

# Correlation in Accelerated Testing

## Principles, Challenges, and Case Studies

### 户外和实验室加速测试的相关性

#### 原理，挑战和案例分析

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# The Question

- In weathering and corrosion, we encounter the same basic question over and over again ...

在老化和腐蚀测试中，我们经常碰到这样的问题。

- “How many hours in my accelerated test correlates to \_\_ years of outdoor service?”

“加速测试多少小时等于户外多少年？”

# The Hard Truth

- There is no Universal Acceleration Factor, or “Magic Number,” between accelerated and outdoor testing

在加速和户外测试中，没有统一的加速因子或“神奇数字”

- Different materials in different service environments have different acceleration factors

不同的材料在不同的使用环境下有不同的加速因子

- Weathering and Corrosion Tests do not give quantitative predictions of Service Life

老化和腐蚀测试不能定量地给出产品的寿命预测

# Why is this such a challenge?

- The problem is not that we just haven't developed the perfect weathering tester yet.  
问题不是我们没有开发很好的老化测试
- The biggest problem is the inherent variability and complexity of outdoor exposures. Consider just some of the many factors in relationships between outdoor and accelerated tests:  
最大的问题是户外曝晒的多变性和复杂性。考虑所有的户外和加速试验关系的因素：

## *Outdoor factors 户外因素*

1. Latitude 维度
2. Altitude 海拔
3. Geography 地理环境
4. Year-to-year variations 每年的气候变化
5. Seasonal variations 季节性变化
6. Specimen Orientation 样品的朝向
7. Environmental particulates 环境污染

## *Laboratory factors 实验室因素*

8. Specimen insulation 样品的散热绝缘
9. Test cycle 测试循环
10. Water delivery 水施加
11. Test temperatures 测试温度
12. Light source 光谱差异

## *And of course...*

13. **The particular materials system tested 样品自身特性**

# What Can Be Done

- Weathering and corrosion testing can have many goals other than determining acceleration factors and service life.

老化和腐蚀测试有很多的目的不仅仅是得到加速因子和寿命预测

- Define goals, set expectations, and from there select an appropriate test program

根据测试目的和预期，选择合适的测试项目

- Although weathering and corrosion tests usually are not predictive, they can often be correlative

尽管老化和腐蚀测试通常不能做寿命预测，他们可以做相关性研究

- Weathering and corrosion tests are comparative, and comparative data can be powerful.

老化和腐蚀测试是相对的，相对数据是很有用的

# Accelerated Testing is a Tool for Decision Making

Accelerated tests can help you decide ...

加速测试可以帮助你。。

- What ingredients to include or not include in a product  
在产品中是否添加某些成分
- Whether a lot or batch is OK to ship to customers  
产品批次的检验
- What vendors to buy from  
供应商的筛选
- What processing and manufacturing parameters should be selected  
在生产过程中需要选择或者调整什么参数
- Make better, faster decisions  
做更好更快的判断

# Accelerated Test Types

## What do we want to learn?

Accelerated Test Type 加速测试目的	Result 结果	Test Time 测试时间	Results compared to 结果和什么比
Quality Control 质量控制	Pass / fail 合格/不合格	<ul style="list-style-type: none"><li>• Defined</li><li>• Short</li></ul>	Material specification 产品规格
Qualification / validation 验证	Pass / fail 合格/不合格	<ul style="list-style-type: none"><li>• Defined</li><li>• Medium-long</li></ul>	Reference material or specification 参比材料或规格
Correlative 相关性	Rank-ordered data 排序数据	<ul style="list-style-type: none"><li>• Open-ended</li><li>• Medium</li></ul>	Natural exposure (Benchmark site) 自然曝晒 (户外基准点)
Predictive 寿命预测	Service life Acceleration factor 加速因子	<ul style="list-style-type: none"><li>• Open-ended</li><li>• Long</li></ul>	Natural exposure (Service environment) 自然曝晒 (使用环境)

