同济大学交通运输工程学院
COLLEGE OF TRANSPORTATION ENGINEERING
TONGJI UNIVERSITY

ICPP 2018, Shanghai, China ・Oct 24-26, 2018

Porous Materials and Permeable Pavement for Heavy Load

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Outline

1. Porous Materials and Eco-Functions of Permeable Pavement

2. Investigation on Application in Heavy Loads

3. Demo Projects

Percentage of Pervious Pavement

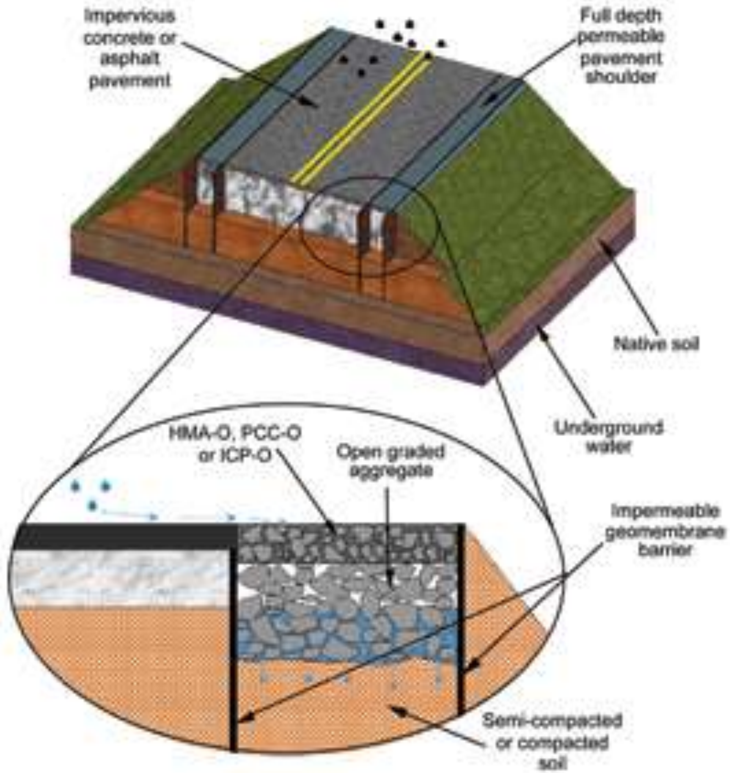
Policy in Shanghai: Effective on Jan 1st 2016， to Dec 31, 2020：

- Overhead road, walkway in car-free zone:
  - >=70% for new projects
  - >=50% for retrofitted projects
- Sidewalk, plaza, parking lot:
  - >=50% for new projects
  - >=30% for retrofitted projects
- Bike path:
  - >=40% for new projects
  - >=20% for retrofitted projects

Porous Material and Permeable Pavement

Porous Concrete

Porous Asphalt



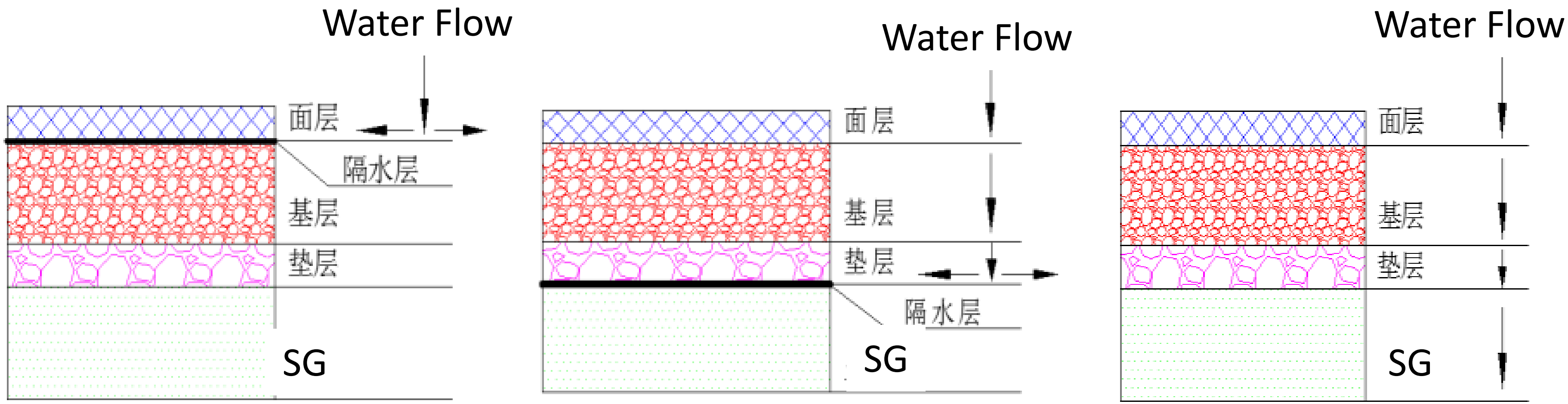
Permeable Pavement

Permeable Pavement: Surface Type

Permeable Pavement

- Porous Asphalt
- Pervious Concrete
- Permeable Paver
- New Materials

Permeable Pavement: Flow Type

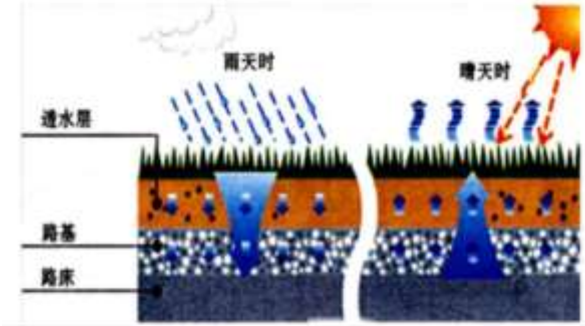


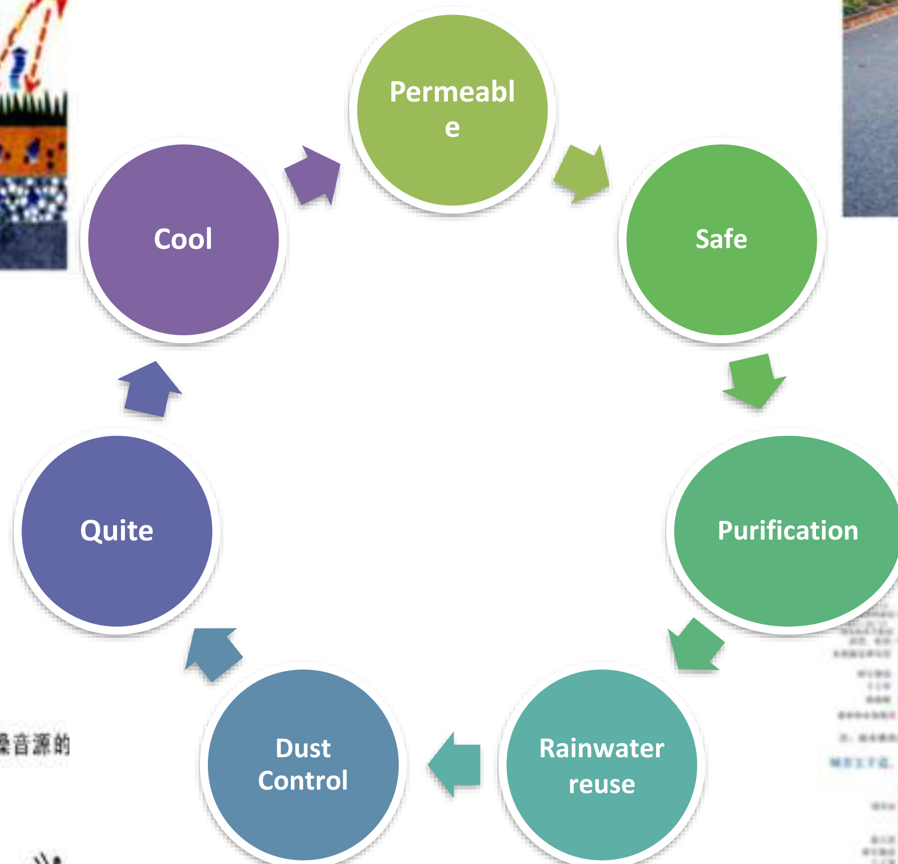
Permeable Surface Only (OGFC)

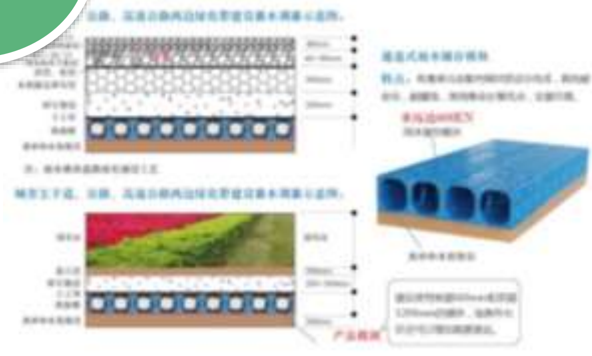
Semi-Permeable

Fully Permeable

Eco-functions of Porous Materials







Applications of Pervious Pavement

Current：Light Traffic Pavement

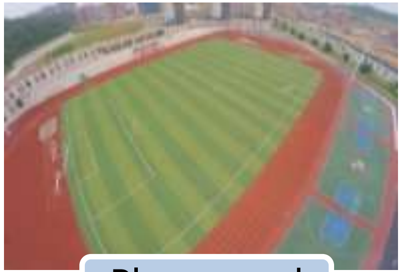

City Street


Plaza


Parking Lot


Walkway


Park Trail


Playground

Potential：Heavy Duty

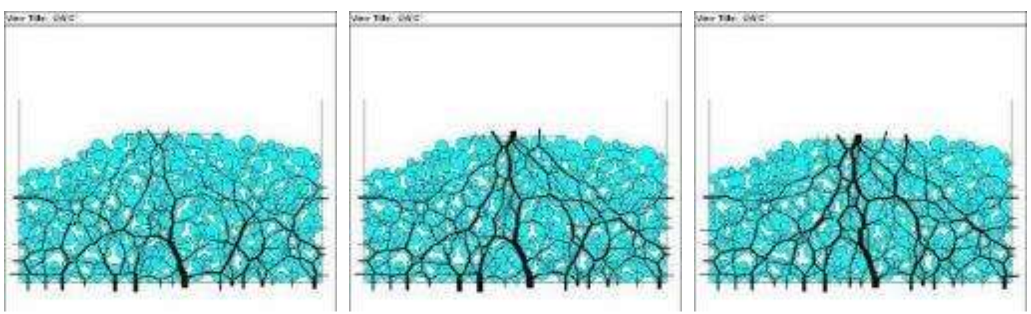

Highway

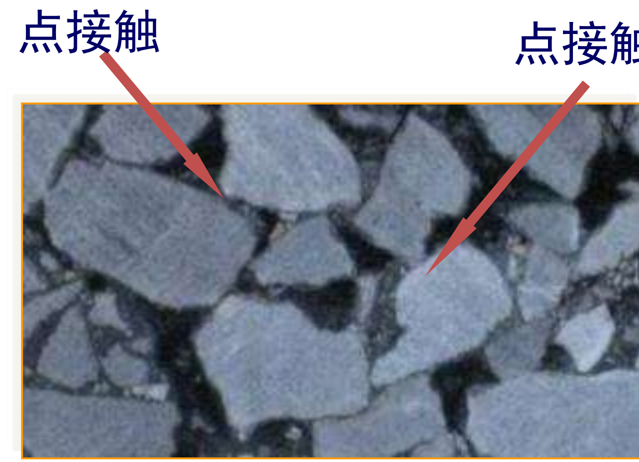

Airport


Port

多孔隙材料骨架结构 Pore Structure

- 材料结构：骨架 - 空隙结构；
- 空隙率：18~22%；
- 粗集料：用量大，约占集料总质量85%；
- 接触状态：集料间接触面积减少约25%，接触点应力高。





透水铺装技术难点 Key Issues

现阶段，透水铺装技术尚未成熟，仍处在探索研究，距离大规模推广应用、特别是在高频重载铺装上的应用还有不少亟待解决的技术难题，主要如下：


透水铺面车辙


透水路面水损害


冻胀破坏

技术难题

耐久性差

耐久性差，易出现剥落、坑槽等水损害

冻胀破坏

寒冷地区，容易因冻胀而产生破坏

强度不足

透水路面结构强度不足，容易产生车辙

孔隙堵塞

孔隙容易被堵塞，失去透水及相关功能

主要研究方向：（高频重载）多孔隙材料与透水铺结构研究

全生命周期评价与管理

- LCCA
- LCA

设计

- 多孔隙材料设计
  - 面层（水泥、沥青、铺砖）
    - 集料
    - 级配
    - 胶结料
    - 改性剂
  - 基层
  - 土基
- 透水铺装结构设计
  - 渗流设计
  - 力学设计

施工工艺

- 材料
- 装备
- 工艺

管养技术

- 检测技术
- 功能养护
- 结构维修
- 路面再生

性能

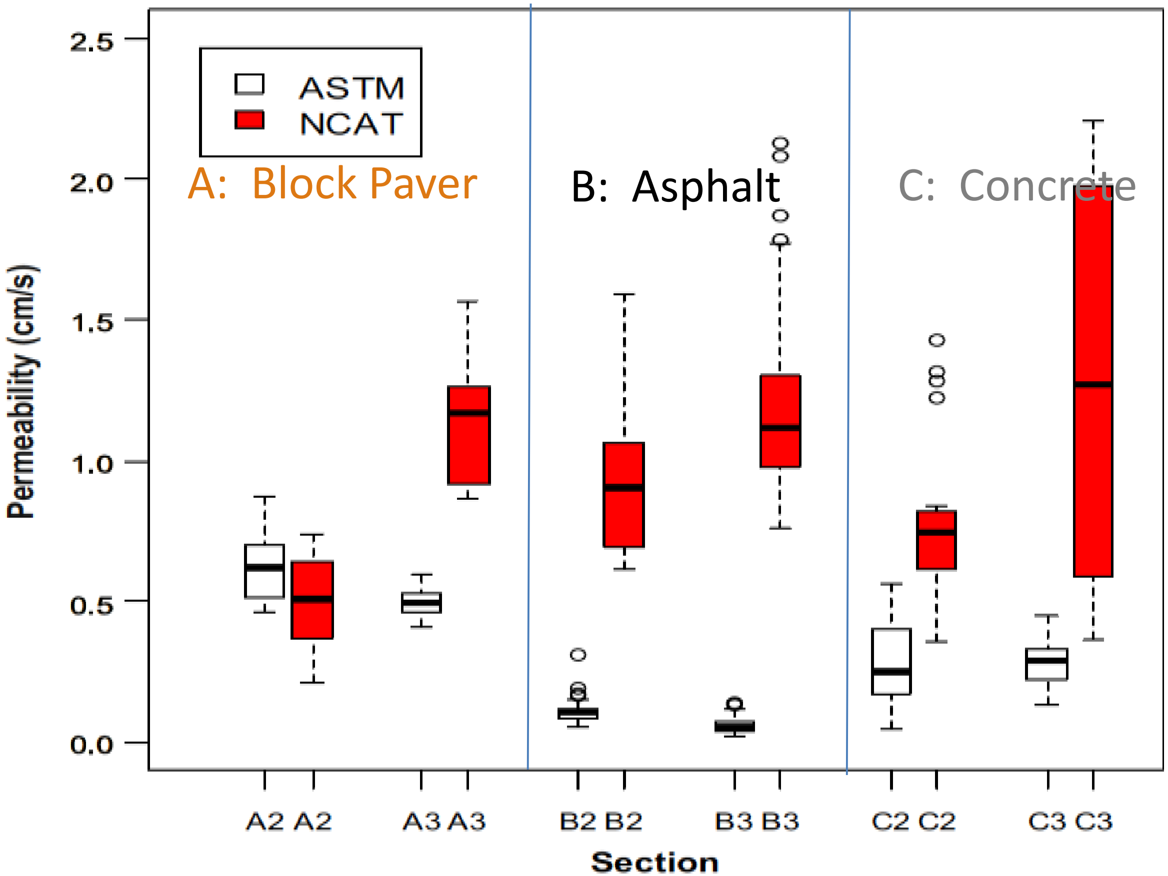
- 环保性能
  - 透水
  - 水净化
  - 降温
  - 降噪
  - 扬尘控制
- 力学性能
  - 强度
  - 模量
  - 永久变形
  - 疲劳
  - 低温开裂
  - 抗剥落
  - 老化

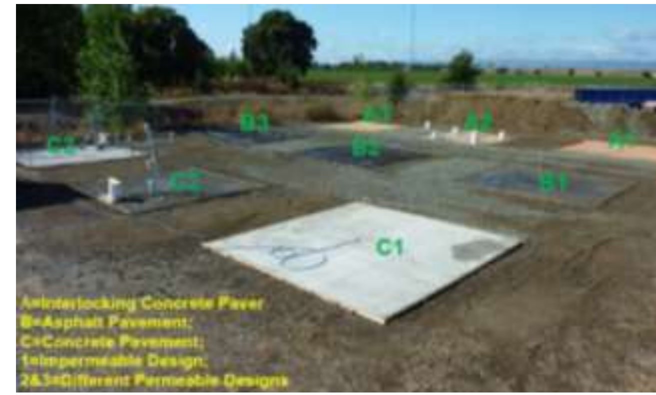
目标：开展系统性研究，注重科研与工程实践相结合，推进道路交通基础设施的多功能化和全寿命周期可持续性。

Water Permeable

Porous in materials,
permeable for water

Permeability





Li H., M. Kayhanian and J. Harvey (2013). Comparative Field Permeability Measurement of Permeable Pavements using ASTM and NCAT Methods. ***Journal of Environmental Management***, *118 (2013): 144-152.* DOI: 10.1016/j.jenvman.2013.01.016 *(SCI, EI, IF: 3.9)*

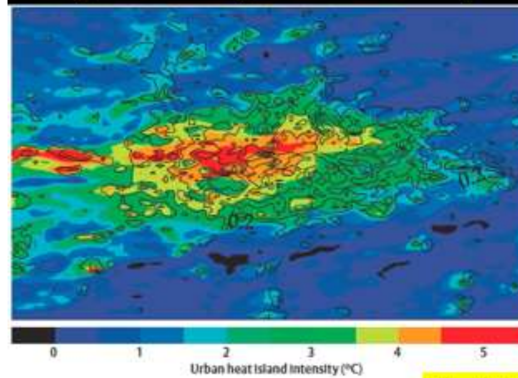
Permeability (a.k.a. hydraulic conductivity or infiltration rate), ASTM & NCAT method

Cooling Effect

- a.k.a “Cool Pavement Technology”；
- High albedo (if any), reflective cooling;
- Porous materials have low thermal capacity and conductivity, high thermal resistance = insulation cooling;
- Evaporative cooling (moisture in porous materials).

Heat Island Effect

was first identified in the early 1800s in London



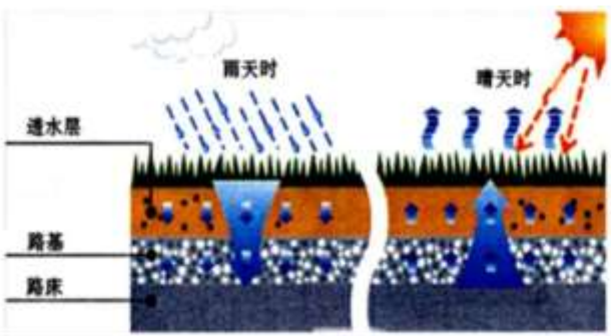
'London's growth over the next decade needs to ensure that new development is located, designed and constructed to minimise, and if possible reduce its contribution to London's urban heat island.'

From London's Urban Heat Island: A Summary for Decision Makers, Greater London Authority 2006

Types of heat island effect
- Urban
- Near-surface air
- Surface (hot spot)

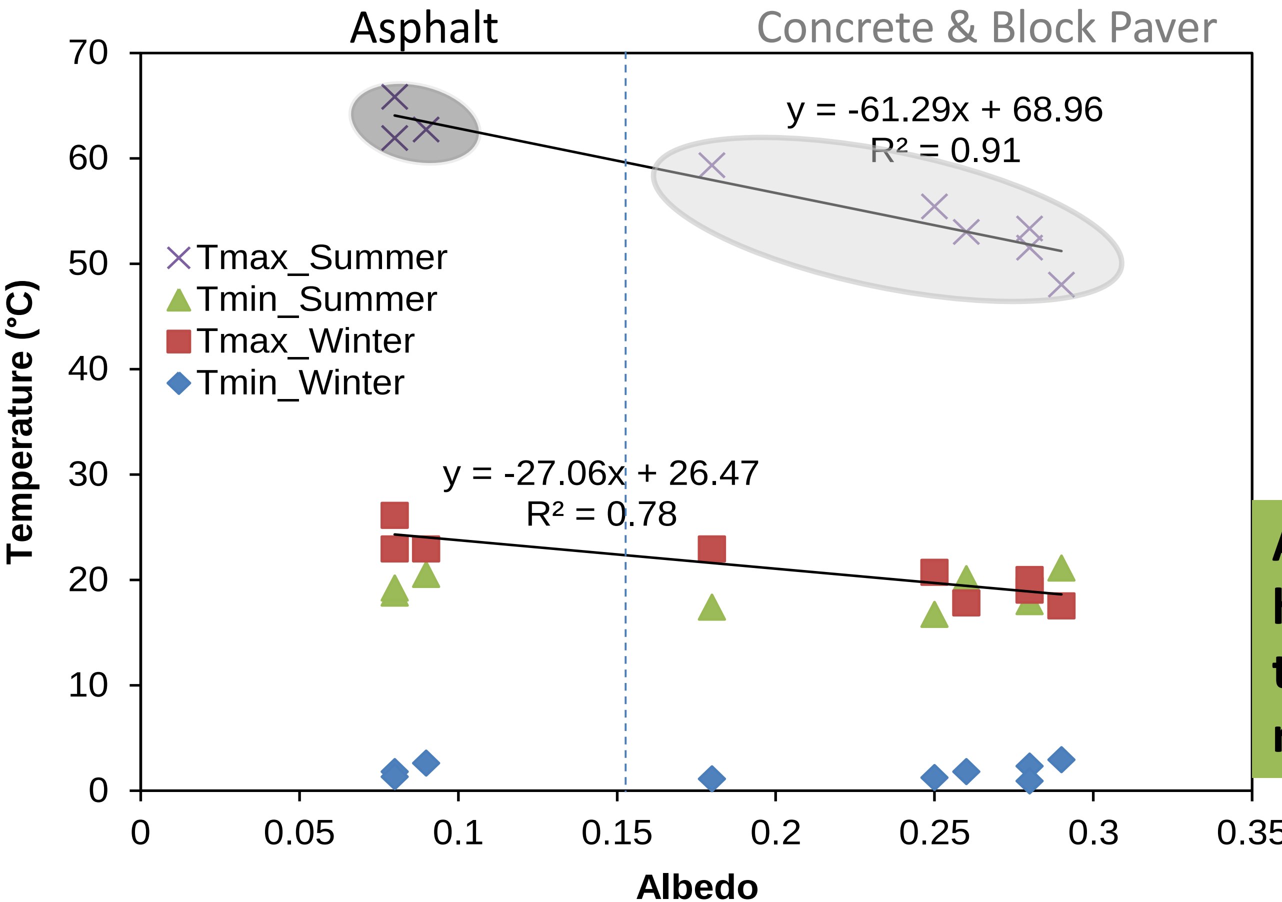
Heat Island Effect:
- Increase heat stress
- Compromise human thermal comfort and health
- Impair air quality (ground-level ozone, i.e. smog)
- Increase cooling energy consumption
  - Total energy use
  - Peak demand for energy

