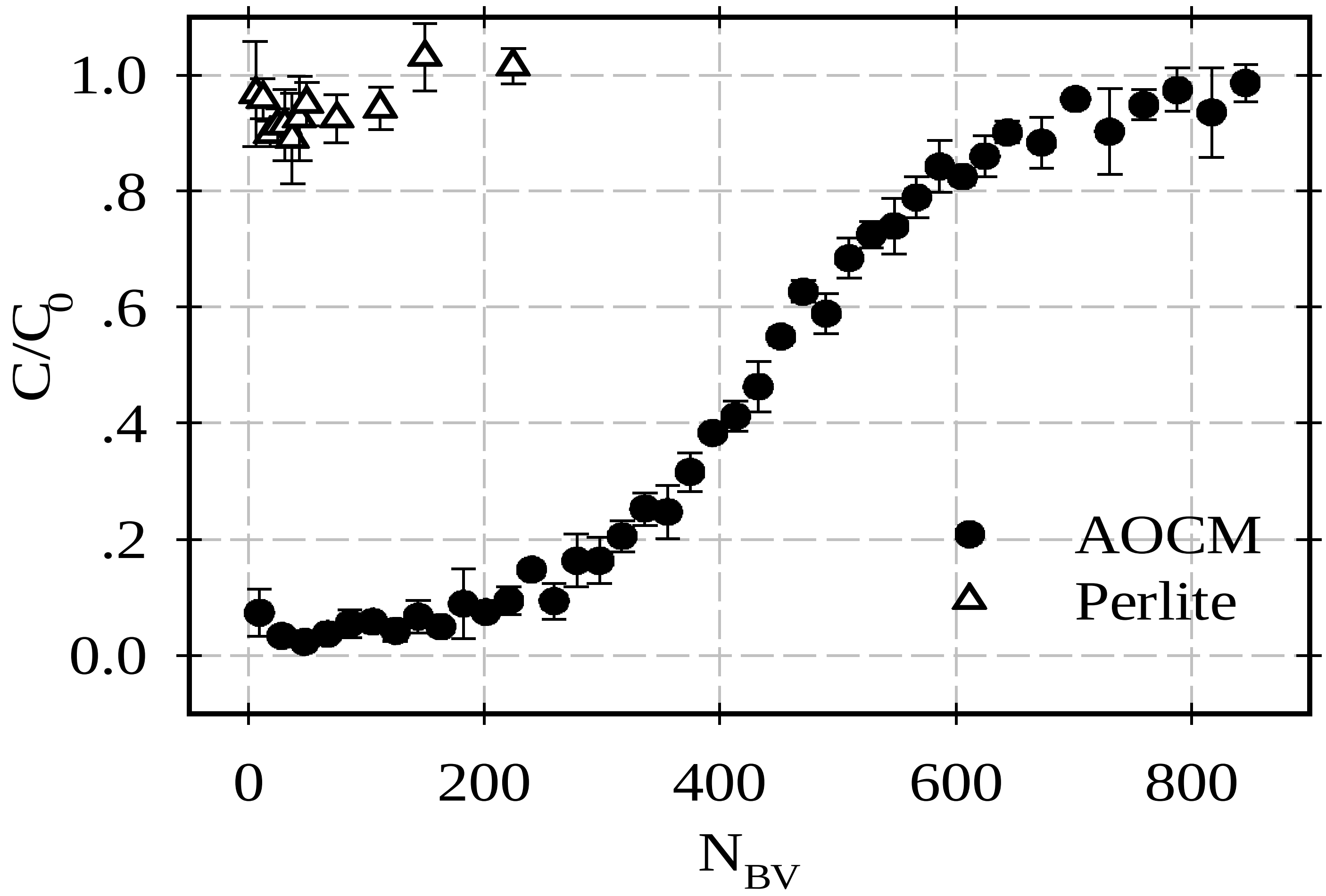
After vacuuming

k_v/k_0 = 96.9%

After sonicating

k_s/k_0 = 99.3%

Breakthrough Comparison of AOCM and Perlite



Experimental conditions:

2. Influent dissolved P = 0.5 mg/L; 2. pH = 7.0; 3. Ionic strength = 0.01M KCl;

4. AOCM size = 2.00 ~ 4.75 mm; 5. Surface loading = 40 L/(m^2-min)

Parametric Comparison of P adsorption on AOCM and Perlite with model parameters

	K_F	n	R^2
AOCM	0.722	0.42	0.985
Perlite	0.002	2.29	0.998

Freundlich Isotherm

$$Q_e = K_F C_e^{\,n}$$

	q_e	k_2	R^2
AOCM	0.117	0.552	0.988
Perlite	0.020	1.370	0.986

2nd order kinetics

$$\frac{dq_t}{dt} = k_2 (q_e - q_t)^2$$

	X/M_b (mg/g)	X/M_{exh} (mg/g)	V_b (BV)	V_{exh} (BV)
AOCM	0.17	0.35	221	673
Perlite	< 0.001	< 0.02	0	<10

Thomas model

$$\frac{C_t}{C_0} = \frac{1}{1 + \exp\left[\frac{k}{F}(Q_e m - C_0 V_b N_{BV})\right]}$$