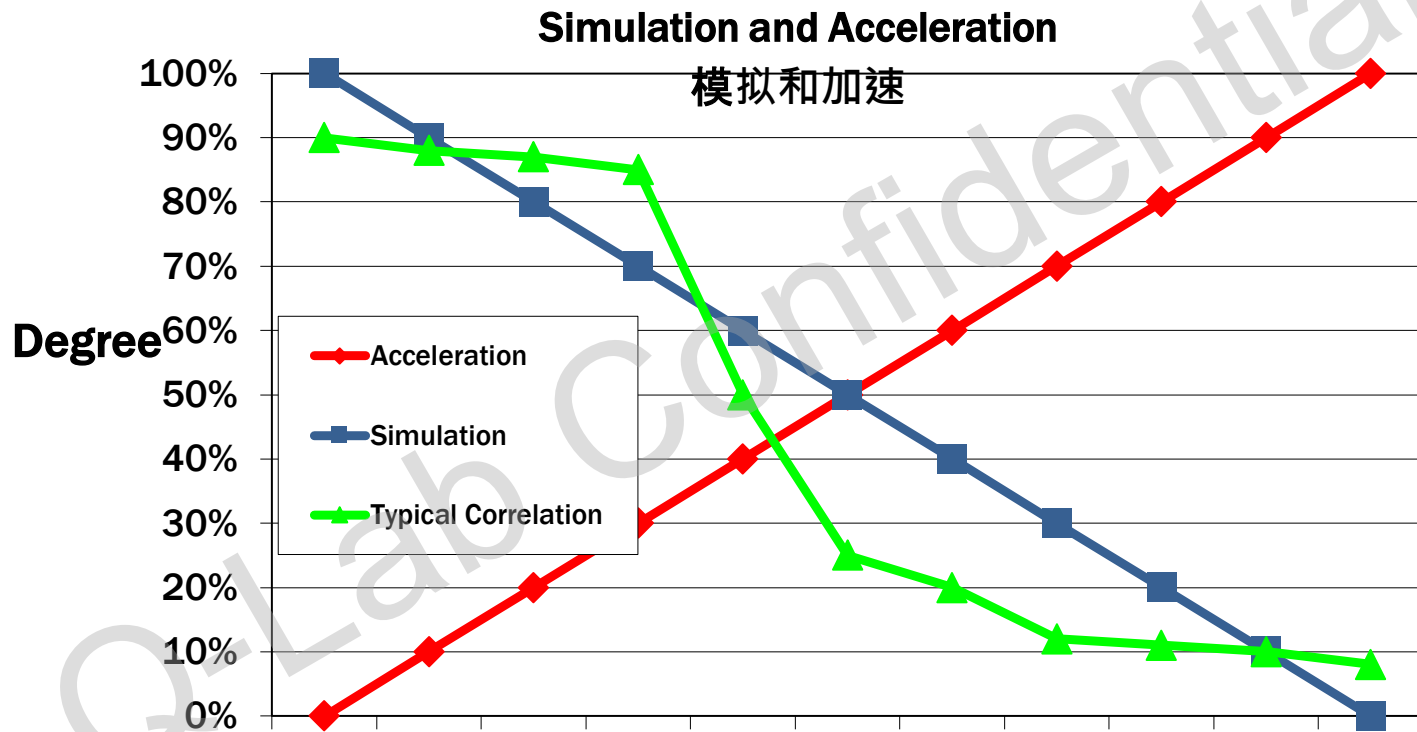
# Accelerated Test Types

## What do we want to learn?

Accelerated Test Type	Result	Test Time	Results compared to
Quality Control	Pass / fail	<ul style="list-style-type: none"><li>• Defined</li><li>• Short</li></ul>	Material specification
Qualification / validation	Pass / fail	<ul style="list-style-type: none"><li>• Defined</li><li>• Medium-long</li></ul>	Reference material or specification
Correlative	Rank-ordered data	<ul style="list-style-type: none"><li>• Open-ended</li><li>• Medium</li></ul>	Natural exposure (Benchmark site)
Predictive	<del>Service life</del> <del>Acceleration factor</del>	<del>• Open-ended</del> <del>• Long</del>	<del>Natural exposure (Service environment)</del>



# Why is correlation such a challenge?



# Correlation

The degree to which sets of data from separate tests agree with one another

一个测试与另外一个测试之间多大程度的关联

- Accelerated vs outdoor weathering

加速方法vs户外

- One accelerated test method vs another

加速方法a vs 加速方法b

- One outdoor environment vs another

户外a vs 户外b

# Why Correlation Matters

- Decision-making tools need to be validated  
决策工具需要被证实
- There is an inherent conflict between acceleration and realism  
在加速和现实中固有的矛盾
- The only way to validate an accelerated weathering test is with outdoor/real world data

唯一的方法去证实加速测试有效的是户外数据

- In other words ... Test the Test!  
换句话说，测试本身需要被测试！

# Methods for Establishing Correlation

Two main methods for correlating two tests (usually outdoor and accelerated)