Research Highlights 2010, http://www.walker-institute.ac.uk 3



雨天：路面不积水，雨水及时渗透排走。
晴天：地气上升，缓解城市热岛效应。

Effect of Albedo on Pavement Temperature



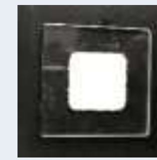
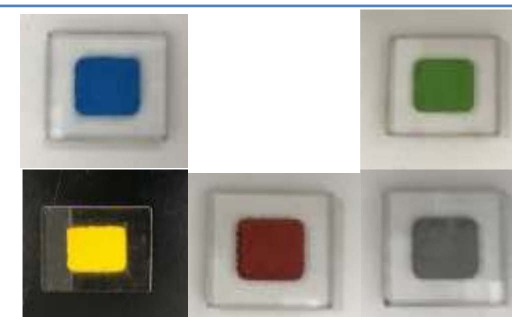
Albedo increase by 0.1，high pavement temperature in summer reduced by ~6 C。

Li H.*, J. Harvey and A. Kendall (2012). Field Measurement of Albedo for Different Land Cover Materials and Effects on Thermal Performance. ***Journal of Building and Environment***, 59(0):536-46. DOI: 10.1016/j.buildenv.2012.10.014 *(SCI, IF: 3.0)*

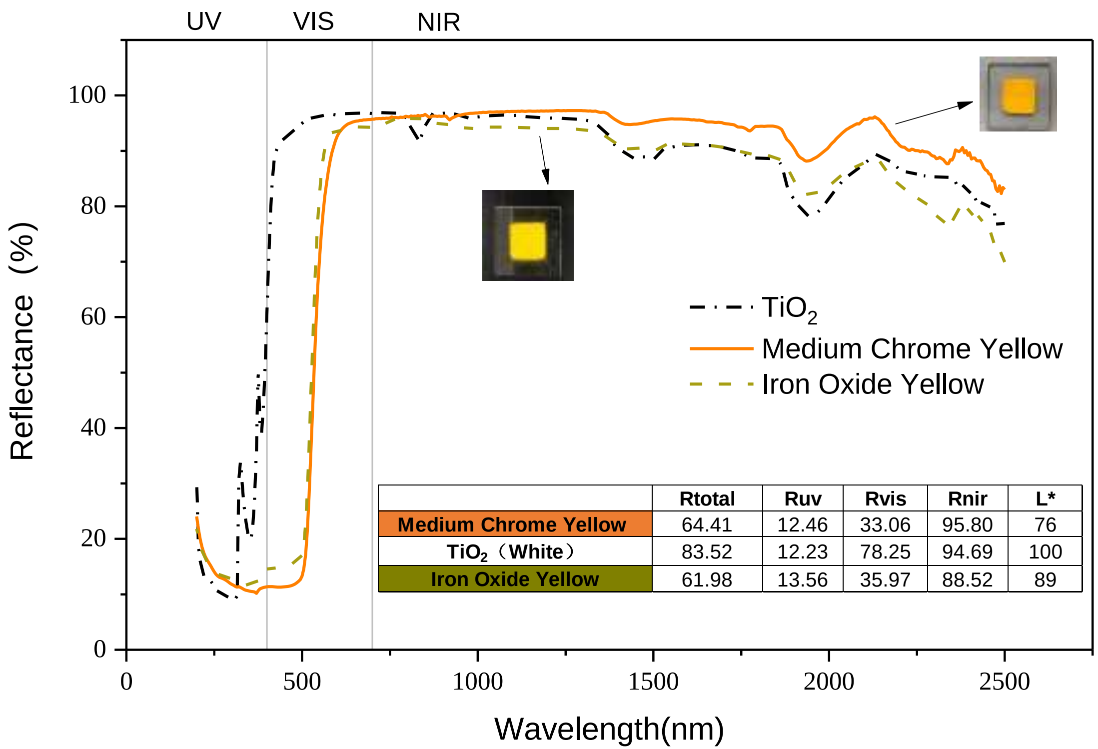
Colored Pavement

- Increased albedo，lowered temperature；
- Adds richness, color, and beauty to landscape design；
- Increases visibility & awareness，enhance safety in walk paths and bike lanes (bus lanes)。

Cool Material—— Functional filler

Type	Color	Sample
二氧化钛Titanium Dioxide	白色White	
二氧化硅Silicon Dioxide		
氧化铝 Aluminium Oxide		
氧化镍Nickel Oxide	黑色Black	
四氧化三铁 Ferriferrous Oxide		
三氧化二铁及其水合物 Ferric Oxide	蓝色Blue	
	绿色Green	
	黄色Yellow	
	红色Red	
	灰色Grey	

Results：Pigment Reflectivity—— Medium chrome yellow

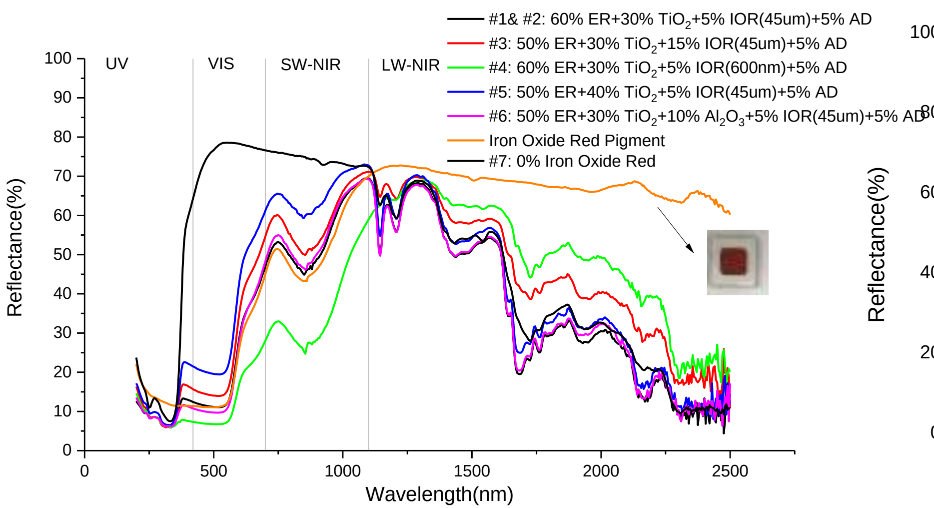


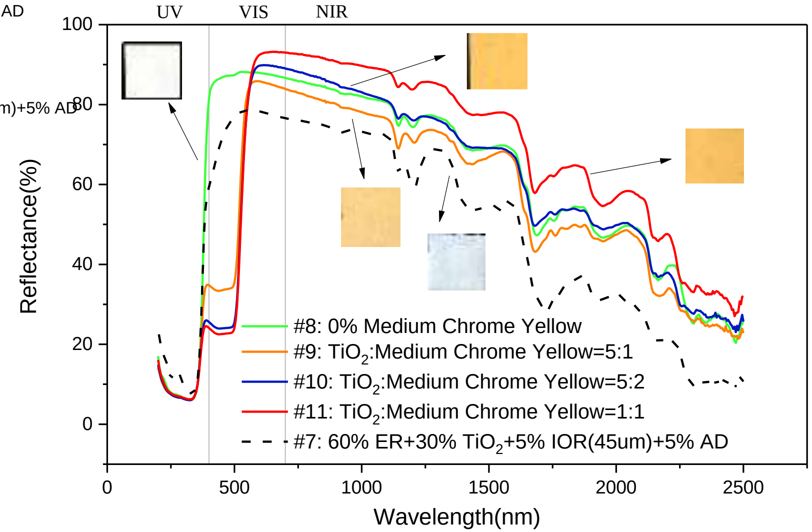
	Rtotal	Ruv	Rvis	Rnir	L*
Medium Chrome Yellow	64.41	12.46	33.06	95.80	76
TiO_2（White）	83.52	12.23	78.25	94.69	100
Iron Oxide Yellow	61.98	13.56	35.97	88.52	89

Compared with titanium dioxide, visible light reflectance is very low, while achieving the same near-infrared light reflectance

Low brightness, high reflective coating

Conclusion1：Optimal Formulation Based on Optical Properties

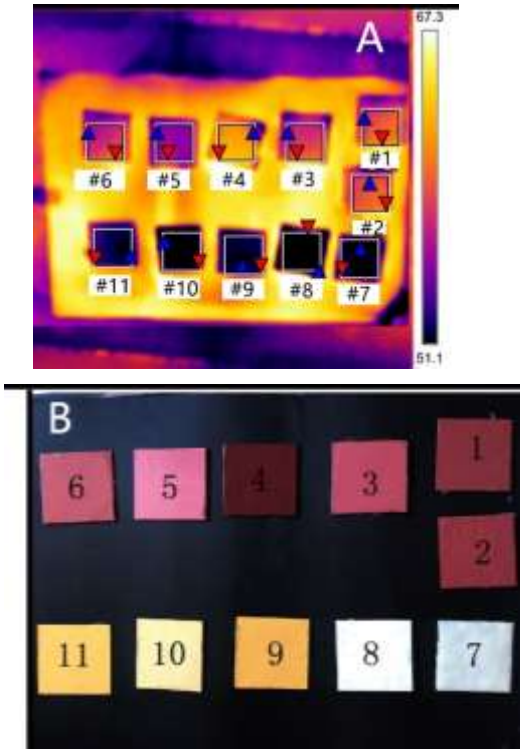




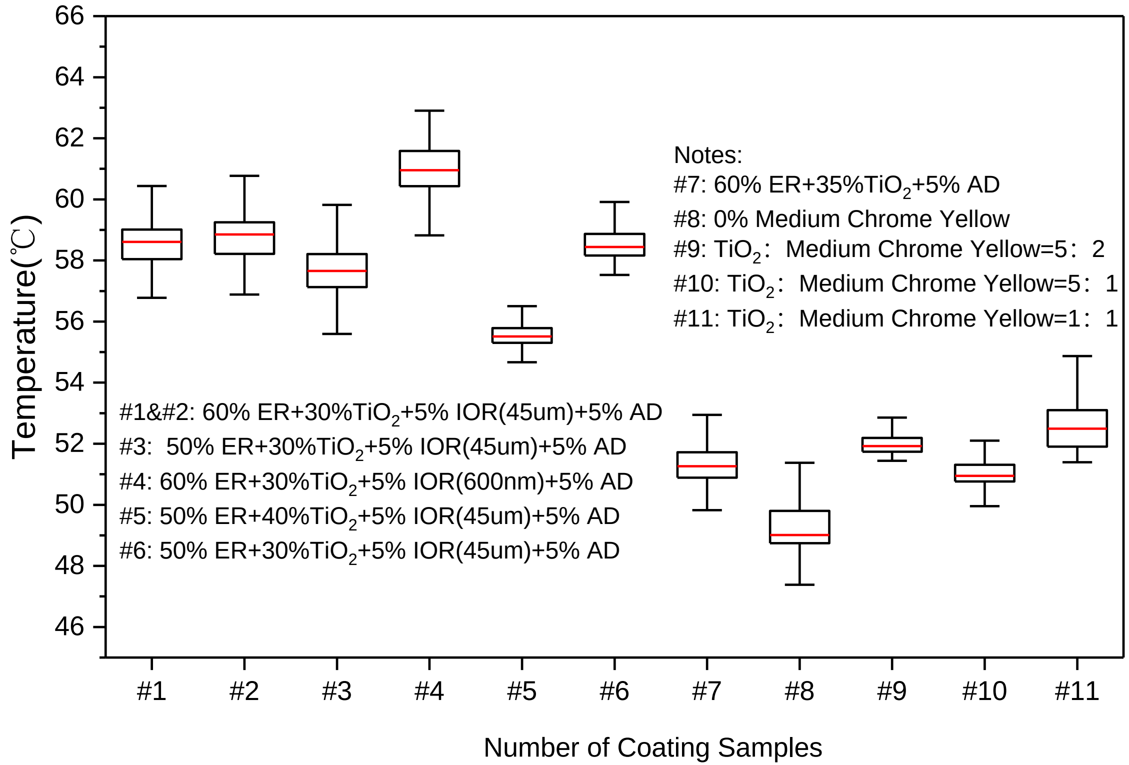
Optimal formulation based on optical properties (% by mass):

- Silicone-acrylic emulsion 50%, functional pigment filler 40%, anhydrous ethanol 5%
- The additive (aqueous defoamer, polyurethane leveling agent, polycarboxylate sodium salt dispersant) has a mass percentage of 5%
- Near-infrared reflectance reaches 86.2%

Conclusion2: Temperature can be reduced by up to 13°C

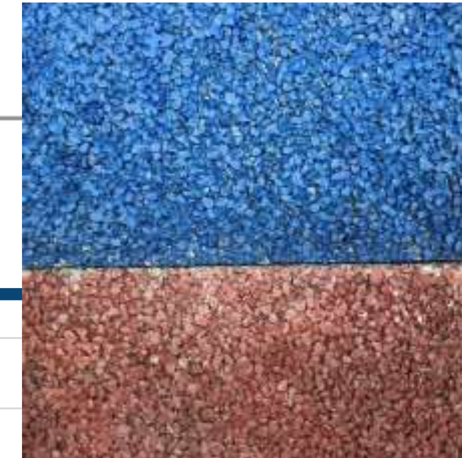


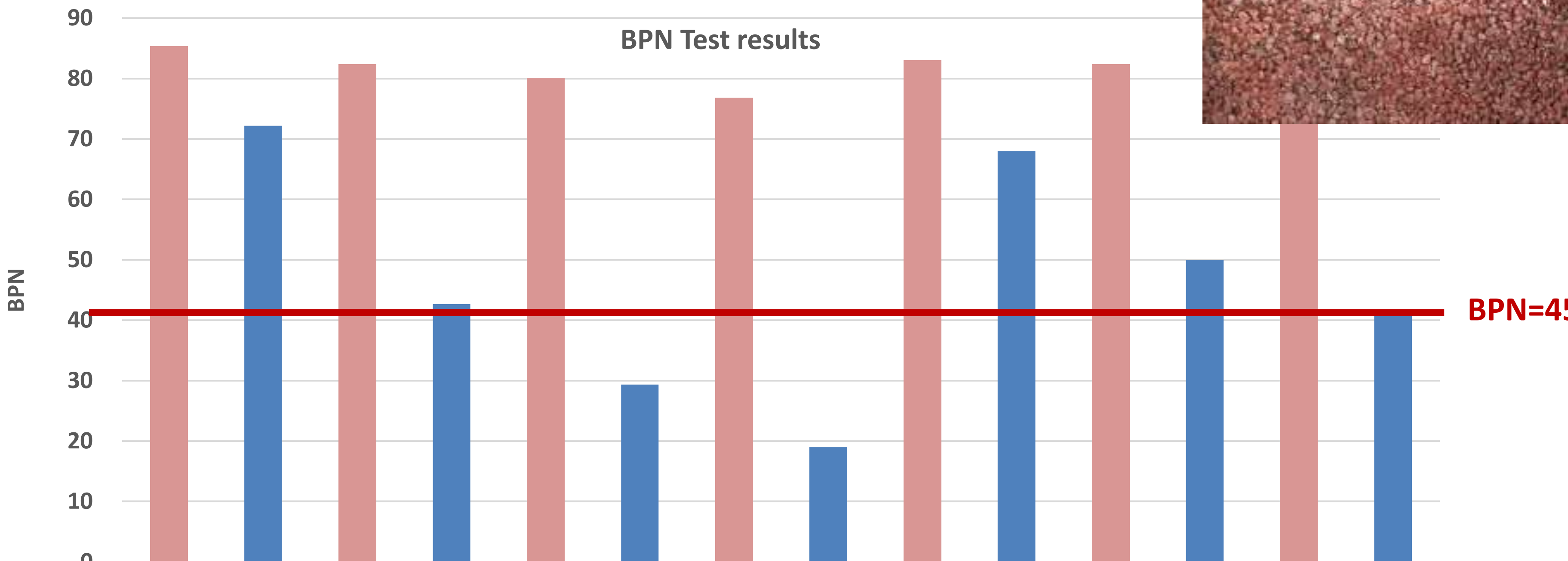
At noon peak hour in summer,



Ning Xie, **Hui Li***, Ahmed Abdelhady, John Harvey, Laboratorial investigation on optical and thermal properties of cool pavement nano-coatings for urban heat island mitigation,Building and Environment, 2019, 147(1), : 231-240.

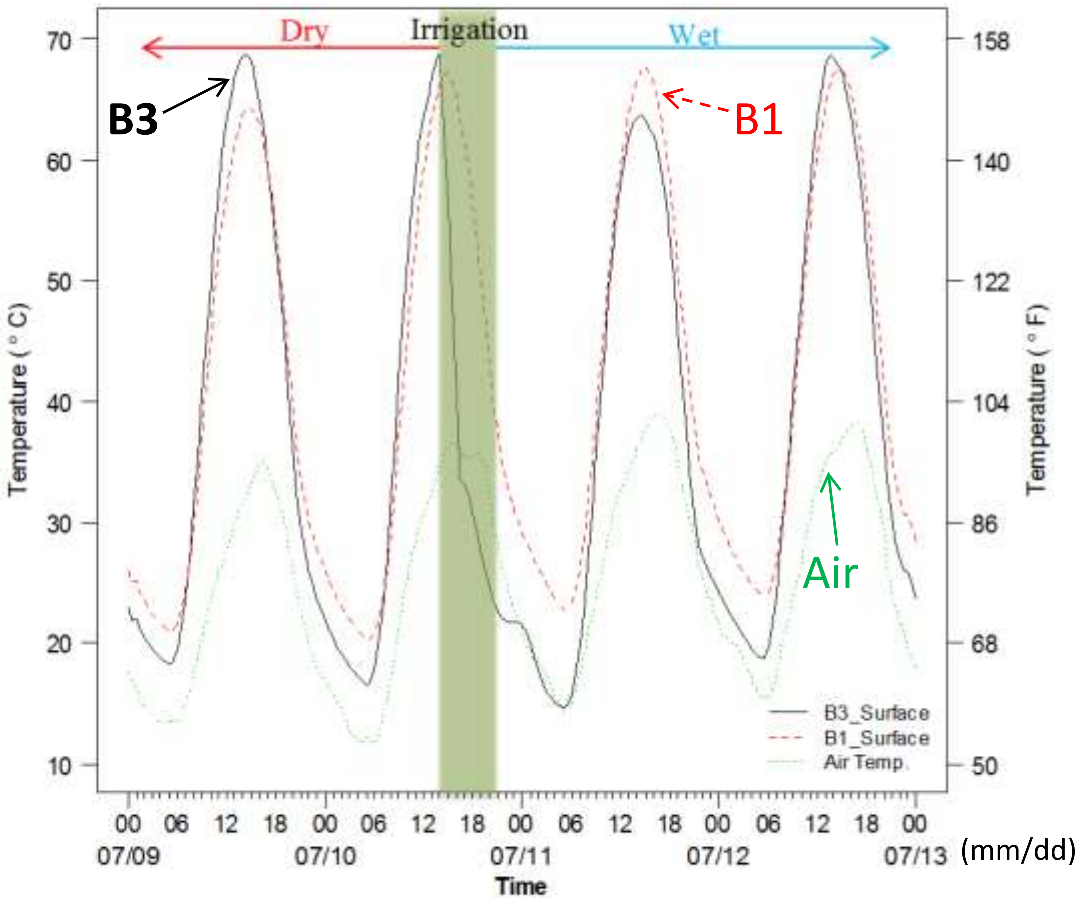
Skid Resistance Performance—use water-based coating with a coating amount of <0.75kg/m2





	原样干燥	原样潮湿	0.25kg/m2干燥	0.25kg/m2潮湿	0.5kg/m2干燥	0.5kg/m2潮湿	0.75kg/m2干燥	0.75kg/m2潮湿	水性0.25kg/m2干燥	水性0.25kg/m2潮湿	水性0.5kg/m2干燥	水性0.5kg/m2潮湿	水性0.75kg/m2干燥	水性0.75kg/m2潮湿
系列1	85.3	72.2	82.3	42.7	80.0	29.3	76.8	19.0	83.0	68.0	82.3	50.0	76.3	41.7

Effect of Water on Temperature



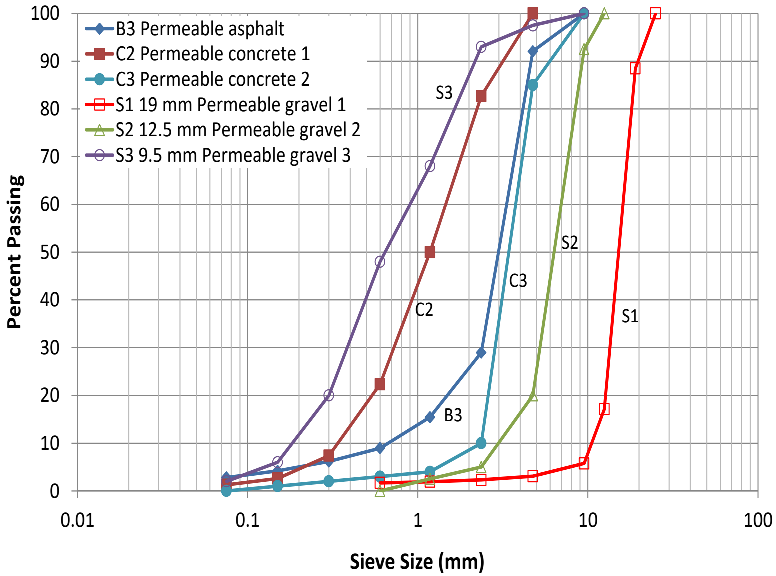
Irrigation

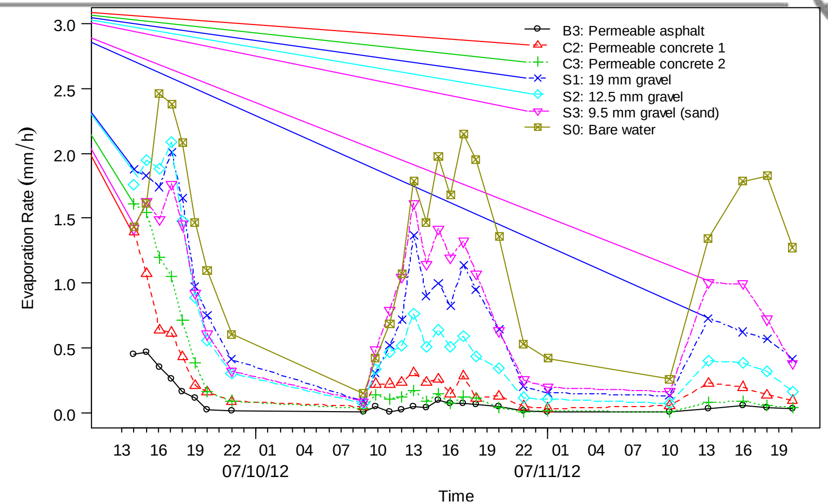
B3: permeable

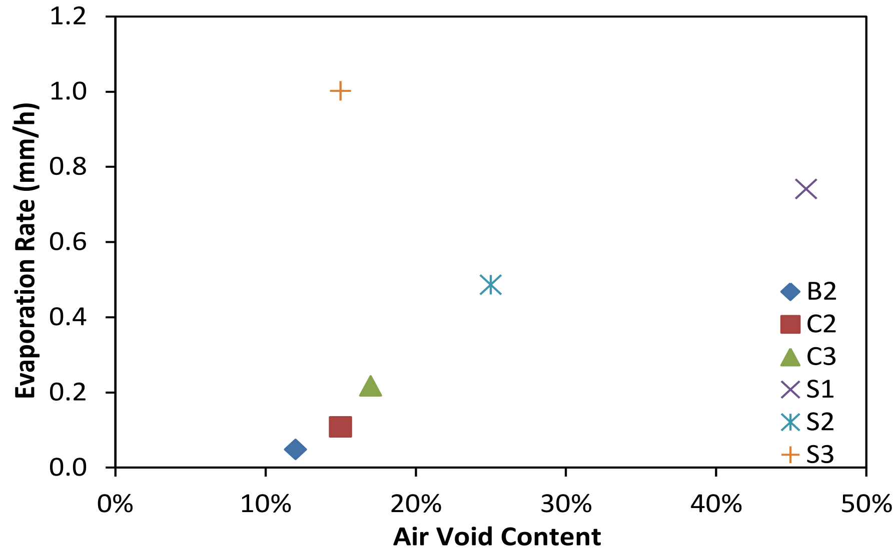
B1: impermeable

LI, H., Harvey J. , Holland J. and Kayhanian M. 2013. **The Use of Reflective and Permeable Pavement Strategies for Heat Island Mitigation and Stormwater Management**. *Environmental Research Letters 8 (2013) 015023* (14pp).