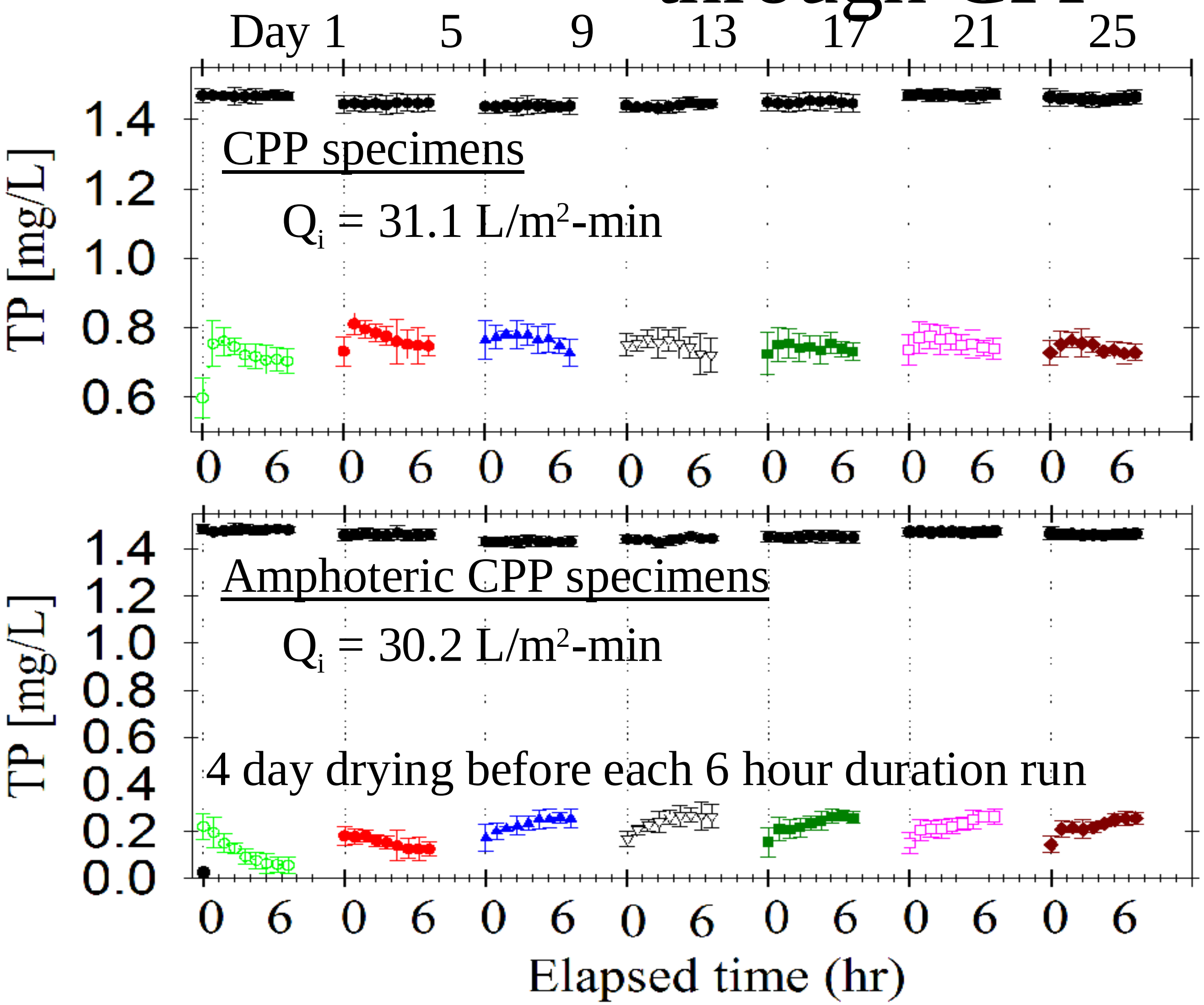
X/M_b = breakthrough capacity as $C/C_0 = 0.1$;

X/M_{exh} = exhaustion capacity as $C/C_0 = 0.9$;

V_b=number of bed volumes (BV) treated at effluent breakthrough as C/C_0=0.1;

V_{exh} number of bed volumes (BV) treated at effluent exhaustion as C/C_0=0.9;

Total Phosphorus (TP) removal after infiltrating through CPP



Removal efficiency

β_{1-7} = 51.4, 46.9, 47.7, 48.9, 49.8, 49.5, 50.1%

Removal efficiency

β_{1-7} = 92.2, 90.0, 84.0, 83.4, 84.3, 83.4, 85.0 %

CPP as an In-situ Control System, including AOCM

1. Hydrology, chemistry, volume and particulate transport are complex and coupled phenomena. Ultimately successful permeable pavement designs will reflect this reality, provide synthesis and incorporate geotechnical issues.

2. Permeable pavement systems require analyses based on **effective porosity** and **weighted tortuosity**. Both hydraulic conductivity and filtration results follow first-order exponential relationships for CPP.

3. Both permeable pavement and engineered granular subgrade must be developed with a calibrated and validated model that can be used as plug-ins to models such as SWMM. As with any control, an **actual** mass balance is a requirement.

4. Restoration of hydraulic conductivity by **vacuuming** or **sonication/vacuuming** can restore nearly all of the hydraulic capacity of the pavement matrix.

5. Granular base or media performance is very, very different as can be seen with a comparison of engineered AOCM as compared to conventional storm water media such as perlite. AOCM exhibits negligible desorption.

6. These systems beneficially enhance hydrologic, chemical and particulate parameters back to pre-modified conditions