Evaporation Rate



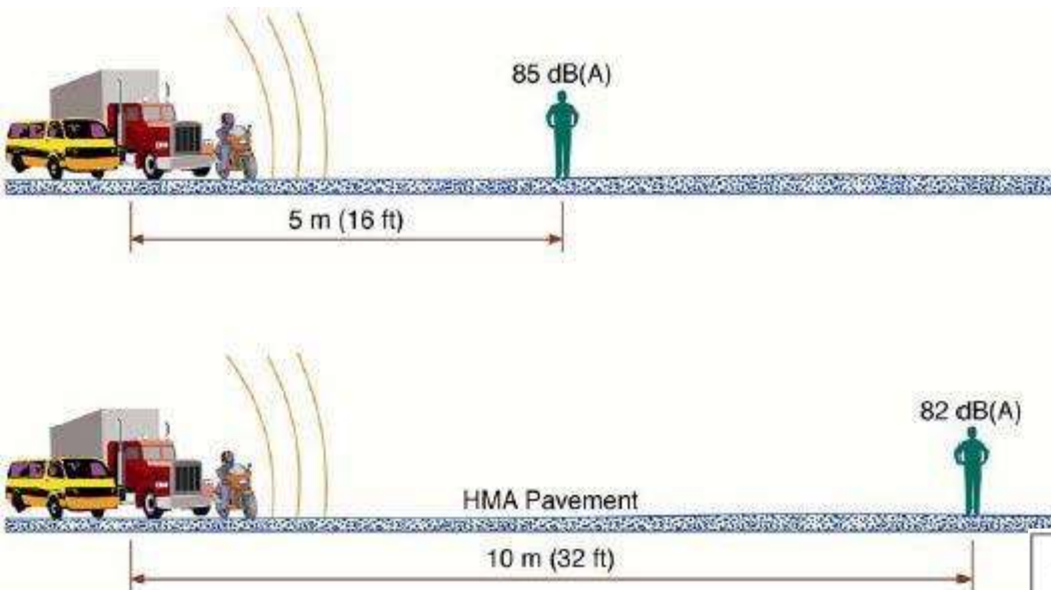


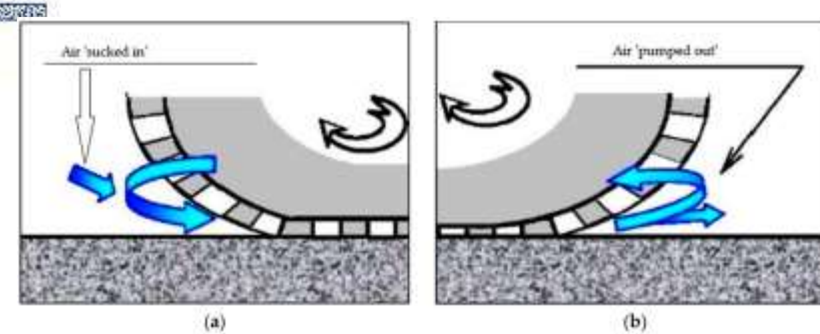


Li H.*, J. Harvey and Z. Ge (2014). Experimental investigation on evaporation rate for enhancing evaporative cooling effect of permeable pavement materials. ***Construction and Building Materials,*** *65 (2014) 367–375.* *DOI: 10.1016/j.conbuildmat.2014.05.004 (SCI, EI, IF: 2.8)*

Reduced Road Noise

Porous materials, sound-absorbing。





Water Pollution Removal

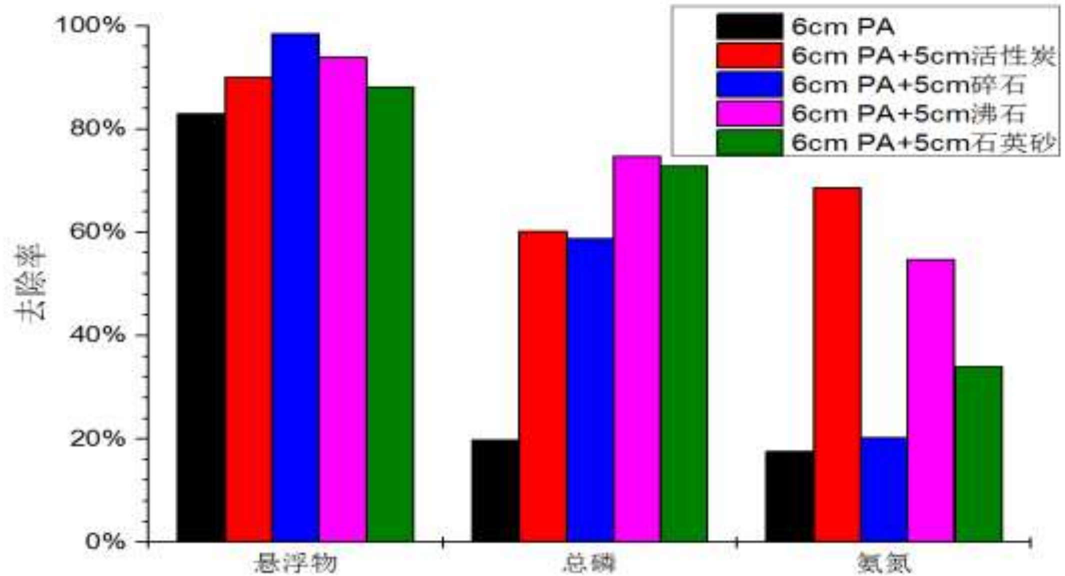
Runoff	SS	TP	TN	TKN	Cu	Zn
			Removal Rate（%）			
50～93	58～94	10～78	＞75	20～99	74～99	73～99

Kayhanian, M., D. Jones, J. Harvey. 2010. "Water Quality Evaluation of Leachate Produced from Pavement Specimens under Controlled Laboratory Conditions." Road Materials and Pavement Design.

透水路面生态功能-水净化性能

Removal Rate

	Pervious Concrete	Porous Asphalt
TP	14.6%	18.7%
TN	14.4%	19.5%



单一多孔隙水泥混凝土和多孔隙沥青混合料对氨氮总磷的**净化效果十分有限。**

组合净水滤料模式能够有效提高多孔隙水泥混凝土对总磷、氨氮的净化能力，**最高净化率**可以达到**70%-80%。**

- Liang X, **Li H***, Yu T, et al. Laboratorial Investigation on Filtrate Biological Toxicity and Pollutant Removal Effect of Porous Concrete[J]. **Journal of Cleaner Product** (under revision)
- **发明专利：**多孔隙水泥混凝土浸出液及其制备方法与浸出液生物毒性检测方法，CN201710900256.1， 2017.9

Toxicity Bioassay of Porous Concrete: Zebrafish Test

Zebrafish culture laboratory

Zebrafish culture box

Embryo selection

Putting embryo in 96 - well cell culture plate

The embryo are cultured in biochemical incubators

Observing embryo hatching condition

Sampel waiting for hatch

Hatched Sample

Dead Sample

Outline

Investigation on Permeable Pavement under Heavy Load

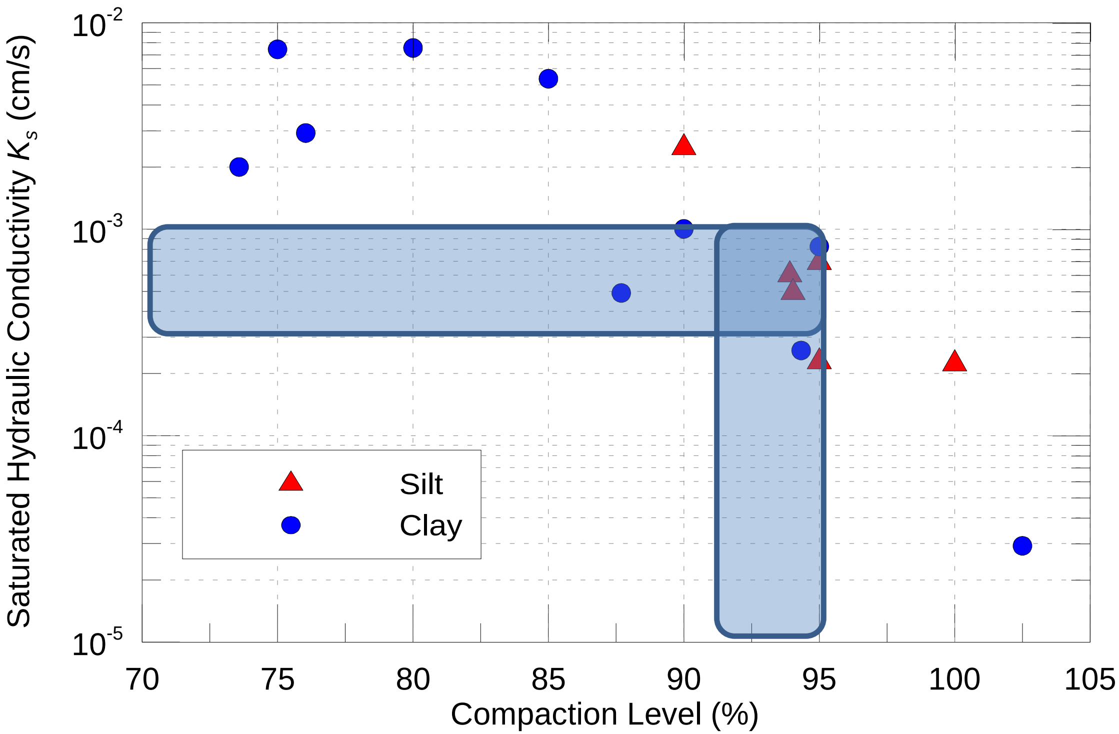
I. Martials
- Subgrade Soil
- Base Aggregate
- Permeable Surface

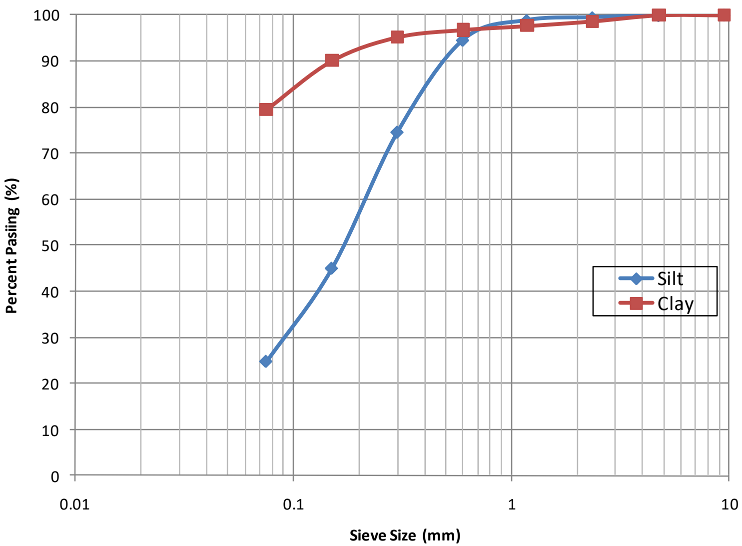
II. Structures
- Analysis
- Design

III. Life Cycle Analysis
- LCCA
- LCA

IV. APT Testing

Effect of Compaction Level on Soil Permeability

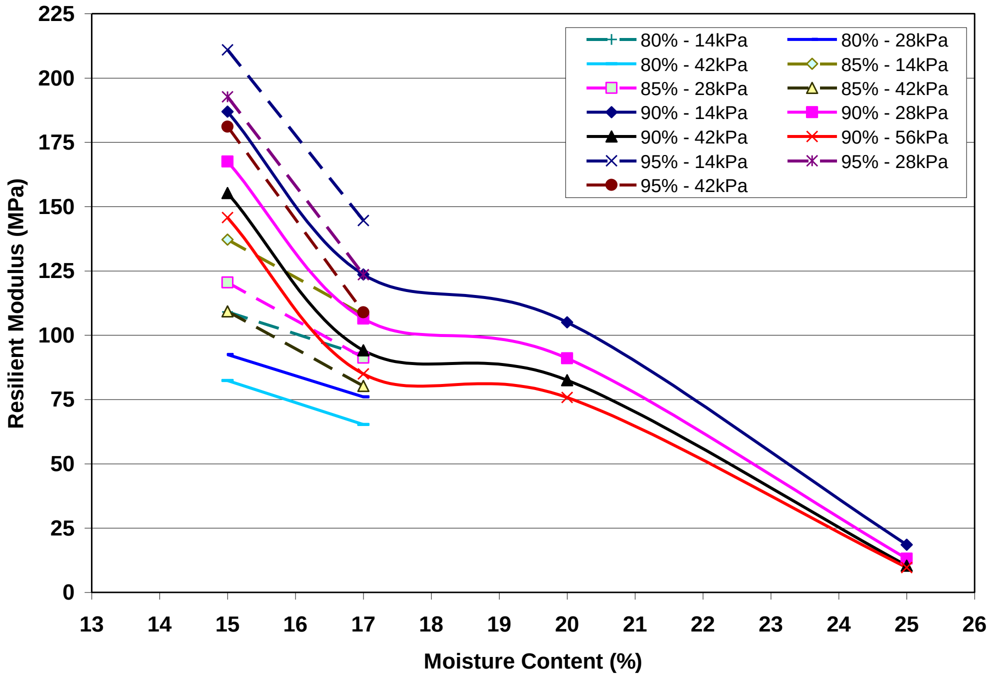




Jones D., J. Harvey, **H. Li,** T. Wang, R. Wu and B. Campbell (2010). **Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements under Heavy Traffic: Final Report**. *Prepared for the California Department of Transportation Division of Environmental Analysis - Storm Water Program.* Sacramento, CA. CTSW-RT-10-249.04/UCPRC-RR-2010-01, Jun. 2010.

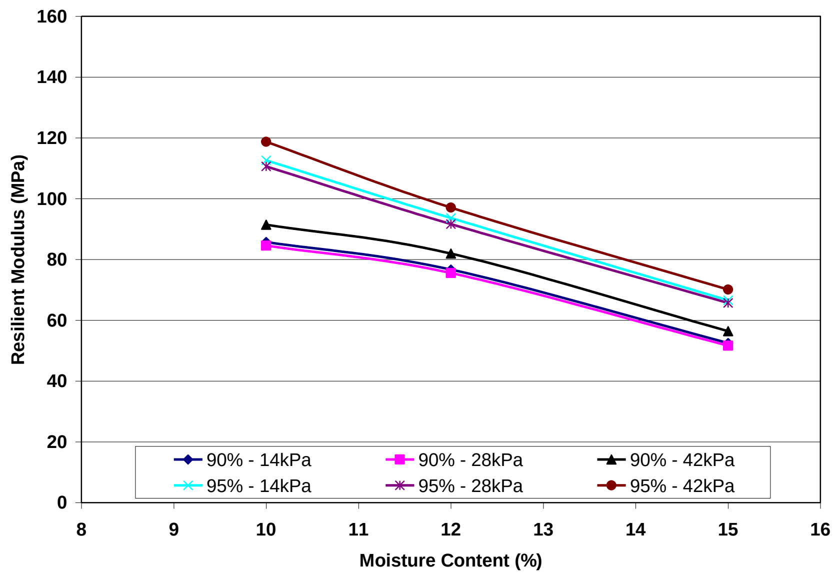
Soil Stiffness

Jones D., J. Harvey, **H. Li,** T. Wang, R. Wu and B. Campbell (2010). **Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements under Heavy Traffic: Final Report**. *Prepared for the California Department of Transportation Division of Environmental Analysis - Storm Water Program.* Sacramento, CA. CTSW-RT-10-249.04/UCPRC-RR-2010-01, Jun. 2010.



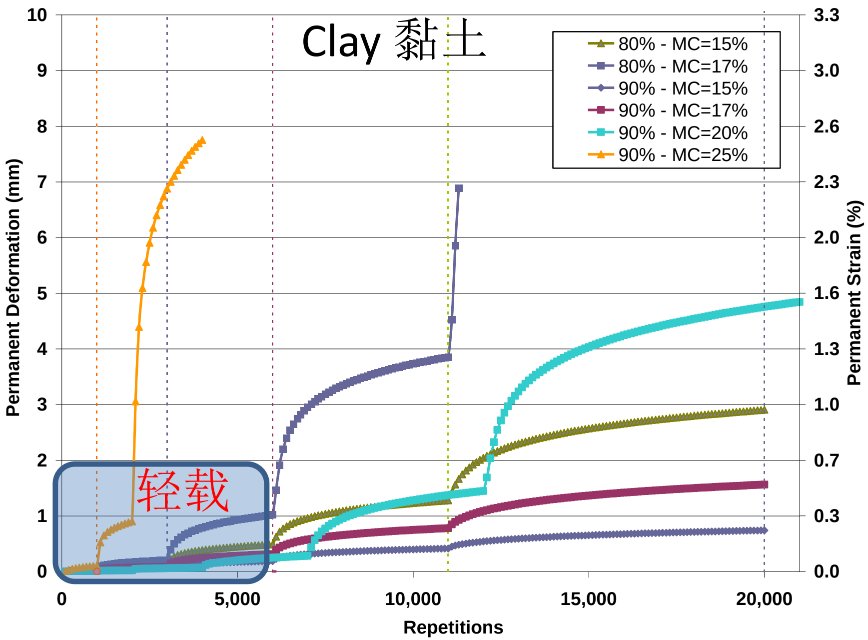
Clay

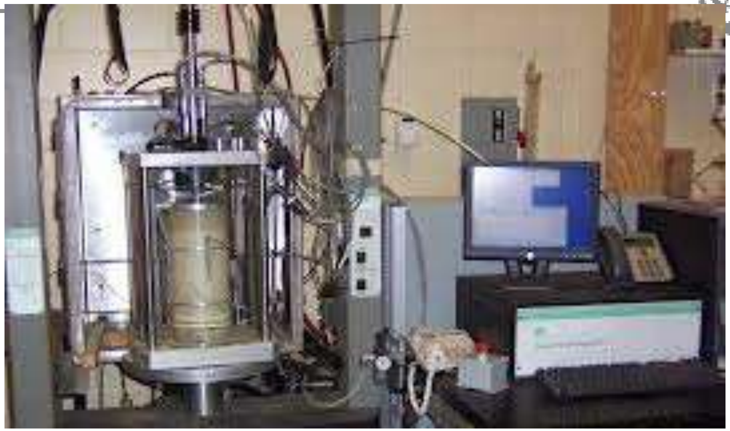
Silt

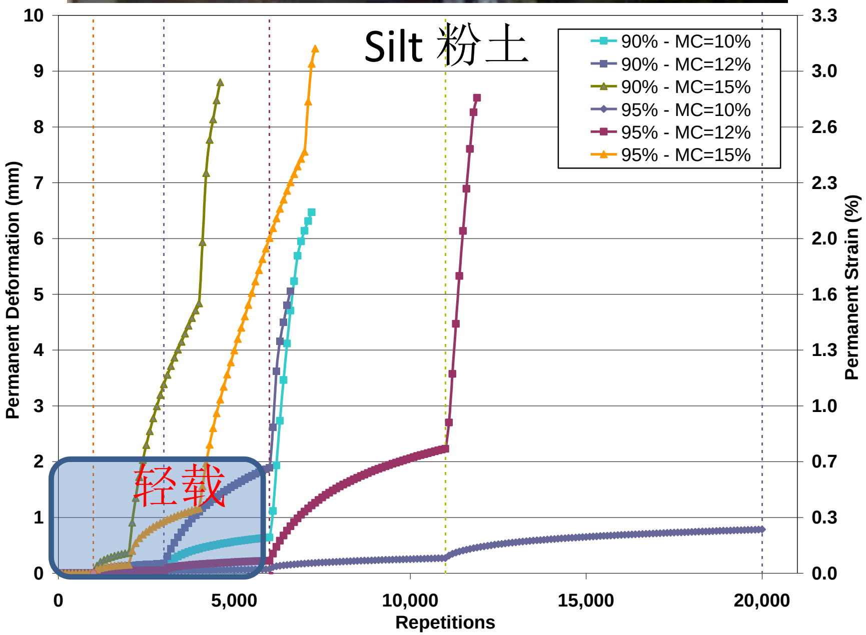


Stress-Dependent

Rutting in Subgrade Soil







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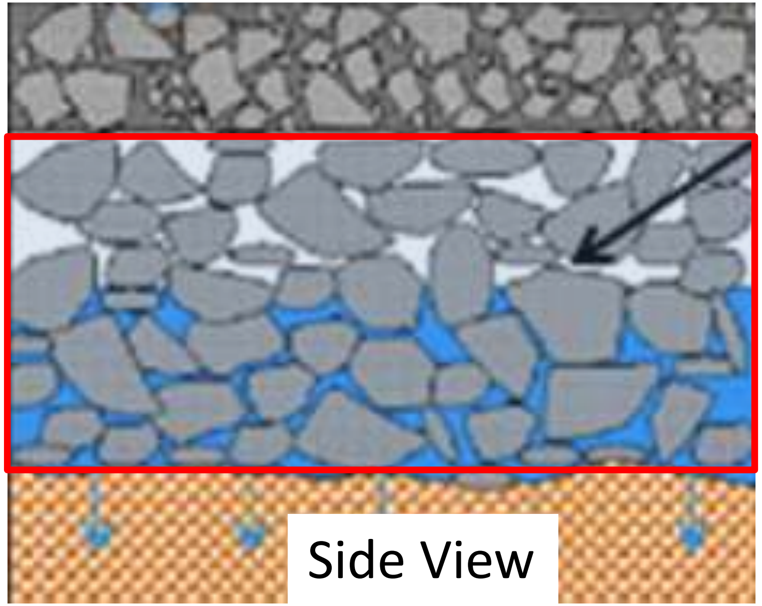
Base Layer

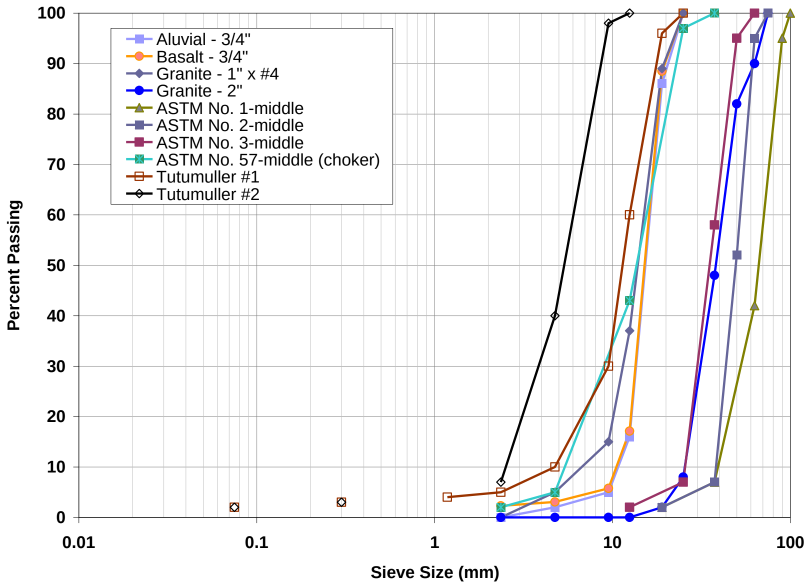
Single size 19mm +， carry load and store water.

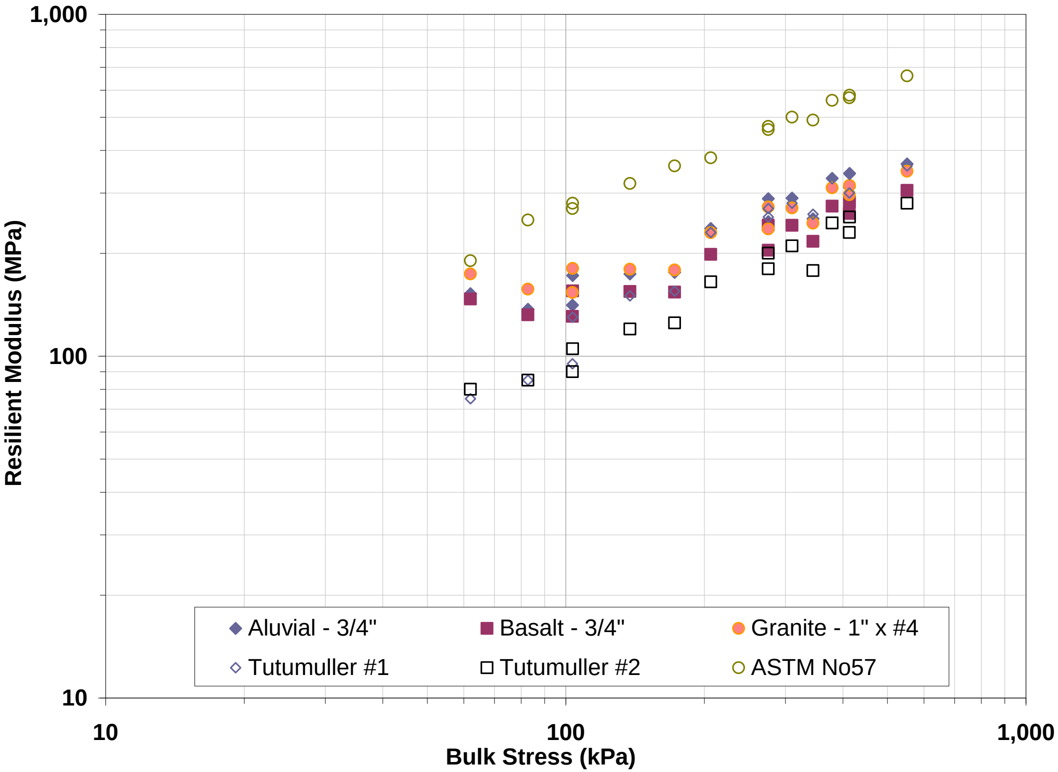


Li H., D. Jones, R. Wu, and J. Harvey (2014). Development and HVS Validation of Design Tables for Permeable Interlocking Concrete Pavement: Final Report. *Prepared for Concrete Masonry Association of California and Nevada (CMACN)*. Davis and Berkeley, CA: University of Californian Pavement Research Center. UCPRC-RR-2014-04. Dec. 2014.

Stiffness of Base Layer

Jones D., J. Harvey, **H. Li,** T. Wang, R. Wu and B. Campbell (2010). Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements under Heavy Traffic: Final Report. *Prepared for the California Department of Transportation Division of Environmental Analysis - Storm Water Program.* Sacramento, CA. CTSW-RT-10-249.04/UCPRC-RR-2010-01, Jun. 2010.



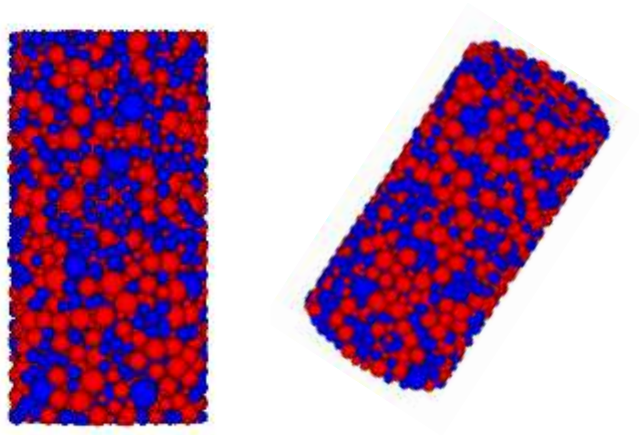


Stress-Dependent

Enhancement to Base

- Use Geo-cell/Geotextile to enchase the base.

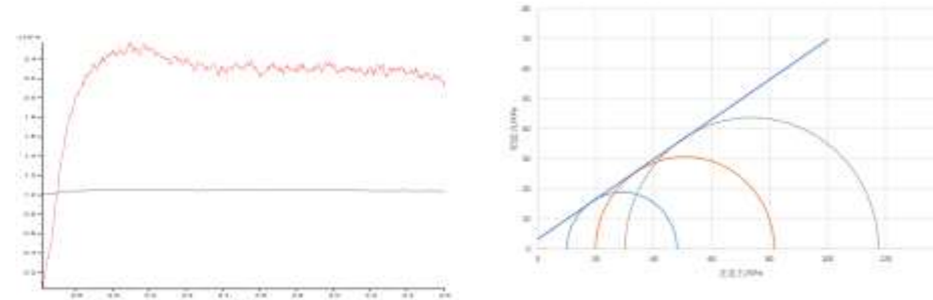
DEM Simulation Method For Triaxial Test



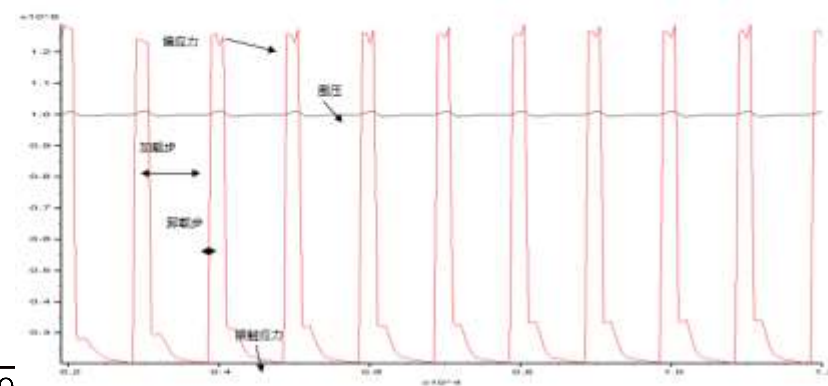
specimen

porosity:39.5%
Height : 30cm
Diameter : 15cm

Mesh diameter/mm	2.36	4.75	9.5	12.5	19.5	26.5
Passing rate/%	0	7	37	89	100	100



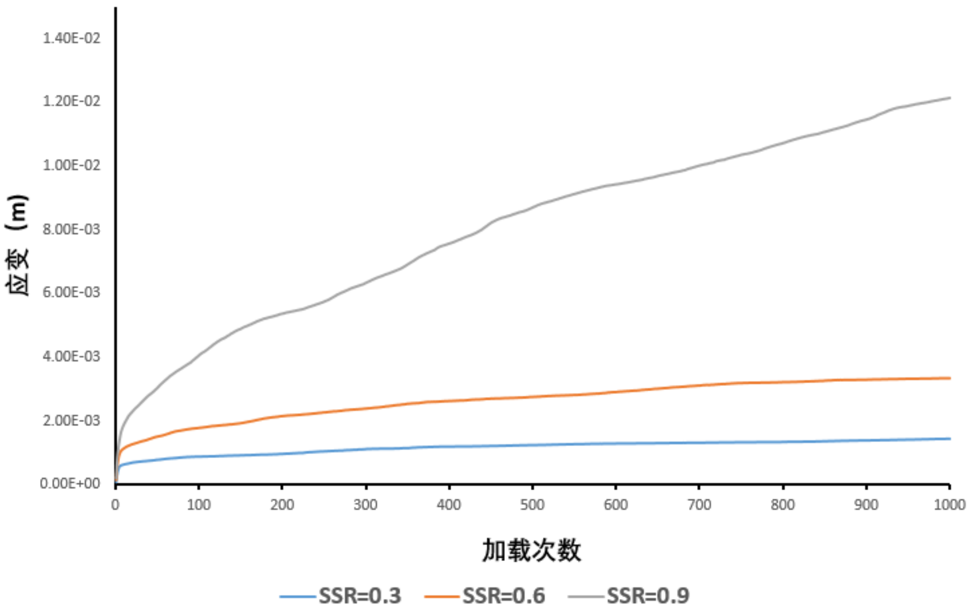
Triaxial shear test simulation



Dynamic triaxial test simulation

SSR And Permanent Deformation

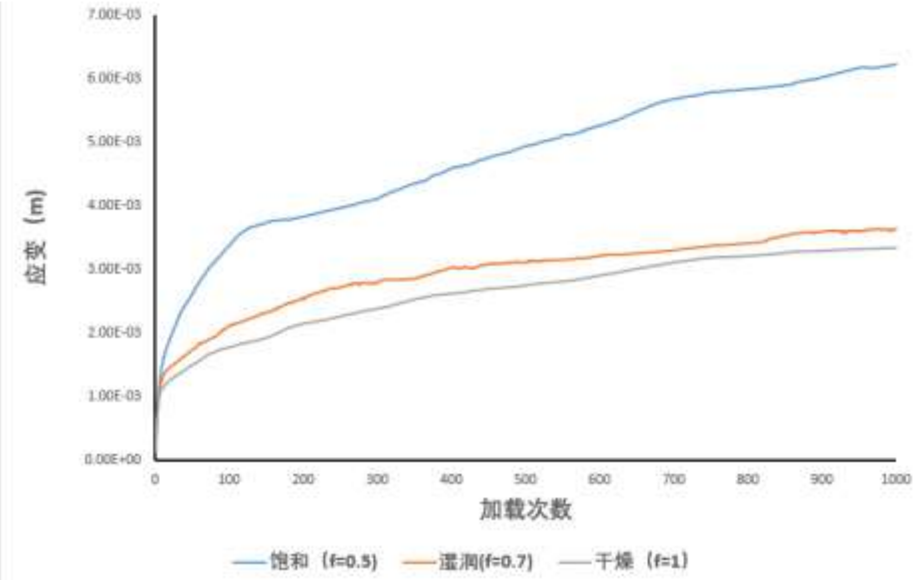
Conclusion one： SSR（Shear stress/strength ratio）has great influence on permanent deformation



Shear stress/strength ratio (SSR /strength ratio) was used to control the load of Graded gravel. Under low (SSR=0.3) and medium stress (SSR=0.6), Graded gravel base had less permanent deformation and tended to be stable and controllable. Under high stress (SSR=0.9), permanent deformation is large, and uncontrollable.

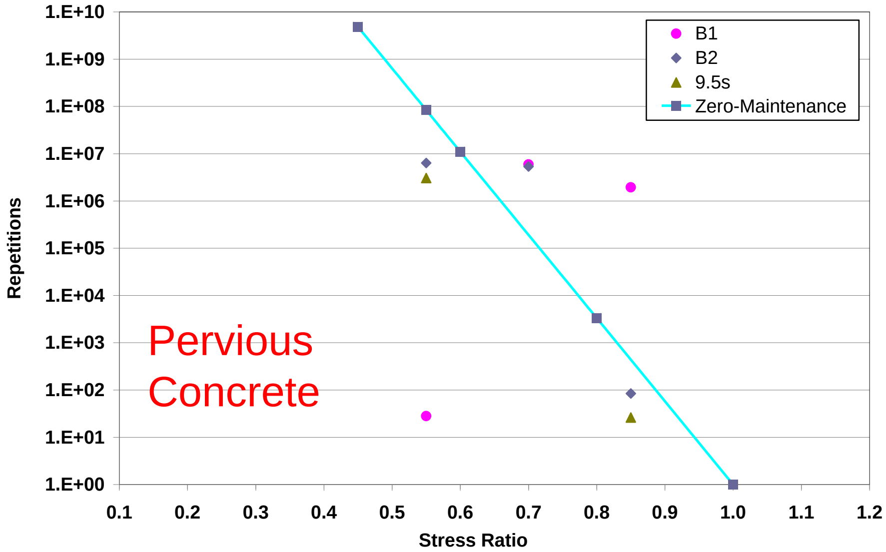
Wet Conditions and Permanent Deformation

Conclusion two：wet condition and the surface state of aggregate have great influence on the permanent deformation



The contact state (friction coefficient) between aggregates has a great influence on the stability of graded gravel, so it is easy to have large permanent deformation under the wet condition. To increase the coefficient of friction between aggregates can effectively avoid large permanent deformation.

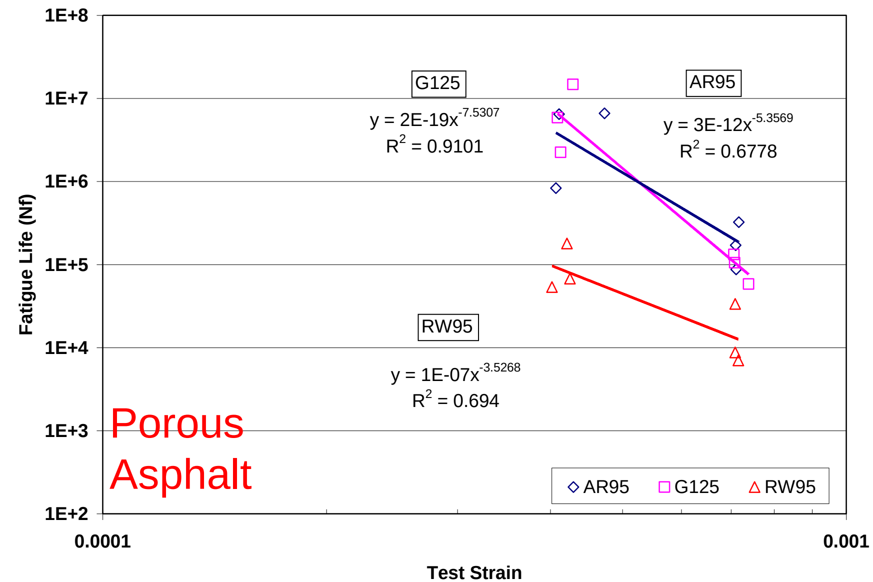
Surface Layer: Fatigue 疲劳破坏



$$N_i = 10^{17.61(1-\sigma_i / MR)}$$

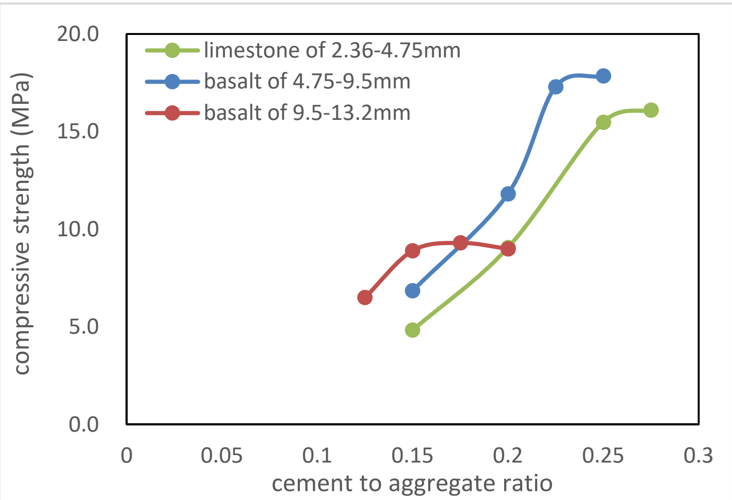
Li H.*, J. Harvey and D. Jones (2012). Developing a Mechanistic-Empirical Design Procedure for Fully Permeable Pavement under Heavy Traffic. ***Transportation Research Record: Journal of the Transportation Research Board***, 2305(0):83–94. DOI: 10.3141/2305-09 *(SCI, EI, IF: 0.6)*

- AR95 [9.5mm open-grade with conventional binder],
- RW95 [9.5mm open-grade with rubberized binder],
- G125 [12.5mm open-grade with conventional binder plus lime and fibers])

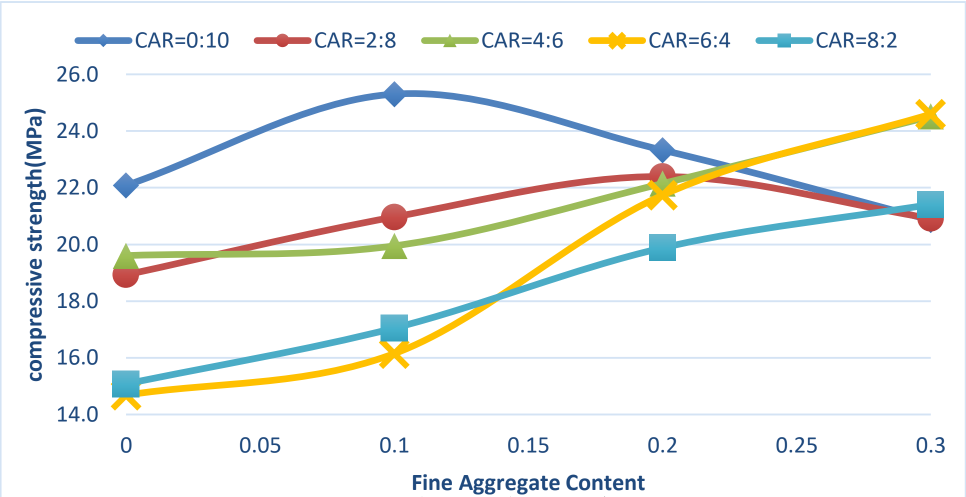


面层材料：透水水泥混凝土材料优化设计

基于最优抗压强度灰集比的透水水泥混凝土材料设计研究



抗压强度-灰集比

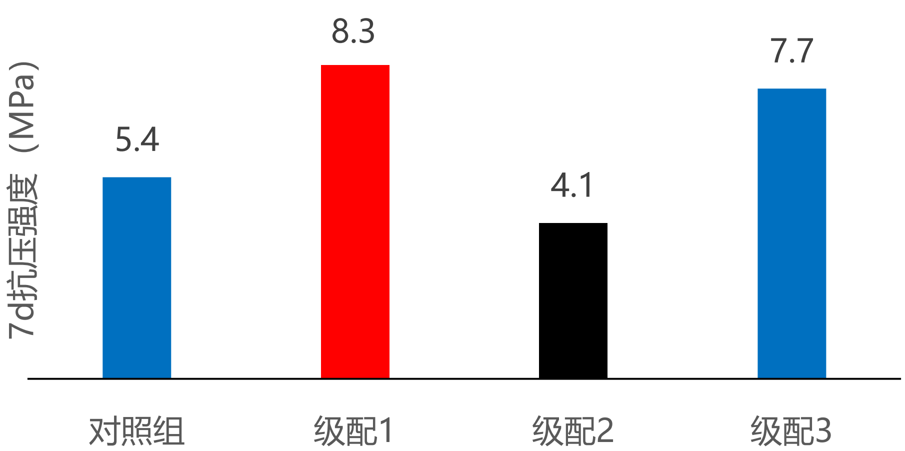


抗压强度–细料掺量

- ✓ 按抗压强度变化趋势及离析程度确定最佳灰集比范围
- ✓ 集料种类对最佳灰集比范围影响较小
- ✓ 按各组抗压强度最高的配合比，成型试件后，测定劈裂抗拉强度。

性能优化——级配优化

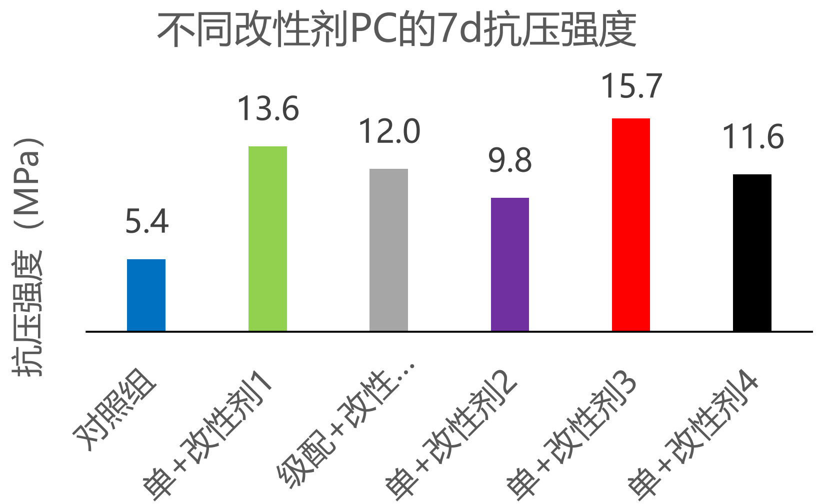
试验组	级配比例			抗压强度			平均值	标准差
	3-5	5-10	10-20	1	2	3		
对照组	0	1	0	5.3	5.4		5.4	0.07
级配1	**0.25**	**0.45**	**0.3**	**8.1**	**8.3**	**8.6**	**8.3**	**0.25**
级配2	0.25	0.15	0.6	4.5	3.6	4.3	4.1	0.47
级配3	**0.2**	**0.8**	**0**	**7.3**	**6.9**	**8.9**	**7.7**	**1.06**



根据抗压强度比选，
选用级配1、3

性能优化——改性剂比选

实验组	抗压强度			平均值	标准差
	1	2	3		
对照组	5.3	5.4	-	5.4	0.07
单一粒径+改性剂1	20	10	10.9	13.6	5.53
级配+改性剂1	9.4	11.5	15	12.0	2.83
改性剂2	11.7	8.4	9.4	9.8	1.69
改性剂3	15.2	16.5	15.4	15.7	0.70
改性剂4	13.4	11.2	10.1	11.6	1.68



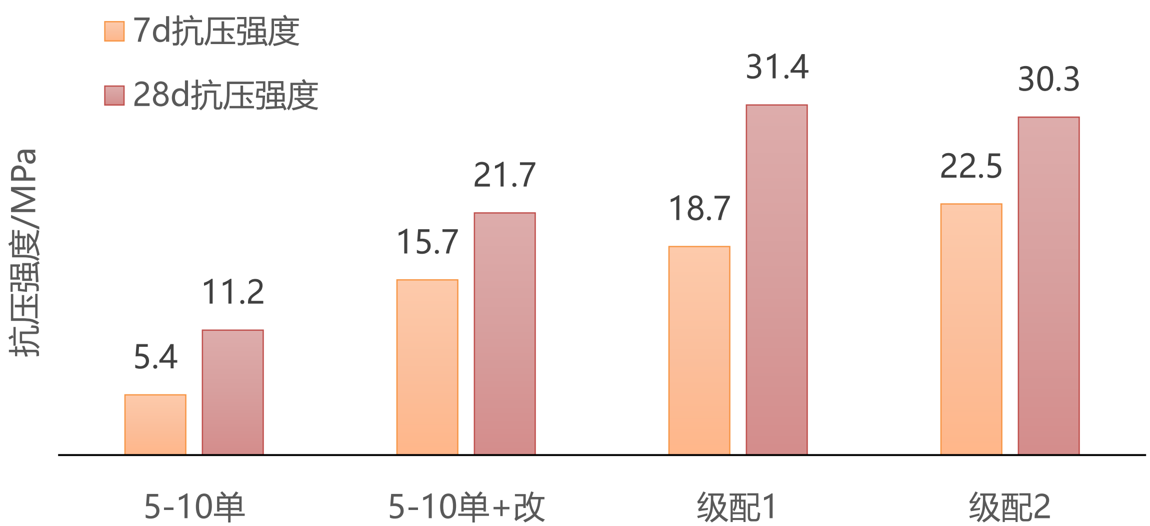
- 集料采用5-10mm单一粒径
- 选用改性剂3
- 除改性剂外，加入粉煤灰、硅灰（分别占粉料质量的15%与6%）

优化配合比设计

两种级配透水混凝土配合比设计及抗压强度

<table>
<tr><td colspan="2" rowspan="2">材料</td><td colspan="4">级配1(细)</td><td colspan="4">级配2(粗)</td></tr>
<tr><td colspan="2">每立方米重量/kg</td><td colspan="2">配合重量比</td><td colspan="2">每立方米重量/kg</td><td colspan="2">配合重量比</td></tr>
<tr><td colspan="2">42.5水泥</td><td>297.2</td><td rowspan="3">376.2</td><td>0.180</td><td rowspan="3">0.228</td><td>266.6</td><td rowspan="3">337.5</td><td>0.157</td><td rowspan="3">0.199</td></tr>
<tr><td colspan="2">粉煤灰</td><td>56.4</td><td>0.034</td><td>50.6</td><td>0.030</td></tr>
<tr><td colspan="2">硅灰</td><td>22.6</td><td>0.014</td><td>20.2</td><td>0.012</td></tr>
<tr><td colspan="2">水</td><td colspan="2">120.4</td><td colspan="2">0.073</td><td colspan="2">108.0</td><td colspan="2">0.064</td></tr>
<tr><td rowspan="3">集料粒径/mm</td><td>3-5</td><td>330</td><td rowspan="3">1650</td><td>0.2</td><td rowspan="3">1</td><td>425</td><td rowspan="3">1700</td><td>0.25</td><td rowspan="3">1</td></tr>
<tr><td>5-10</td><td>1320</td><td>0.8</td><td>510</td><td>0.3</td></tr>
<tr><td>10-20</td><td>0</td><td>0</td><td>765</td><td>0.45</td></tr>
<tr><td colspan="2">改性剂3</td><td colspan="2">10</td><td colspan="2">0.006</td><td colspan="2">10</td><td colspan="2">0.006</td></tr>
<tr><td colspan="2" rowspan="2">7d强度/MPa</td><td>20.1</td><td colspan="2">16.7</td><td>19.2</td><td>24.8</td><td colspan="2">23.1</td><td>19.6</td></tr>
<tr><td colspan="4">18.7</td><td colspan="4">22.5</td></tr>
<tr><td colspan="2" rowspan="2">28d强度/MPa</td><td>32.1</td><td colspan="2">29.4</td><td>32.7</td><td>29.9</td><td colspan="2">29.3</td><td>31.7</td></tr>
<tr><td colspan="4">31.4</td><td colspan="4">30.3</td></tr>
<tr><td colspan="2">设计强度</td><td colspan="8">C30</td></tr>
</table>

优化后性能大幅提升



- 不添加改性剂时，水泥胶浆难以裹附在集料表面，强度偏低。改性剂对单一粒径透水混凝土提升强度约为10MPa。
- 级配透水混凝土抗压强度明显高于单一粒径透水混凝土。28d强度均达到30MPa。

实际施工条件下透水水泥面层力学性能

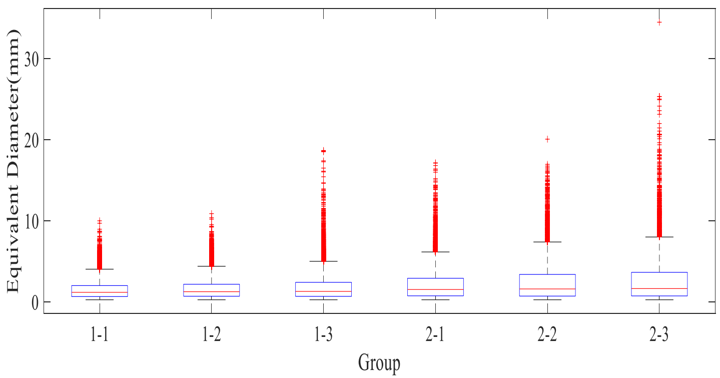
在上海某道路透水机动车道，**现场成型水泥试件（加入改性剂5）并进行现场养护，28d力学性能测试强度超设计强度**

性能指标	设计强度	测试强度（MPa）	折合标准强度（MPa）	达到设计强度（%）	备注
抗压强度	C35	41.5	39.4	112.6	100mm立方体试件
抗折强度	4.5MPa	4.65	4.65	103.3	550*150*150mm试件

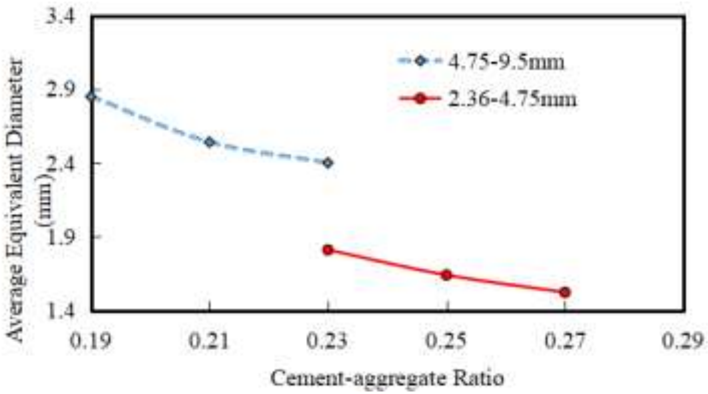
Pore Characterization & Performance Relationship

objectives	contents	Experiments
		…teristics

Pore Characteristic



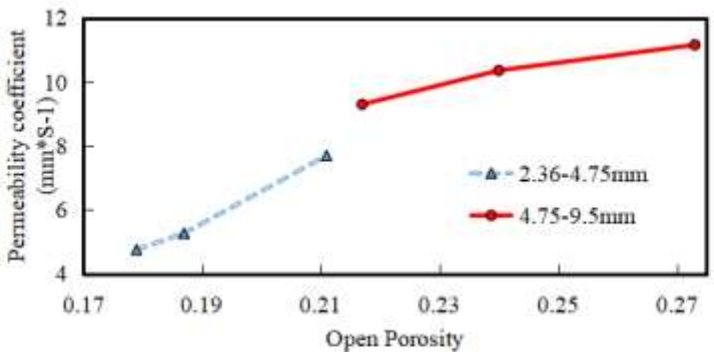
equivalent diameter



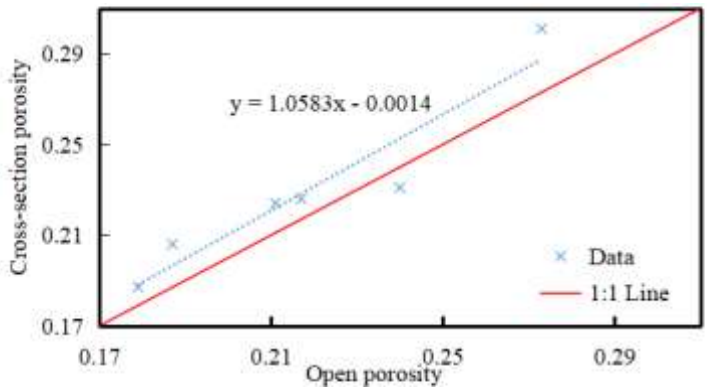
influence of cement content on equivalent diameter

Both the aggregate size and cement-aggregate ratio exhibited an evident effect on the pore size.

Permeability



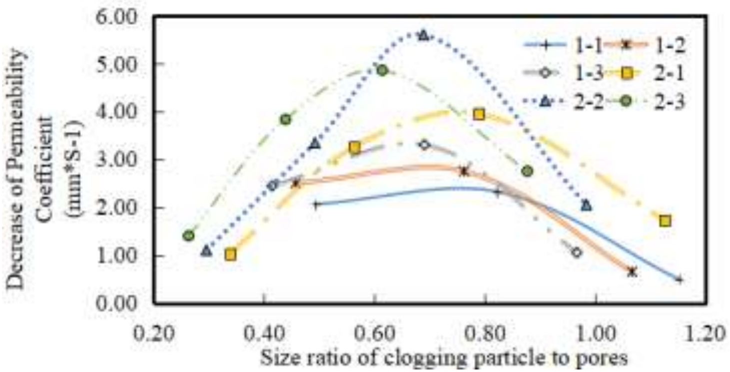
Permeability coefficient before clogging- porosity



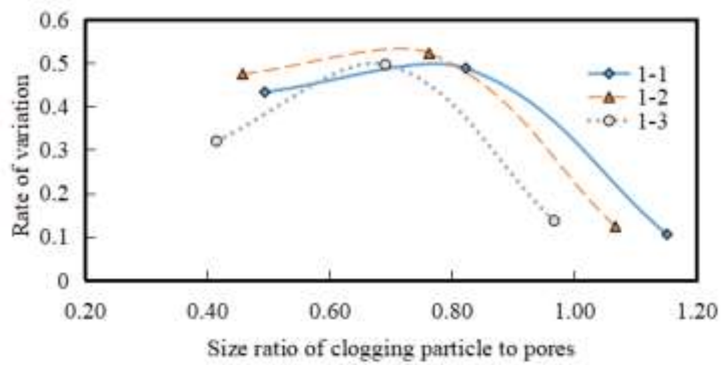
Porosity

Cross section porosity is usually slightly larger than open porosity, and this may be related to closing some parts in the cross section porosity.

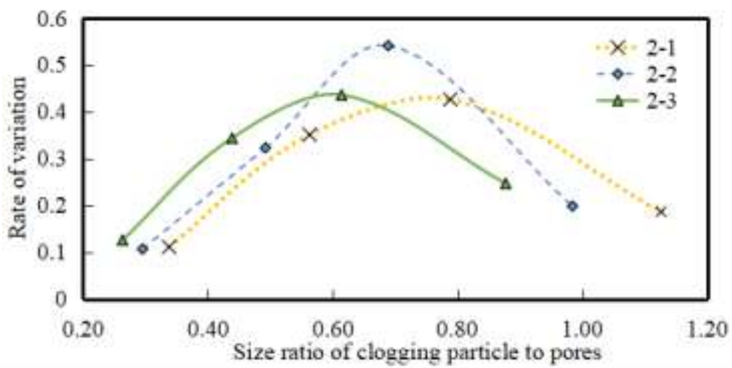
Clogging： Size Ratio of Clogging Particle to Pore



The relationship between the Permeability Coefficient and size ratio of clogging particle

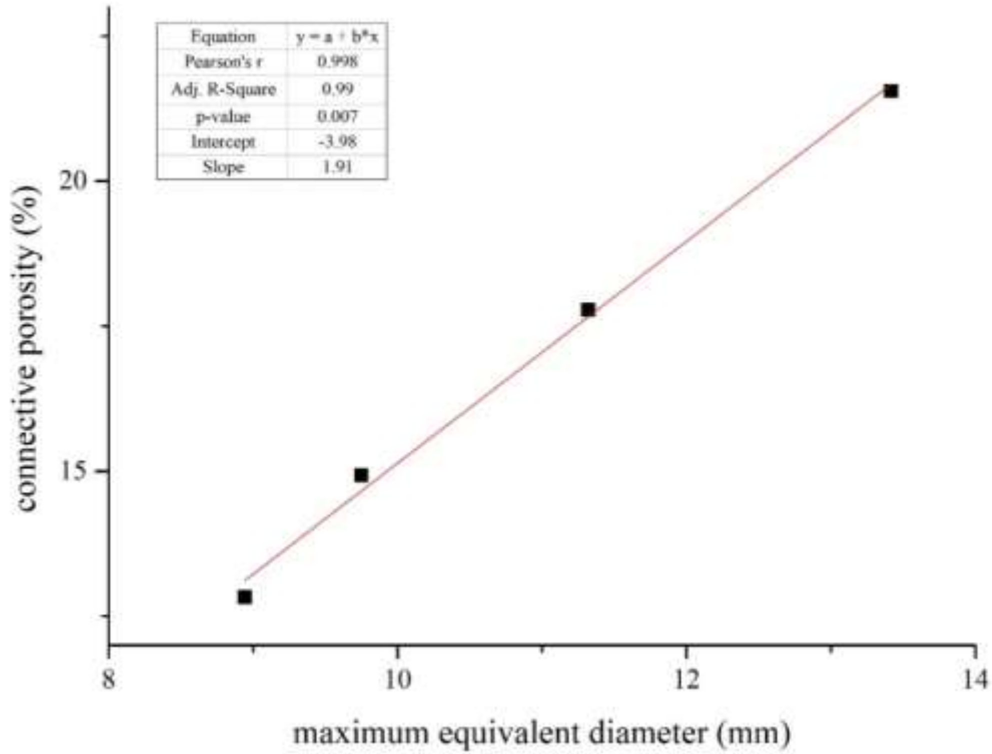


Percentage of decrease in permeability of group 1 (2.36-4.75mm aggregate size) after clogging



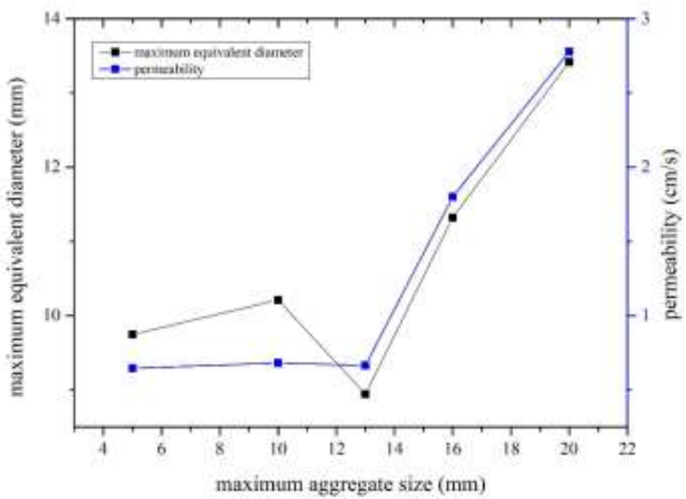
Percentage of decrease in permeability of group 2 (4.75-9.5mm aggregate size) after clogging

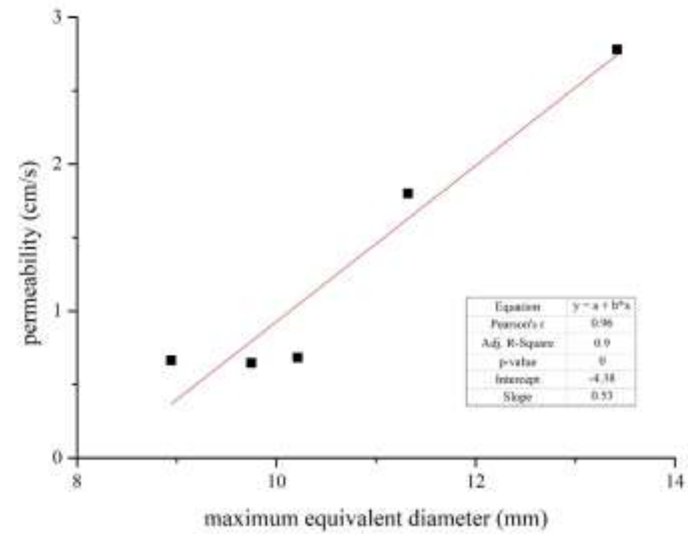
Connected Porosity



- Maximum equivalent diameter is similar to connected porosity of different NAMS
- 10-mm NAMS may be a error point

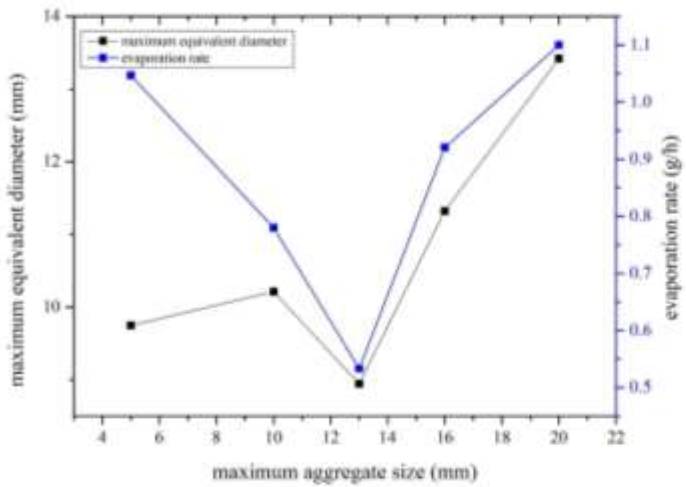
Permeability

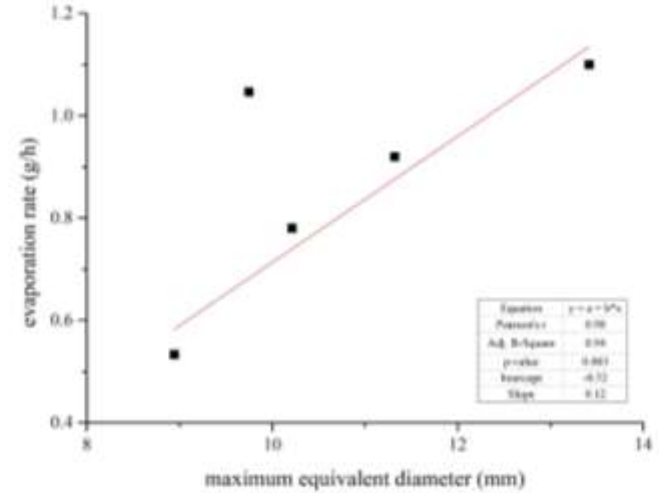




Maximum equivalent diameter is similar to permeability of different NAMS

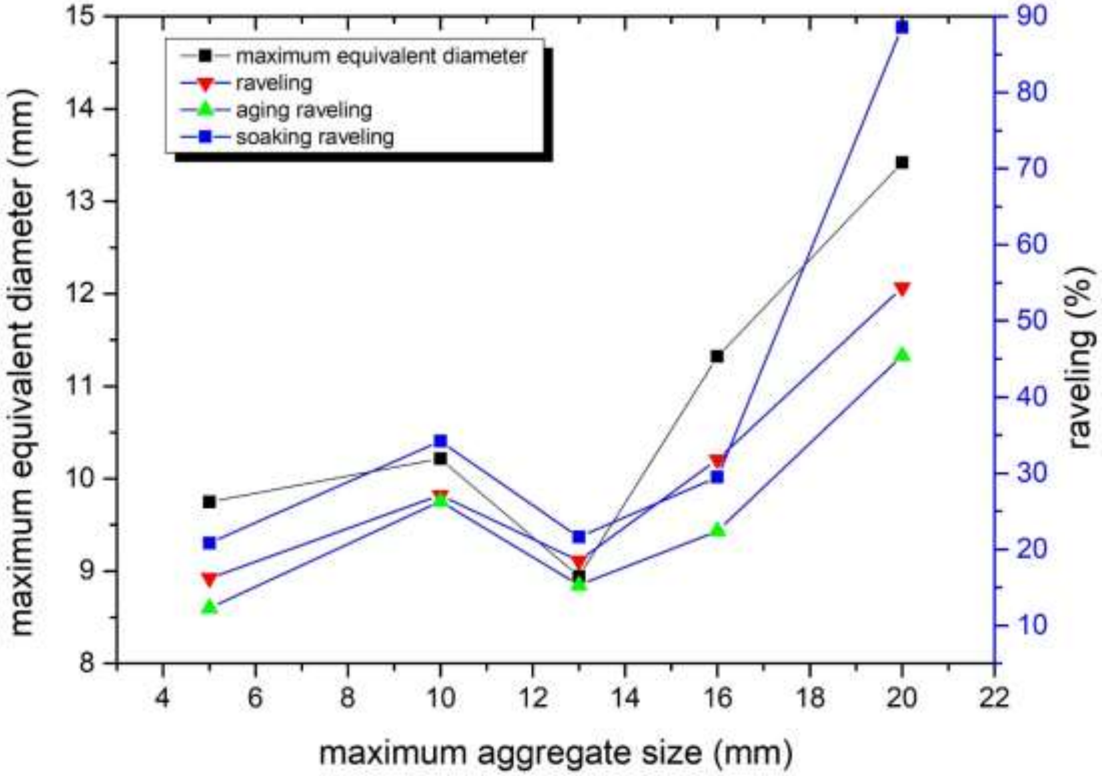
Evaporation Rate





If 5-mm NAMS is omitting, with increasing of maximum equivalent diameter, there is liner increasing trend between evaporation rate and maximum equivalent. In other word, the evaporation cooling effect will be better.

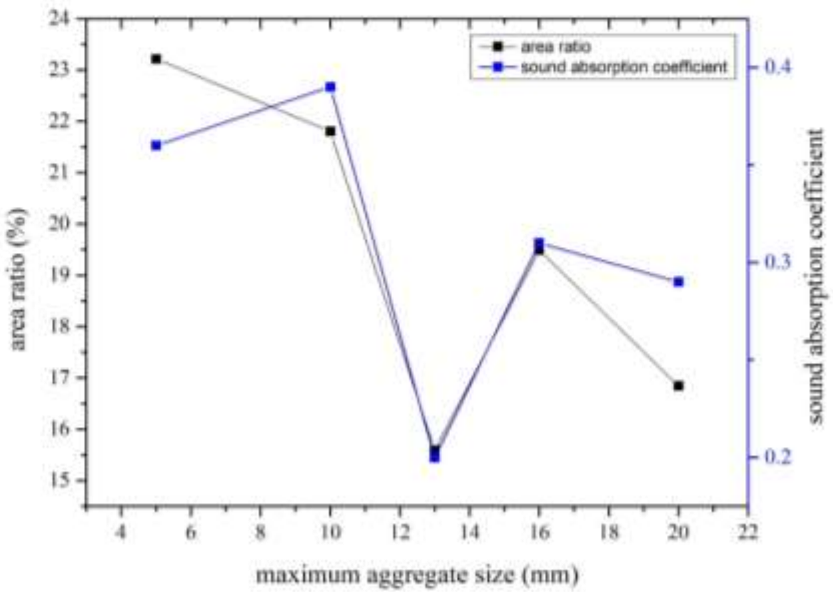
Resistance To Raveling

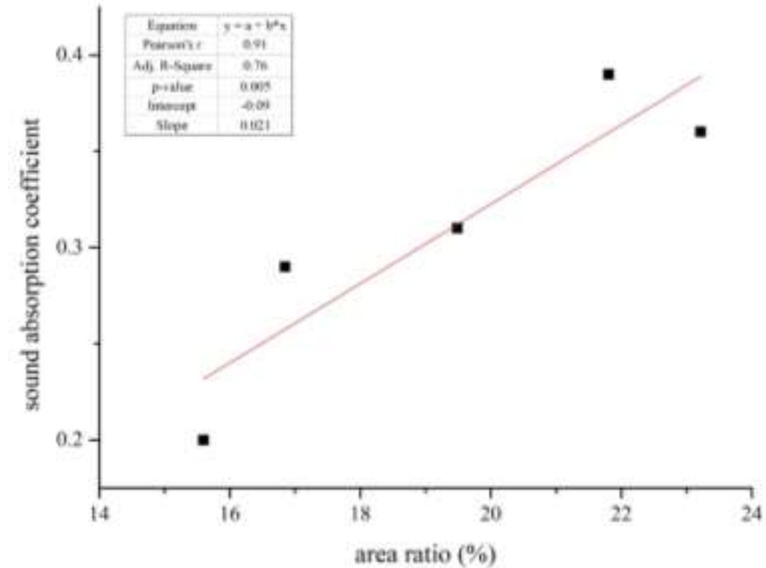


Sound Absorption

Aggregate Size Effects:

Sound Absorption (Impedance Tube Test)



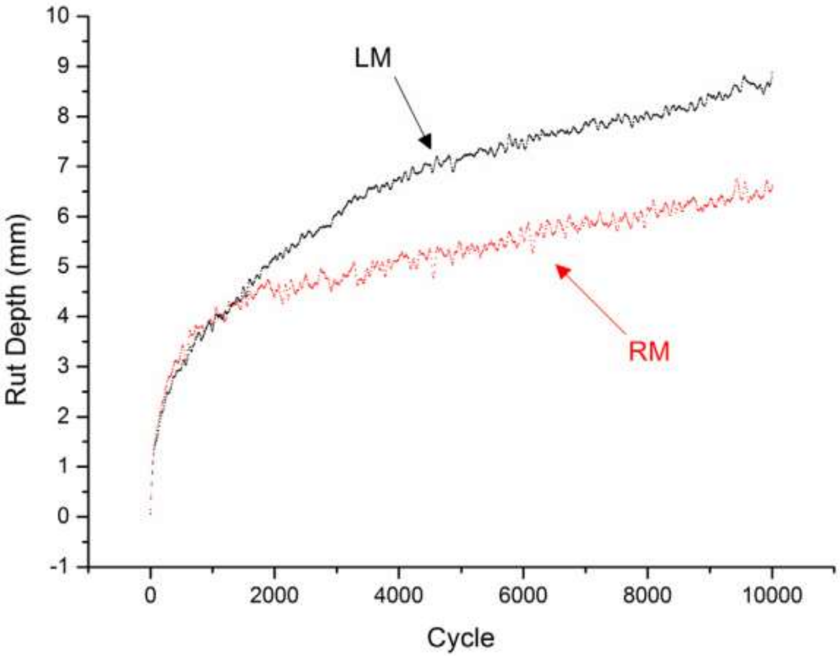


|R|=0.91， Adj.R^2=0.82

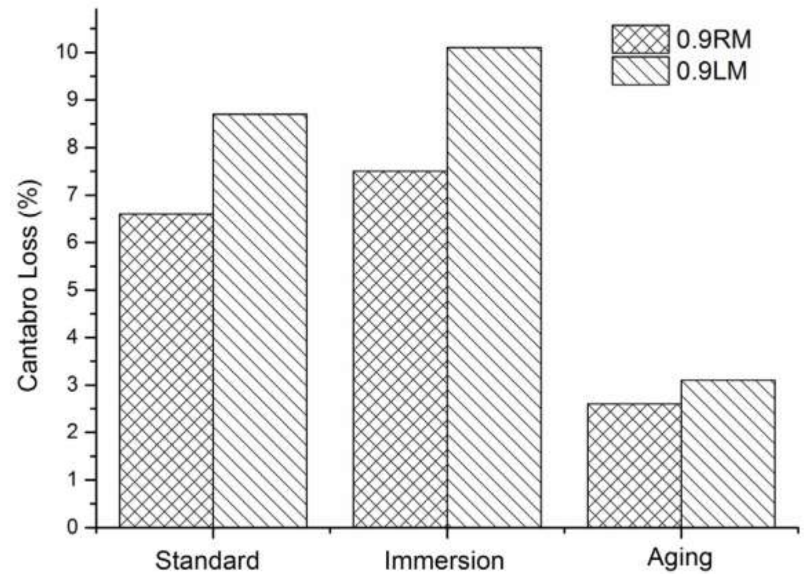
As the area ratio (porosity) increases, the sound absorption coefficient of the mixtures increases.
In other word, the bigger area ratio, the higher sound absorption coefficient, the better noise reduction.

全透水路面（透水性能、力学性能）-材料耐久性提升、固废利用

- 赤泥（Red Mud, 一种矿渣固废），作为改性剂应用，可显著提高基质沥青的性能。



抗车辙性能



飞散性能

- Zhang H, **Li H***, Zhang Y, et al. Performance enhancement of porous asphalt pavement using red mud as alternative filler[J]. **Construction & Building Materials**, 2018, 160:707-713.
- **发明专利**：一种固废改性沥青及其制备与应用，CN201710840202.0， 2017.9

Outline

Investigation on Permeable Pavement under Heavy Load

I. Martials
   - Subgrade Soil
   - Base Aggregate
   - Permeable Surface

II. Structures
   - Analysis
   - Design

III. Life Cycle Analysis
   - LCCA
   - LCA

IV. APT Testing

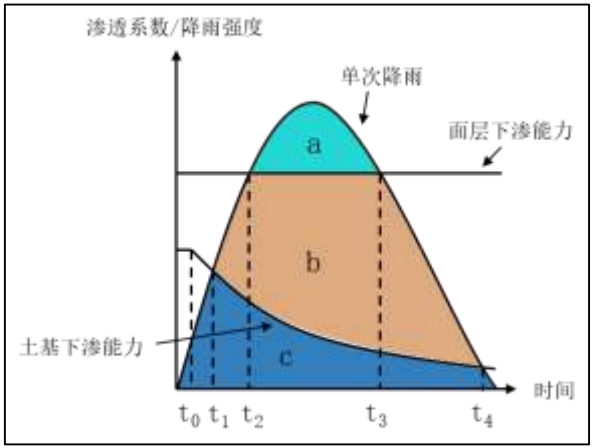
Structural Design

- Hydraulic Design
  - Design for on-site stormwater management
- Structural Design
  - Design for traffic carrying

LI, H.*, Harvey J. and Jones, D. 2012. **Development of Mechanistic-Empirical Design Procedure for Fully Permeable Pavement under Heavy Traffic**. Transportation Research Record. 2305(0):83–94.

全透水路面（透水性能、力学性能）-结构设计

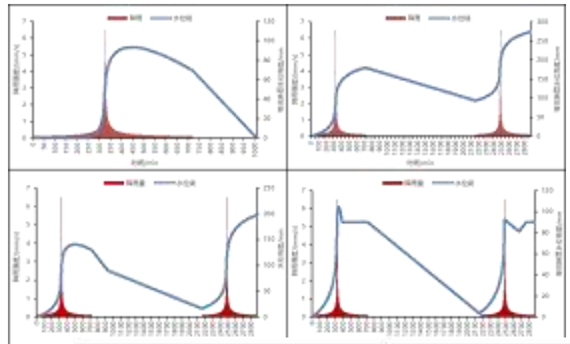
- ◆ 基于渗流平衡及应力与强度比的透水路面结构的水文学和力学双性能设计理论与方法
- ◆ 基于强度的材料与结构一体化设计方法



雨水渗蓄模型

$$i=\frac{1600(1+0.846\log T)}{(t+7)^{0.656}}$$

暴雨强度公式



透水铺装路面结构水文设计

Layer	Rut Model[1]	Moisture Condition	Model Parameters *a*	*b*	*c*
Combined bedding and base	$RD_{BB}=a\times h\_SB+b$	Dry	0	4.0	-
		Wet	-0.012	13.1	-
Subbase	$RD_{SB}=(a\times SSR^{b})\times N^{c}$	Dry	3.10E-06	2.70	1
		Wet	3.10E-06	2.70	1
Subgrade (Silty clay)	$RD_{SG}=(a\times SSR+b)\times N^{c}$	Dry	0.03	-0.01	0.5
		Wet	0.03	-0.01	0.5

[1] RD_{xx}, rut depth of *xx* layer (BB=surface(paver, bedding and base); SB=subbase; SG=subgrade), mm;
h_SB, thickness of subbase, mm;
SSR, shear stress/strength ratio at the top of the layer;
N, load repetition;
a, *b*, *c*, model constants.

控制土基顶面剪应力-剪切强度比 (SSR)，通常SSR<0.3， 土基变形风险低， SSR>0.7， 土基变形风险则很高。

Hydraulic Design

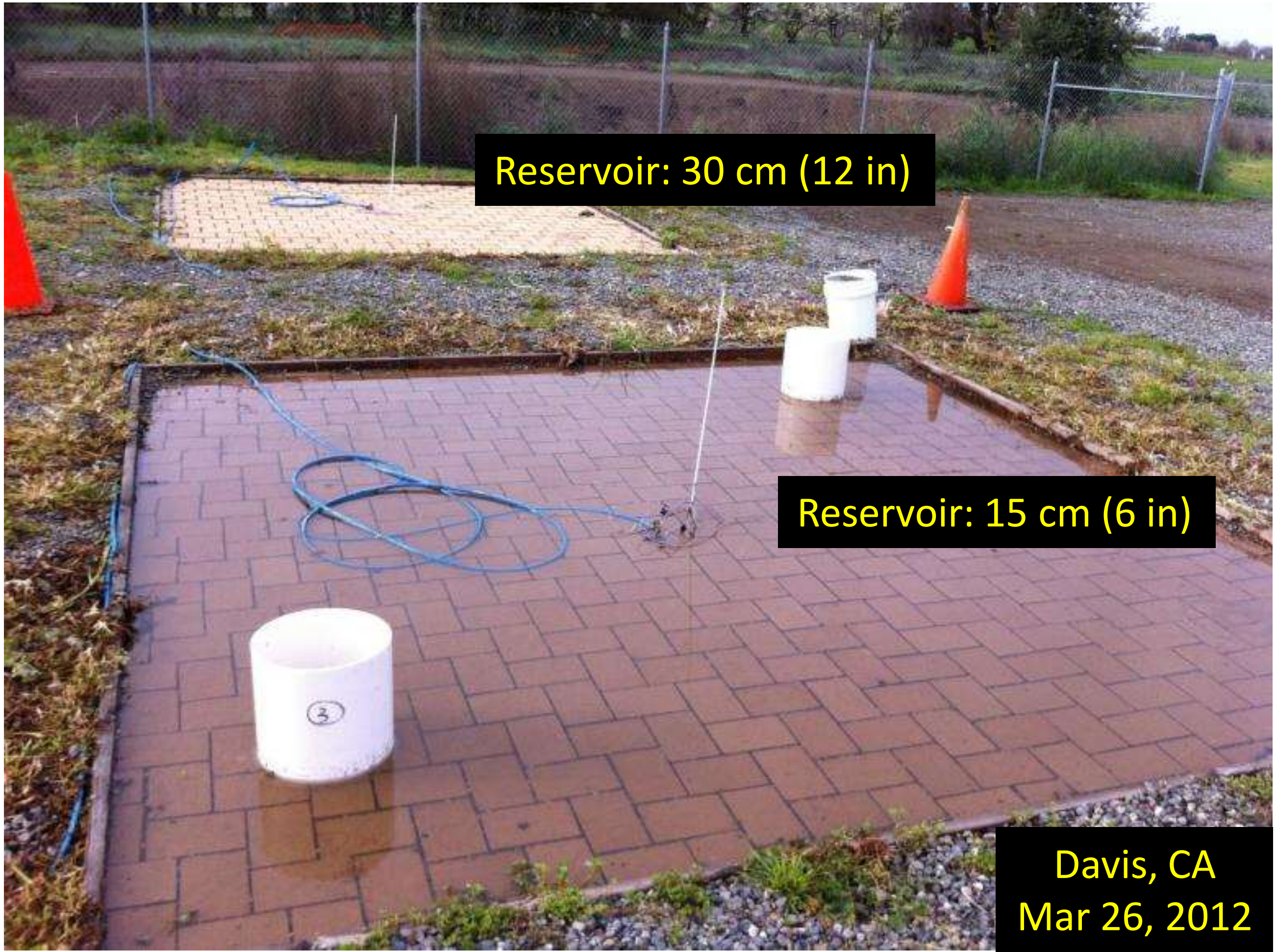
- Reduce **Runoff**
  - *Surface permeability > Rainfall intensity*
  - Unit: cm/hr or in/hr

Capture stormwater

- Reduce **Overflow**
  - *Reservoir capacity > Rainfall load*
  - Rainfall load/volume
    - Intensity, duration & frequency
  - Reservoir capacity
    - Thickness and void content of granular base/subbase layer
    - Infiltration rate (i.e. permeability) of subgrade soil
    - Evaporation rate from pavement
    - Overflow capacity

Store stormwater

Surface Overflow, Pond

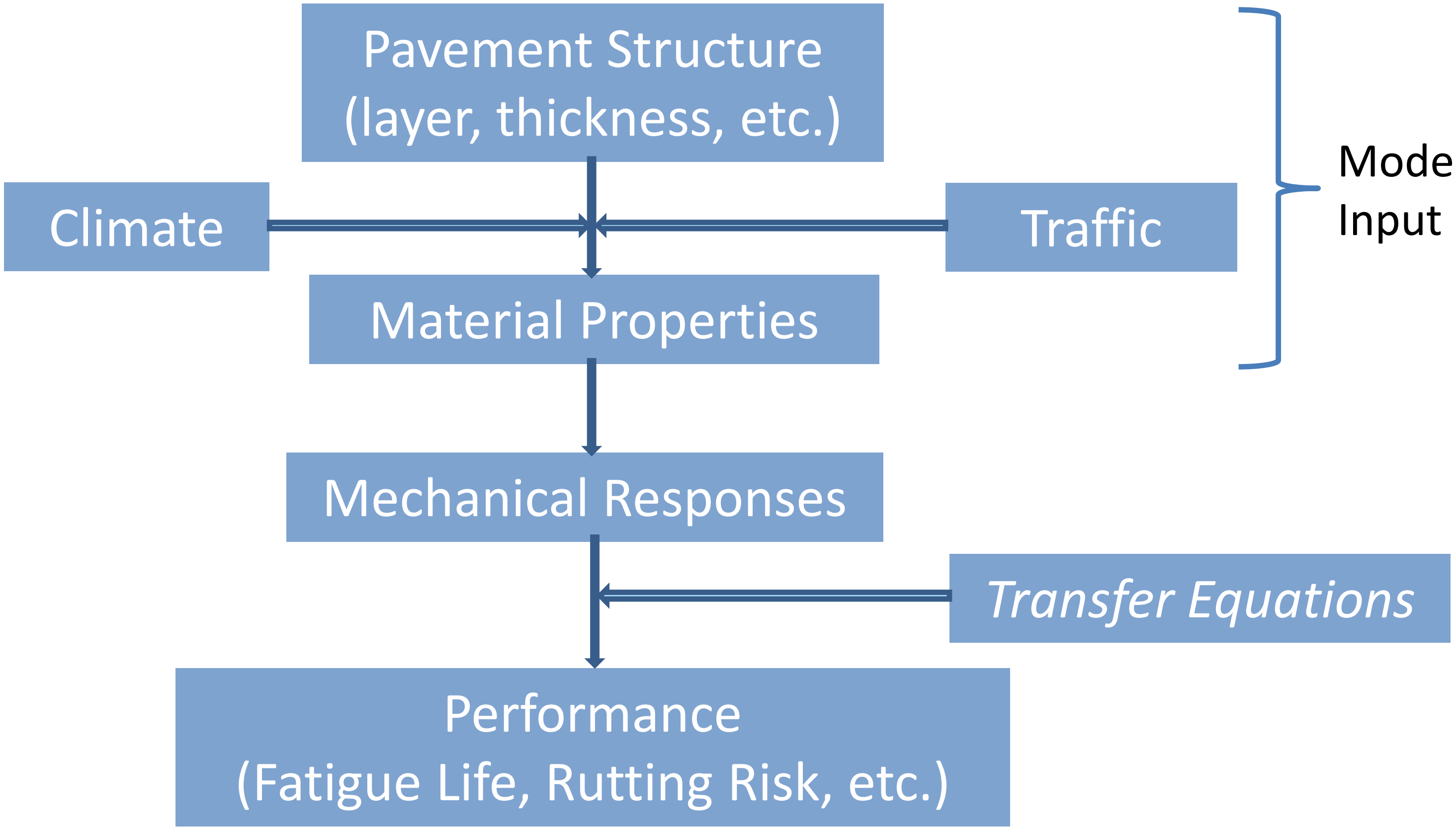


Structural Design

- Design Criteria
  - Deflection
  - Rutting
  - Fatigue cracking
  - …
- Design Methods
  - Empirical approach
  - Mechanistic-Empirical (M-E) approach

Similar to conventional impermeable pavement design.

Analysis Process for M-E Design



Li H.*, D. Jones, R. Wu, and J. Harvey (2016). Development and Validation of a Mechanistic-Empirical Design Method for Permeable Interlocking Concrete Pavement (*TRB 16-0019*). ***Transportation Research Record: Journal of the Transportation Research Board*** *2590 (09): 92–102.* *DOI: 10.3141/2590-09* *(SCI/EI, IF: 0.6)*

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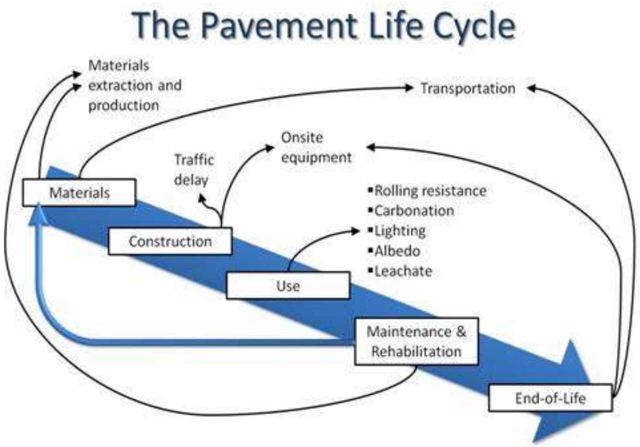
功能型环保道路基础设施全寿命周期分析

全寿命周期环境清单数据
全寿命周期成本评价数据

全寿命周期评价方法
全寿命周期评价工具



From: Santero, N. (2009). Pavements and the environment: A life-cycle assessment approach. Ph.D. Thesis, UC Berkeley.

- ✓ 制定了可持续性道路工程全寿命周期分析的框架；
- ✓ 建立了透水铺装道路全寿命周期经济与环境影响耦合评价模型与方法；
- ✓ 开发了路面全寿命周期分析在线软件(http://lca.gowisdom.org)。

Wang Y., **Li H.***, et al (2017). Initial Evaluation Methodology and Case Studies in China for Life Cycle Impact of Permeability of Permeable Pavements. **Transportation Research Board 97th Annual Meeting Compendium of Papers**, Washington, D.C .January 7-11, 2018.

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I. Martials
- Subgrade Soil
- Base Aggregate
- Permeable Surface

II. Structures
- Analysis
- Design

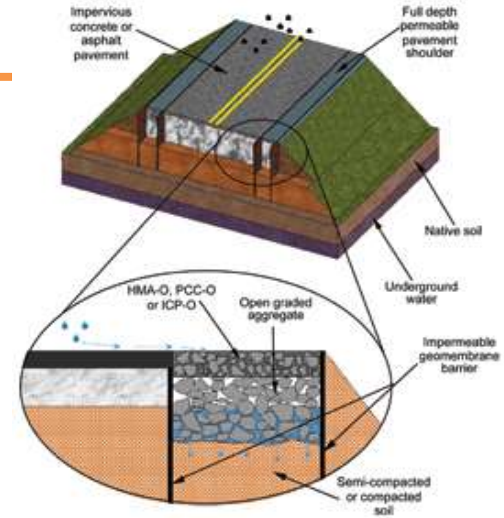
III. Life Cycle Analysis
- LCCA
- LCA

IV. APT Testing

Full-scale Structural Testing and Development of M-E Design Method for Permeable Interlocking Concrete Pavement Under Heavy Traffic

Introduction

- Interest in using permeable pavements in higher traffic applications
- Previous work by UCPRC
  - Preliminary Caltrans Study (2008 – 2010) on permeable concrete and asphalt pavements, materials testing & structural modeling
  - No validation with traffic
- Validation study funded by industry
- Study objective
  - Develop mechanistic-based design method and tables for PICP



Design Method

- Distress
  - Unbound layer rutting
- Approach
  - Shear stress to shear strength ratio (SSR) at top of layer
  - $0.3 \leq SSR \leq 0.7$
- Required inputs
  - Unbound layer stiffness, strength, and other mechanic properties
  - Obtained from lab and field testing

$$Shear\ Stress\ Ratio\ (SSR) = \frac{\tau_f}{\tau_{max}} \quad (1)$$

$$\tau_f = \frac{\sigma_1 - \sigma_3}{2} cos\phi = \frac{\sigma_d}{2} cos\phi \quad (2)$$

$$\tau_{max} = c + \sigma_f tan\phi \quad (3)$$

$$\sigma_f = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} sin\phi = \frac{\sigma_d + 2\sigma_3}{2} - \frac{\sigma_d}{2} sin\phi \quad (4)$$

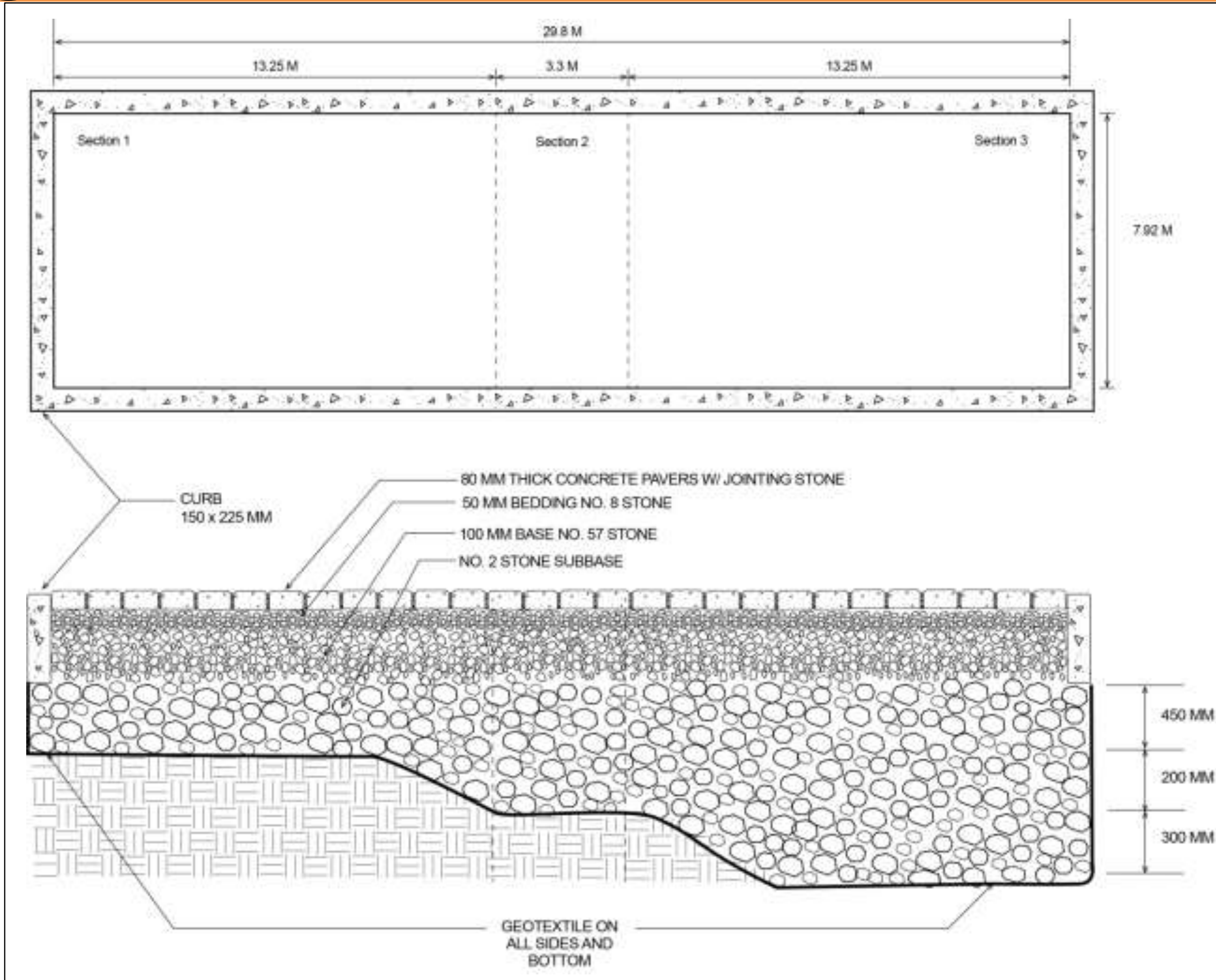
Where:
τ_{max} is applied shear stress acting on the failure plane oriented at an angle of $45° + \phi/2$
σ_f is applied normal stress acting on the failure plane oriented at an angle of $45° + \phi/2$
τ_f is shear strength of the material under a certain stress state
σ_1 and σ_3 are the major and minor principal stresses, respectively
σ_d is the deviator stress, $\sigma_d = \sigma_1 - \sigma_3$
c is the cohesion of the material
ϕ is the internal friction angle of the material ($\phi = 0$ for stress-independent materials)

Design – Subbase Thickness

- Surface
  - 80 mm interlocking concrete paver
- Bedding layer
  - 50 mm ASTM #8 aggregate
- Base layer
  - 100 mm ASTM #57 aggregate
- Subbase layer
  - Varying thickness ASTM #2 aggregate
- Subgrade soil
  - Silty clay, compacted after excavation

Subbase Thickness	Shear Stress Ratio (SSR)	Calculated (mm)		As-Built
		Dry	Wet	
Thin	0.8	450	650	450
Medium	0.5	800	950	650
Thick	0.2	1,350	1,450	950

Design



29.8 M
13.25 M
3.3 M
13.25 M
Section 1
Section 2
Section 3
7.92 M
CURB
150 x 225 MM
80 MM THICK CONCRETE PAVERS W/ JOINTING STONE
50 MM BEDDING NO. 8 STONE
100 MM BASE NO. 57 STONE
NO. 2 STONE SUBBASE
450 MM
200 MM
300 MM
GEOTEXTILE ON
ALL SIDES AND
BOTTOM

UCPRC Facility

Test Track Construction

Test Track Construction

Instrumentation

- Aggregate size limited options
- Stress (pressure cell)
  - Top of base
  - Top of subgrade
- Deformation (profiler + dipsticks)
  - Surface
  - Top of base
  - Top of subgrade
- Deflection (RSD)
- Water level
  - Manual and automated

APT – Test Program

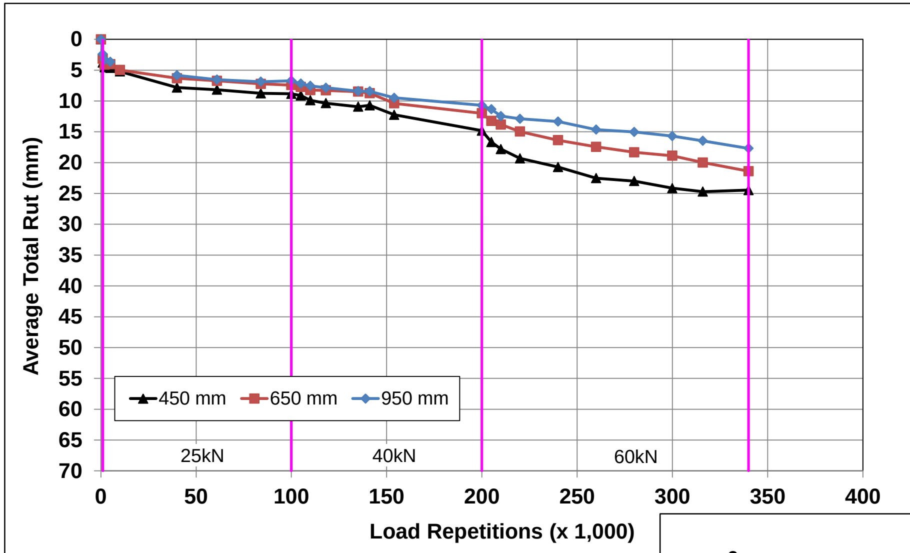
- Extended HVS (13m) used to test all sub sections together
  - Bidirectional trafficking with wander
  -
- Th
  -
  -
  -
  -
- Fa
  -

APT – Wet Testing

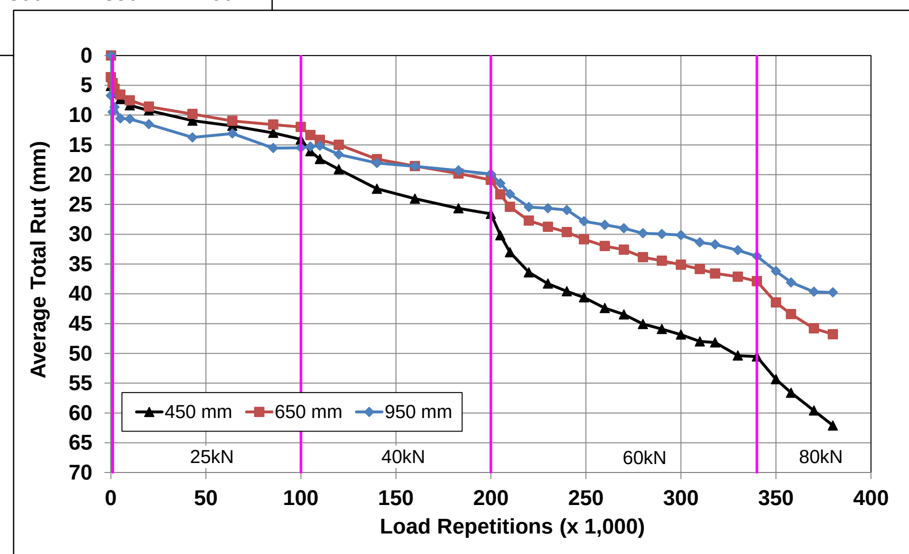
APT – Visual Assessment

APT – Total Surface Rut

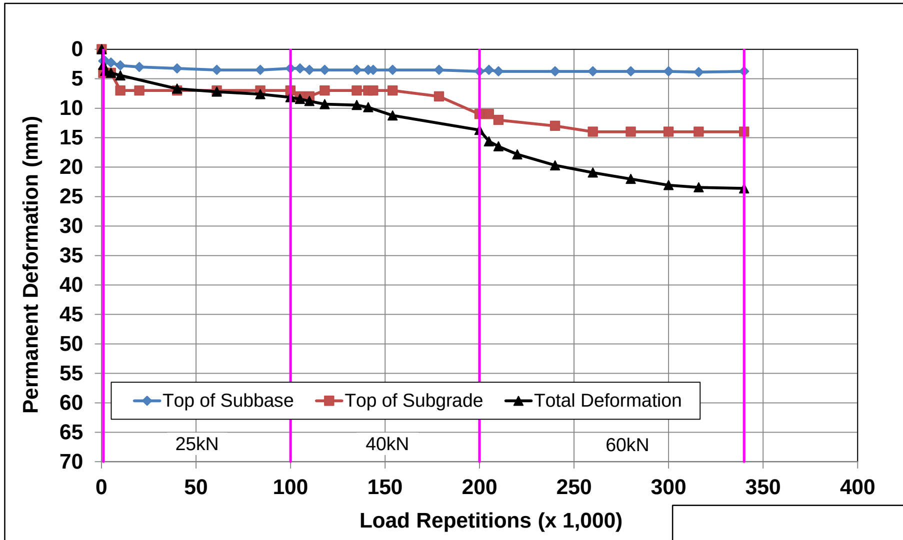
Dry



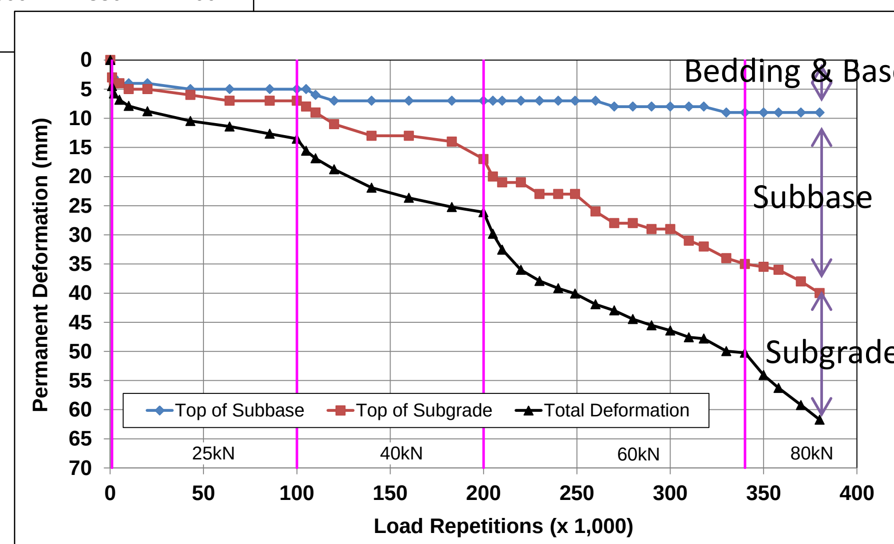
Wet



APT – Down Rut: 450mm Subbase



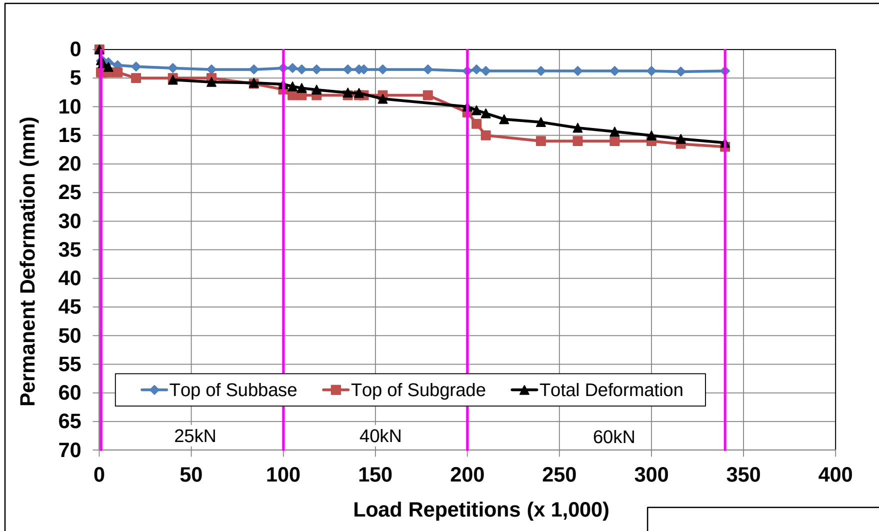
Dry

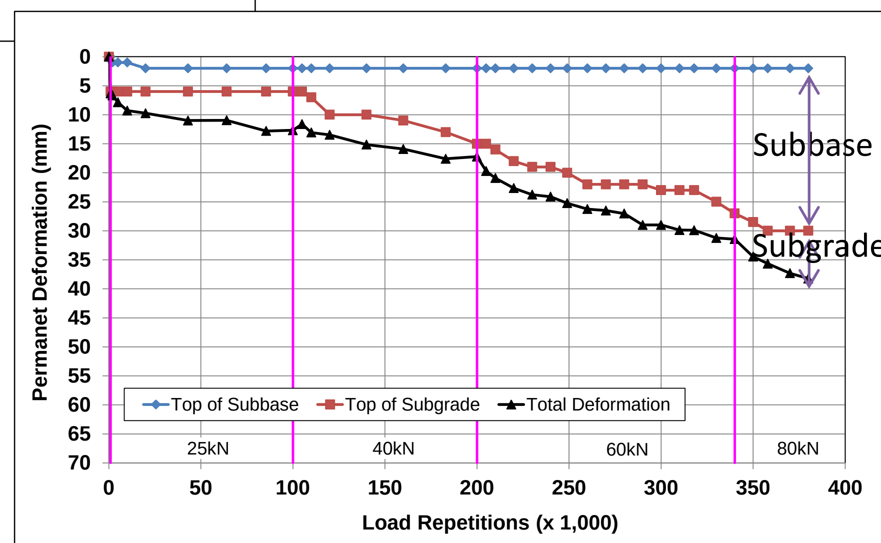


Wet

APT – Down Rut: 950mm Subbase

Dry





Wet

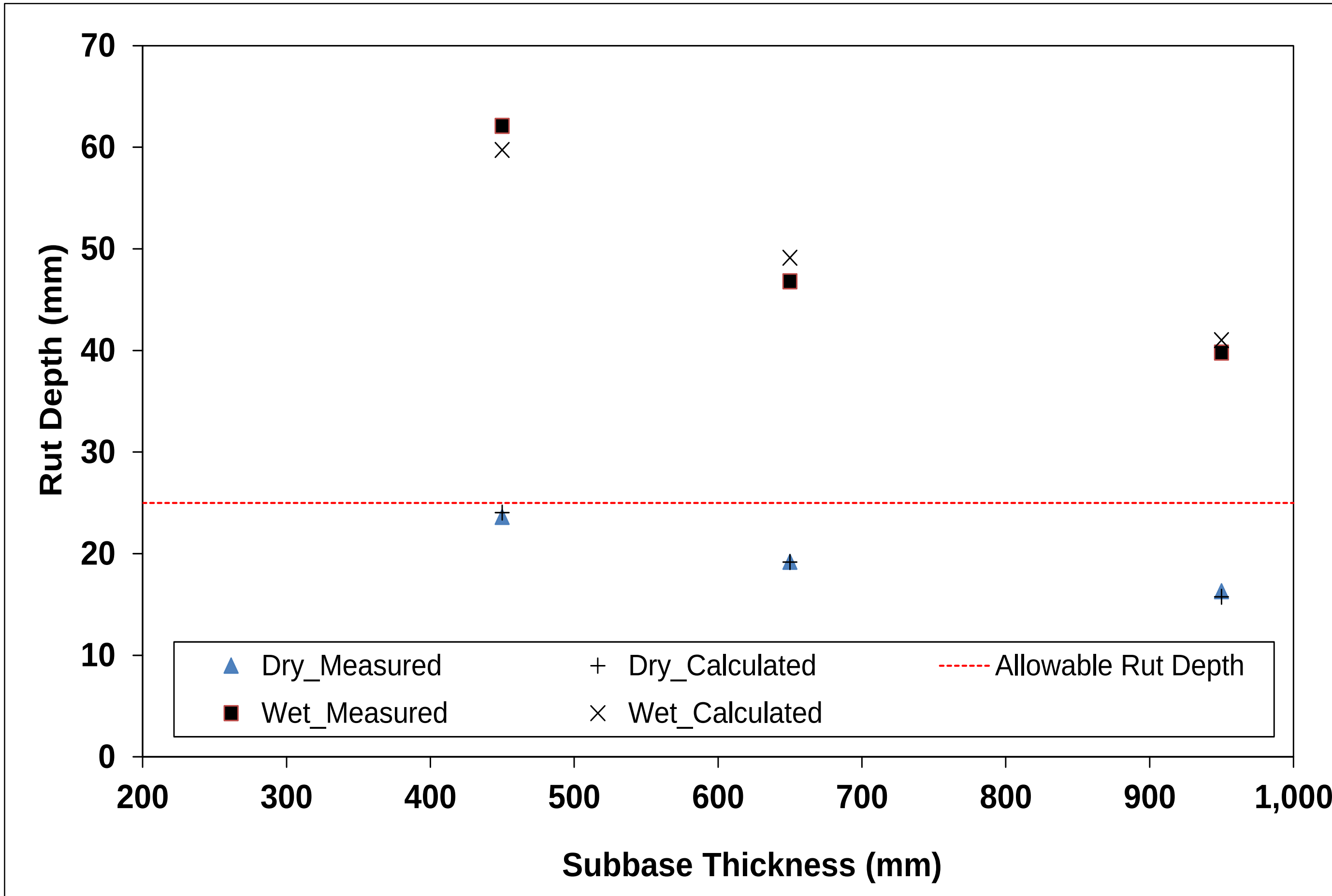
Rut Models for Different Layers

TABLE 1 Summary of Rut Models Developed for Different Layers in a PICP

Layer	Rut Model[1]	Moisture Condition	Model Parameters		
			a	*b*	*c*
Combined bedding and base	$RD_{BB} = a \times h\_SB + b$	Dry Wet	0 -0.012	4.0 13.1	- -
Subbase	$RD_{SB} = (a \times SSR^{b}) \times N^{c}$	Dry Wet	3.10E-06 3.10E-06	2.70 2.70	1 1
Subgrade (Silty clay)	$RD_{SG} = (a \times SSR + b) \times N^{c}$	Dry Wet	0.03 0.03	-0.01 -0.01	0.5 0.5

[1] RD_{xx}, rut depth of *xx* layer (BB=surface(paver, bedding and base); SB=subbase; SG=subgrade), mm;
h_SB, thickness of subbase, mm;
SSR, shear stress/strength ratio at the top of the layer;
N, load repetition;
a, *b*, *c*, model constants.

Validation of M-E Design Method



M-E Design Tool for PICP

PICP Design Tool

Input

Structure & Materials

Layer	Moisture Condition	Thickness (mm)	Stiffness (MPa) [1]	Poisson's Ratio	c (kPa)	ϕ (°)
Surface (80 mm concrete paver plus 50 mm #8 bedding and 100 mm #57 base)	Wet	230	87	0.35	-	-
	Dry		110	0.35	-	-
Subbase (ASTM #2)	Wet	150	73	0.35	*0*	*30*
	Dry		122	0.35	*0*	*45*
Subgrade (Clay)	Wet	-	37	0.35	*9*	*15*
	Dry		60	0.35	*15*	*25*

Climate

Number of Days in a Year When the Subbase has Standing Water (Wet Days) [2]
20

1. The wet stiffness to dry stiffness ratio can be assumed as 0.8, 0.6 and 0.6 for surface, subbase and subgrade layers, respectively.
2. Seasons when the subbase has standing water.

Traffic

Traffic Volume Calculation	
AADT (two-way)	*250*
Percent Trucks, T	*5.0%*
Direction Distribution Factor, D	*0.5*
Lane Distribution Factor, L	*0.9*
Annual Growth Rate, r	*2.0%*
Design Life (years), Y	*20*
Traffic Days (days/year), TD	*365*
Traffic Safety Factor, TSF	*1.0*
Truck Traffic Volume, V	**50,055**

$$V = AADT \times T \times D \times L \times (1+r)^{Y/2} \times Y \times TD \times TSF$$

Axle Type	Axle Load (kN)	Axle-Load Distribution (%)	Lifetime Repetition: Wet Season [2]	Lifetime Repetition: Dry Season	Lifetime Repetition: Total	Lifetime Repetition: ESALs	Lifetime ESALs (Millions)
Single	10	3.25	89	1,538	1,627	0	0.01
	20	5.97	164	2,823	2,987	12	
	30	5.83	160	2,756	2,916	58	
	40	4.43	121	2,095	2,217	139	
	50	3.23	89	1,528	1,617	247	
	60	2.80	77	1,324	1,401	443	
	70	3.13	86	1,481	1,567	919	
	80	2.40	66	1,137	1,203	1,203	
	90	0.85	23	400	424	679	
	100	0.15	4	69	73	177	
	120	0.03	1	15	15	78	
	160	0.01	0	5	5	80	
Tandem	20	1.59	44	755	798	0	
	40	5.79	159	2,738	2,897	23	
	60	6.76	186	3,201	3,386	134	
	80	4.48	123	2,118	2,241	280	
	100	3.42	94	1,617	1,711	522	
	120	3.86	106	1,824	1,930	1,221	
	140	4.12	113	1,950	2,063	2,419	
	160	1.94	53	918	971	1,943	
	180	0.29	8	139	147	471	
	200	0.05	1	24	25	123	

Outcome

Rut Depth

Layer	Moisture Condition	Shift Factor	Rut Depth by Layer (mm)	Expected Total Rut Depth (mm)	Allowable Rut Depth (mm)	Satisfactory ?
Surface (80 mm concrete paver plus 50 mm #8 bedding and 100 mm #57 base)	Wet	1.30	0.8	23.0	25.0	*Y*
	Dry	1.10	4.2			
Subbase (ASTM #2)	Wet	1.30	0.8			
	Dry	1.10	9.2			
Subgrade (Clay)	Wet	1.30	2.8			
	Dry	1.10	5.2			

Calculate Rut Depth

Design Subbase Thickness

同济大学交通运输工程学院
COLLEGE OF TRANSPORTATION ENGINEERING
TONGJI UNIVERSITY

Permeable Pavement for Heave Load

Deployment Projects

高抗压强度彩色透水整体路面，重载透水铺装

Permeable Interlocking Concrete Paver for Travel Lanes and Heave Loads

Berkeley, BART Station, 2017

http://interlockdesign.org/why-arent-all-streets-like-this.html

M1 Tank on PICP in Colorado

Fire Tuck on PICP

成果应用-河北曲港绿色生态服务区 - 规划设计与工程示范

小车停车区、广场、篮球场，1/3重车停车区做**透水铺装**。

绿化面积做**下凹式绿地**，种植抗洪耐旱园林景观植物，设置景观水体（雨水收集净化利用）。

施工现场

简介（中设集团）

【愿　景】：成为城市发展与交通建设的顶尖技术专家

【使　命】：让世界更通达　让城市更宜居

【价值观】：伙伴共生　卓越致远

中設設計集團
China Design Group Co.,Ltd.

中設設計集團
China Design Group Co.,Ltd.

同济大学 + 中设集团

互联互通，资源共享

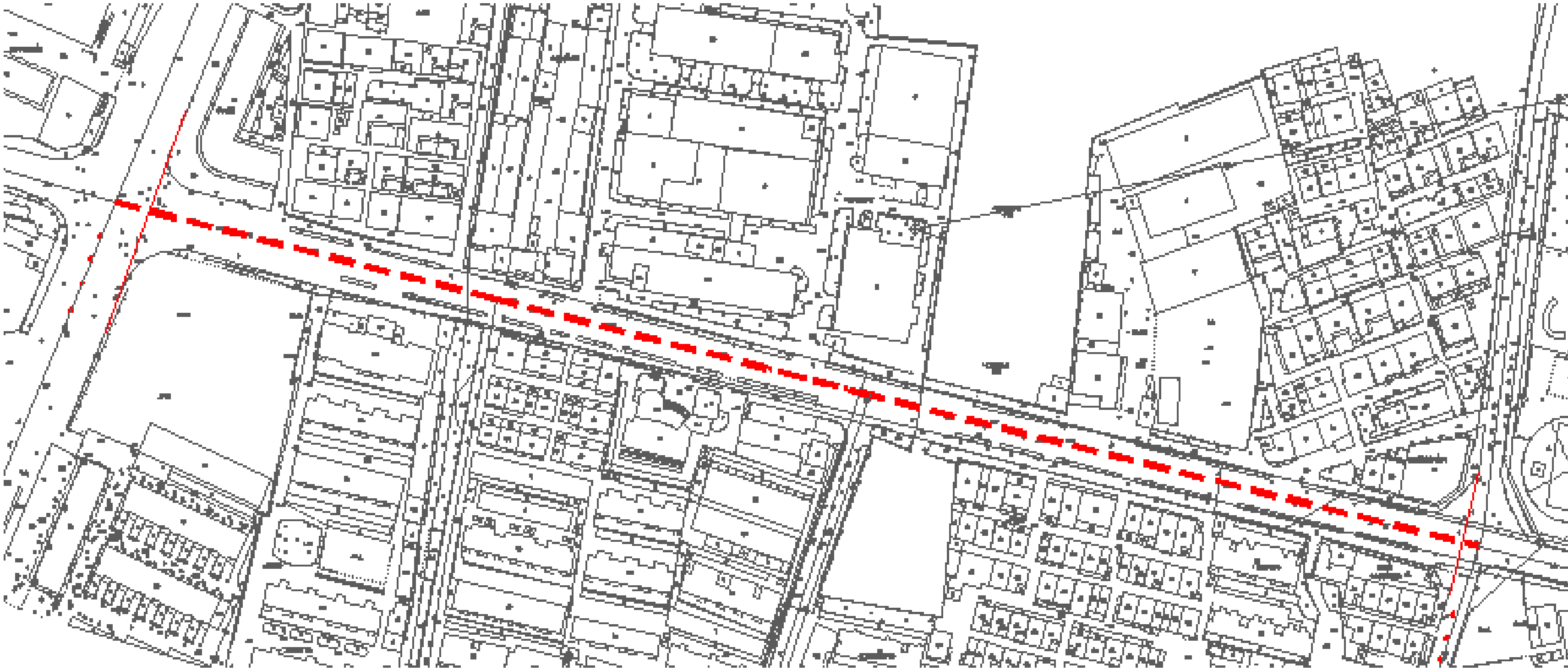
优势互补，合作共赢

如东洋口港危化品停车场透水路面项目
（洋口港物流综合服务中心一期项目）

洋口港以其独特的区位优势、深水条件及腹地市场容量，有望跻身亚洲第一的LNG仓储中心。

危化品停车场一期占地130亩、二期500亩、三期3000亩。通过采用**透水铺装、彩色铺装、智慧停车场**等多种生态环保铺装技术，降低停车场对生态环境的负面影响，打造危化品停车场样板工程。

靖江海绵城市试点：江山路（人名北路～东兴街）路段透水路面改造



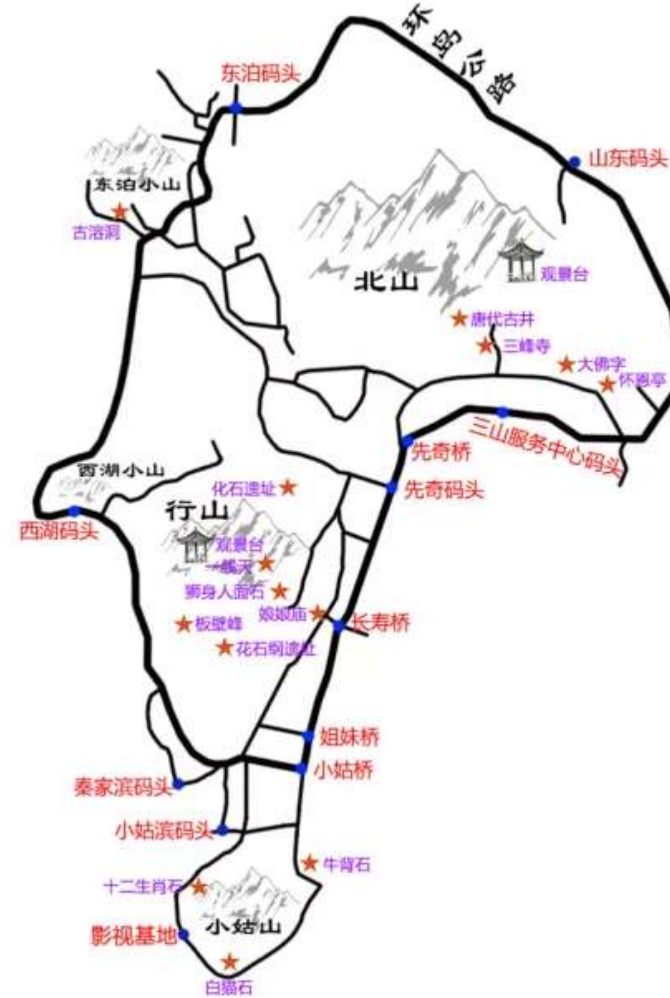
长度约560米，标准断面宽度25米，道路为三块板形式，两侧人行道宽度4.2米，侧分带1.8米，机动车道宽13米。机动车道改造为透水沥青路面，人行道改为透水砖铺装。

该项目是靖江海绵城市试点工程的重要部分，起到起承转结的作用。周边有其他海绵城市示范项目（海绵小区，海绵绿地等），通过将江山路改造为透水路面，连接其他海绵城市的项目，各个项目相得益彰，方便集中展示。

四好农村公路创意设计大赛：生态景观铺装

“四好农村路”是中共中央总书记、国家主席、中国共产党中央军事委员会主席习近平于2014年3月4日提出的。为深入贯彻习总书记关于“四好农村路”建设的指示精神，江苏省交通厅决定开展2018年“中设杯”江苏农村公路创意设计大赛。大赛以“江苏农村公路”为主题。

选取国家5A级景区苏州太湖三山岛环岛公路为创作对象，在结合当地自然人文风情的基础上，综合采用透水路面、彩色铺装、发光路面等技术，在提升生态环保效益的同时，打造兼具自然风光、人文风情的旅游胜地。



智慧透水铺装振动搅拌施工列车

不同铺装性能对比

类别	不透水铺装（传统）	排水铺装	半透水铺装	全透水铺装
技术特点（结构、材料、施工、养护，适用范围）	• 各结构层均密实不透水 • 施工养护工艺成熟 • 适用于各种场合	• 面层排水，其他结构层均密实不透水 • 施工养护工艺较为成熟 • 部分高频重载区域也可采用	• 降雨可以从面层渗透入道路结构内部，但是不能渗透到土基 • 施工养护工艺较为不完善 • 主要适用于轻载道路，部分高频重载区域也可采用	• 降雨可以从面层自然渗透至土基 • 施工养护工艺不完善 • 适用于土基较为稳定的中轻载道路
环保功能	• 环保性能较差	• 排水 • 降噪	• 排水 • 降温 • 降噪 • 水净化	• 透水 • 降温 • 降噪 • 吸附扬尘 • 水净化 • 补充地下水
经济性	• 材料施工养护经济性优良 • 环保经济性较差	• 材料施工养护经济性较好 • 环保经济性一般	• 材料施工养护经济性略差 • 环保经济性较好	• 材料施工养护经济性略差 • 环保经济性优良
市场规模	• 占有率高	• 占有率较高	• 占有率较低，市场空间大	• 占有率极低，市场空间大

研发成果：科研报告&专著，since 2008

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14. **Li H.***, J. Harvey and A. Kendall (2012). Field Measurement of Albedo for Different Land Cover Materials and Effects on Thermal Performance. ***Journal of Building and Environment,*** 59(0):536-46. DOI: 10.1016/j.buildenv.2012.10.014 *(SCI, IF: 3.0)*
15. **Li H.***, J. Harvey and D. Jones (2012). Multi-dimension Transient Temperature Simulation and Back-calculation for Thermal Properties of Building Materials. ***Journal of Building and Environment***, 59(0):501-16. DOI: 10.1016/j.buildenv.2012.09.019 *(SCI, IF: 3.0)*
16. **Li H.***, J. Harvey and D. Jones (2012). Developing a Mechanistic-Empirical Design Procedure for Fully Permeable Pavement under Heavy Traffic. ***Transportation Research Record: Journal of the Transportation Research Board***, 2305(0):83–94. DOI: 10.3141/2305-09 *(SCI, EI, IF: 0.6)*

科研成果-专利（部分）

序号	专利或著作权名称	授权国家	专利或著作权号	授权公告日	拥有人
1	沥青混凝土高温性能测试方法	中国	CN 100561178 C	2009.11.18	李辉
2	一种沥青混合料圆柱体试件多轴加载试验装置及其试验方法	中国	CN103940674 B	2016.05.04	李辉
3	一种用于重载交通的透水混凝土路面结构	中国	申请	-	李辉
4	一种用于重载交通的透水沥青混凝土路面结构	中国	申请	-	李辉
5	多孔隙水泥混凝土浸出液及其制备方法和该浸出液的生物毒性的检测方法	中国	申请	-	李辉
6	沥青混合料圆柱体试件多轴加载试验装置及其试验方法	中国	申请	-	李辉
7	大孔隙水泥混凝土加铺路面结构	中国	申请	-	李辉
8	半透水铺砖路面结构	中国	申请	-	李辉
9	提高净水效果的半透水重载沥青混凝土路面结构	中国	申请	-	李辉
10	雨水径流污染物的净化方法以及含沸石的净化材料	中国	申请	-	李辉

科研成果-技术标准

团体标准

中国公路学会

关于召开"中国公路学会 2018 年(第一批)标准立项评审会"的通知

各有关单位:

你单位申报的标准项目已通过形式初审，根据中国公路学会标准立项评审程序，定于近日在北京召开"中国公路学会 2018 年(第一批)标准立项评审会"，请贵单位派员出席，具体事项通知如下:

中国公路学会 2018 年度标准(第一批)编制计划

序号	标准名称	申报单位
1	混凝土小型预制构件品质工程技术规程	河南省公路工程局集团有限公司
2	沥青路面快速修复贴材料标准	新疆心路科技有限公司
3	复合混凝土路面设计与施工技术指南	辽宁新发展公路科技养护有限公司
4	工厂化稳定型橡胶沥青	江苏一诺路桥工程检测有限公司
5	高性能沥青路面 Superpave 施工技术指南	苏交科集团股份有限公司
6	聚合物短切纤维沥青混凝土路面施工技术指南	交通运输部公路科学研究所
7	成品天然沥青改性沥青路面施工技术指南	西咸新区众力沥青有限公司
8	连锁混凝土路面砖透水路面设计和施工规程	同济大学

地方标准

X X 省 地 方 标 准

透水砖路面设计与施工技术规程

Technical Specification for Permeable Interlocking Concrete Pavements Design and Construction

(送审稿)

X X 省 地 方 标 准

透水沥青铺装设计与施工技术规程

Technical specification for design and construction of permeable asphalt pavement

(送审稿)

高速公路服务区透水铺装路面技术规范

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X X 省 地 方 标 准

透水混凝土铺装设计与施工技术规程

Technical specification for design and construction of permeable concrete pavement

(送审稿)

主要研究方向：（高频重载）多孔隙材料与透水铺结构研究

全生命周期评价与管理
- LCCA
- LCA

设计
- 多孔隙材料设计
  - 面层（水泥、沥青、铺砖）
    - 集料
    - 级配
    - 胶结料
    - 改性剂
  - 基层
  - 土基
- 透水铺装结构设计
  - 渗流设计
  - 力学设计

施工工艺
- 材料
- 装备
- 工艺

管养技术
- 检测技术
- 功能养护
- 结构维修
- 路面再生

性能
- 环保性能：透水、水净化、降温、降噪、扬尘控制
- 力学性能：强度、模量、永久变形、疲劳、低温开裂、抗剥落、老化

目标：开展系统性研究，注重科研与工程实践相结合，推进道路交通基础设施的多功能化和全寿命周期可持续性。

近年承担主要科研项目

序号	项目名称	项目性质及来源	项目经费	起始年度	终止年度	团队承担人员
1	低影响开发海绵城市透水铺装关键技术研究及应用 （中美）	国家科技部，国家重点研发计划"政府间国际科技创新合作"重点专项	865万	2016	2019	李辉，项目负责人
2	海绵城市生态道路成套技术研究与示范	上海市科委，社会发展科研项目	1000万	2016	2018	李辉，子课题负责人
3	道路铺装功能化及可持续性研究	中组部青年资助项目	400万	2015	2018	李辉，项目负责人
4	城市地表径流雨水污染净化功能型环保材料研究 （中德）	上海市科委，社会发展科研项目	50万	2017	2020	李辉，项目负责人
5	路面材料全频谱光学反射特性与评价模型	国家自然科学基金	25万	2016	2018	李辉，项目负责人

同济可持续交通研究组(18人)-研究生15名(7博8硕)

张毅-2015级博士生

王宇-2015级硕士生

张恒基-2016级博士生

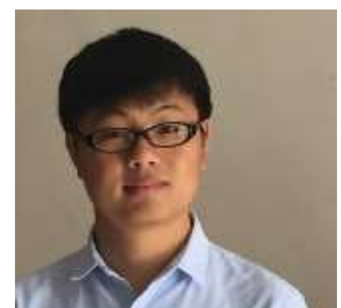
李昊臻-2016级硕士生

Hady-2017级博士生（埃及）

谢宁-2017级直博生

梁萧-2017级硕士生

周浩南-2017级硕士生



王寒冰-2017级硕士生

马瑰宝-2017级硕士生

同济可持续交通研究组(18人) - 研究领域与方向

课题组成员	类型	研究方向	领域
张毅	2015级博士生	透水水泥路面材料疲劳性能	多孔隙透水路面材料（水泥路面材料、沥青路面材料）
周浩南	2017级硕士生	透水水泥路面材料强度性能	
张恒基	2016级博士生	透水沥青路面材料优化设计	
Ahmed Abdel Hady (埃及)	2017级博士生	纤维加强透水沥青路面材料	
王寒冰	2017级硕士生	固体废弃物在透水路面中的应用	
马瑰宝	2017级硕士生	透水路面结构设计与基层材料	透水路面结构设计（水文、力学）
李昊臻	2016级硕士生	透水路面渗流性能与结构设计	
谢宁	2017级直博生	路面材料光学性能及降温性能研究	透水路面生态功能
梁萧	2017级硕士生	透水路面水污染净化	
朱浩然	博士后-2015	多孔隙透水铺装雨洪管理效果评价分析	多孔隙透水铺装耐久性及全生命周期评价
Behzad Ghadimi (澳大利亚)	博士后-2018	多孔隙透水铺装材料与结构耐久性研究	
王宇	2015级硕士生	透水路面全生命周期经济与环境影响综合分析	

第96届TRB，海绵城市透水铺装论坛，2017.1.12，DC，US

894 CM (4.00) HOT TOPIC

Thursday, 08:00 a.m. - 12:00 p.m., Convention Center, 204B

Low-Impact Development for Road Stormwater Runoff Management to Reduce the Risk of Flooding and Water Pollution

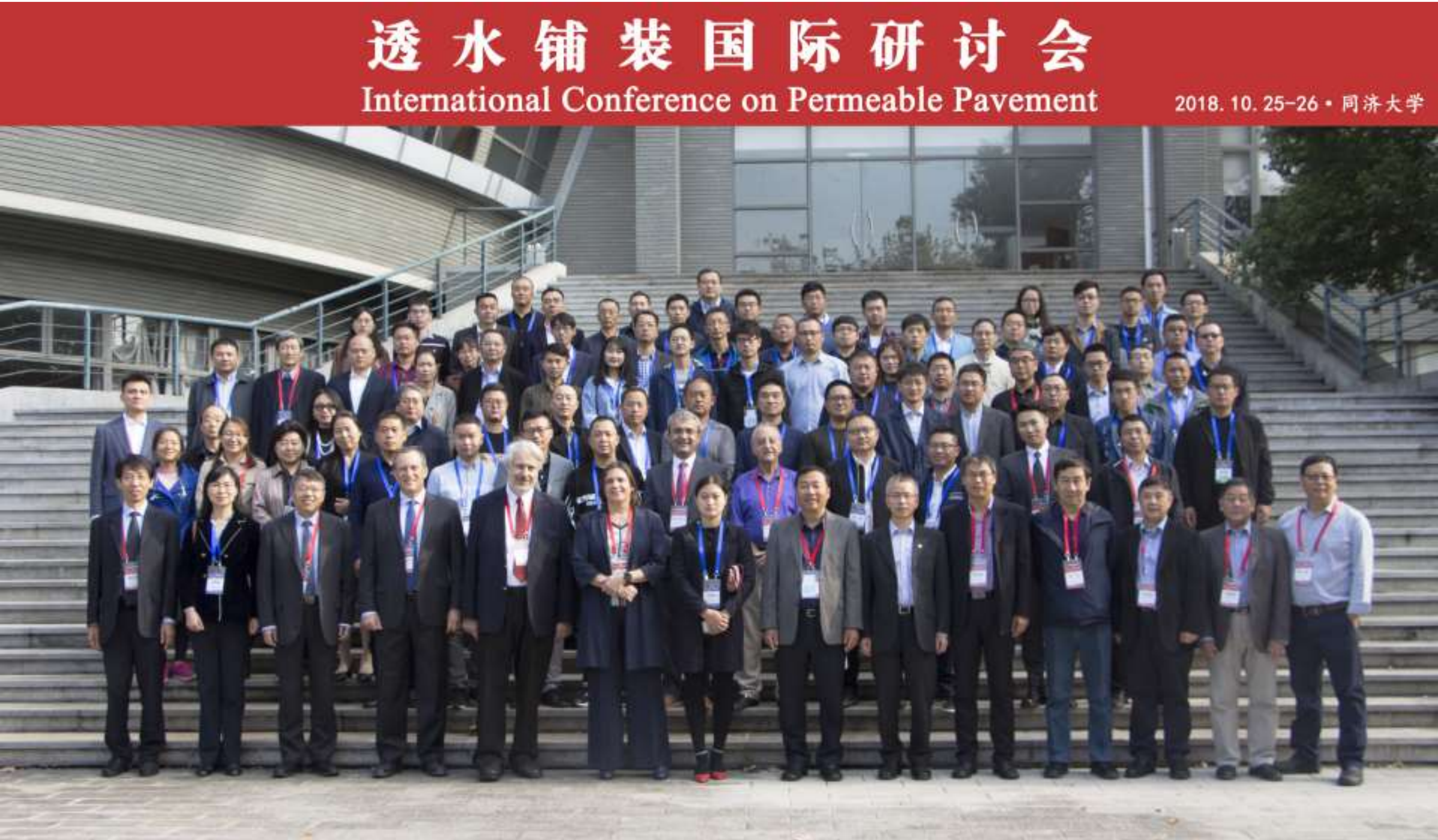
Hui Li, Tongji University, presiding

Sponsored By Standing Committee on Environmental Analysis in Transportation, Standing Committee on Transportation and Sustainability, Standing Committee on Hydrology and Hydraulics

参加院校、研究机构：加州大学戴维斯校区、佛罗里达大学、密苏里大学、田纳西大学、美国铺砖路面协会等。

国家重点研发计划项目，透水铺装第一次会议，同济大学，2017.2.23

透水铺装国际研讨会，美国加州，2017.11.14-15


透水铺装国际研讨会
International Conference on Permeable Pavement
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Special Issue on Porous Pavement and Stormwater Runoff Management

Description:

With the rapid development of the cities, the hardening of the large surface area hindered the natural infiltration of stromwater, especially the impervious pavement surface area. Whereas, road pavement area accounts for 20%-30% even more of the land in the city area. When the stoemwater exceeds the maximum capacity of municipal drainage flood control facilities, the surface runoff happened in many places. And thus, this creates an imminent risk for the flooding and runoff water pollution in cities. A new development strategy is desired to restore urban rainfall natural infiltration and solve the problem associated with stormwater runoff. In the last decades, the concepts of stormwater runoff management have been established by many countries such as; the Best Management Practices (BMPs) proposed by the United States in the early stage and the subsequent Low Impact Development (LID), the

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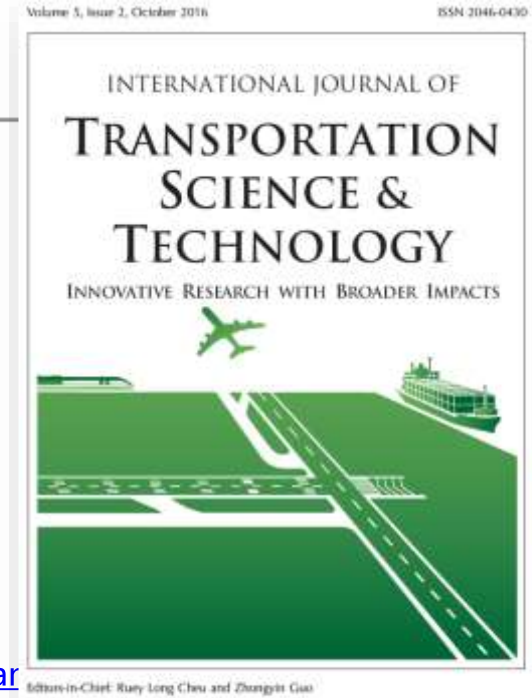

海绵城市：“政、产、学、研、用”交流合作

同济海绵城市及透水铺装(中转群)

该二维码7天内(11月2日前)有效，重新进入将更新

李 辉

同济大学 交通学院

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13601789941

同济大学交通运输工程学院

COLLEGE OF TRANSPORTATION ENGINEERING

TONGJI UNIVERSITY

Thanks!

Q&A!