将两个测试(通常是户外和实验室加速测试)关联起来的方法

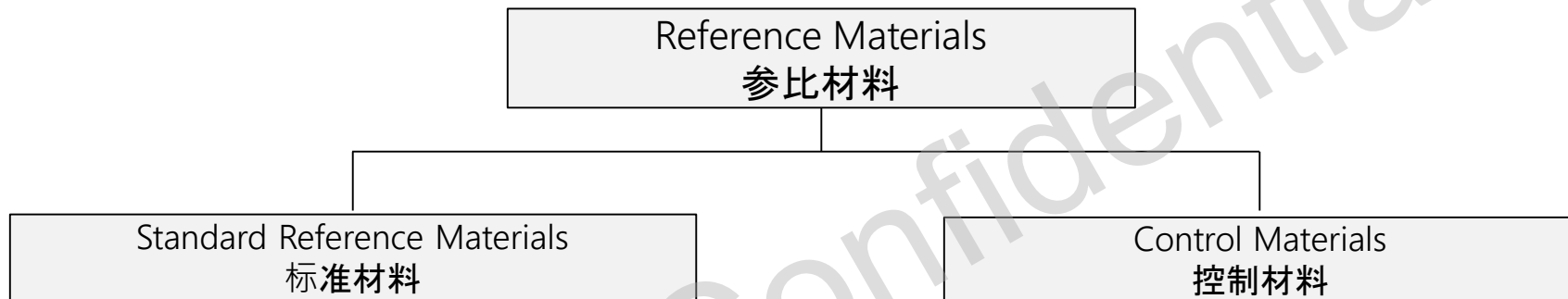
- Reference and Control Materials

参比材料

- Rank Order Evaluation

排序相关分析

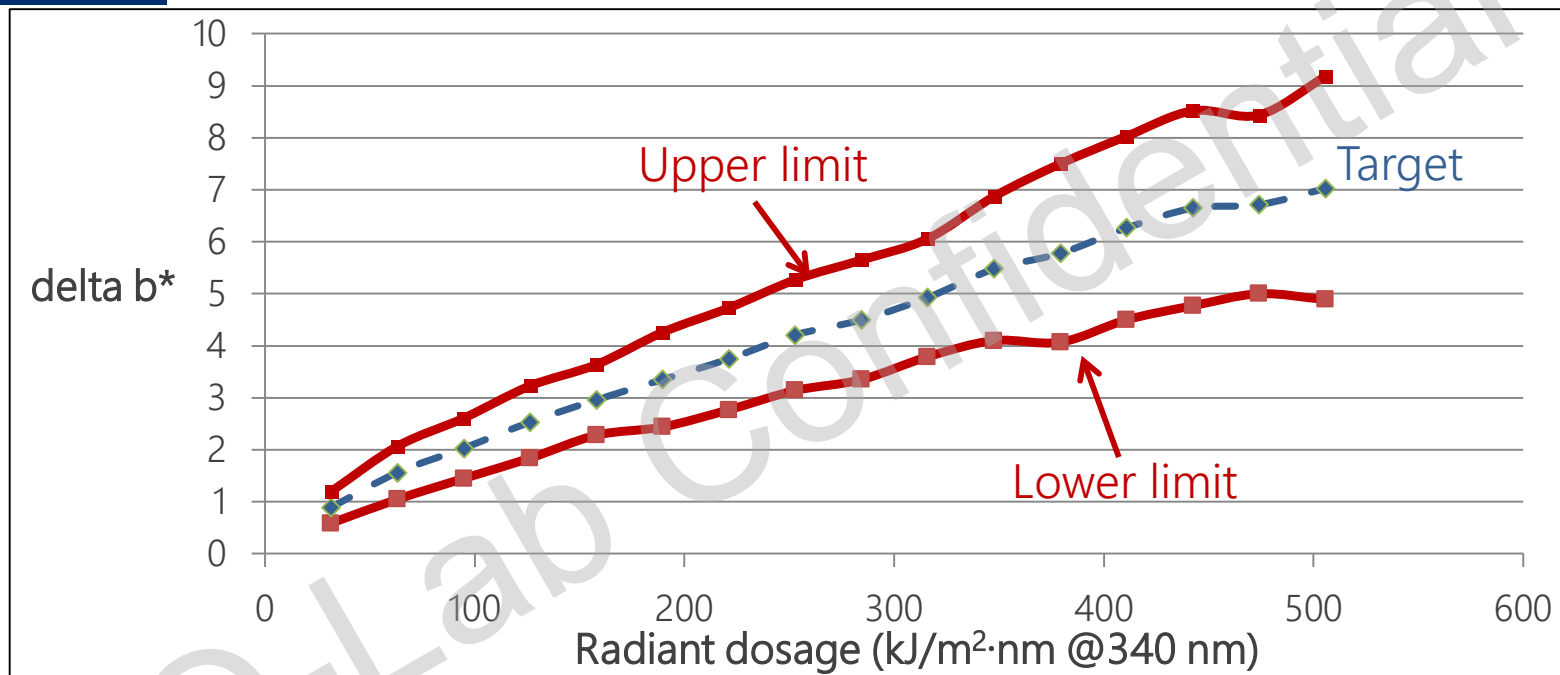
# Reference and Control Materials



- Known performance in test environments  
在测试中性能已知
- Not necessarily similar to test specimens  
不一定是同材质样品
- Performance may not match test specimens  
表现可能和测试样品不一致
- Verify that lab tester is operating properly  
确认实验正常运行

- Similar characteristics to test specimens  
和测试样品相同的特性
- May be your products or competitors'  
自家产品或者竞品
- Give confidence in lab exposure  
增加测试可信度

# Standard Reference Material (Polystyrene)



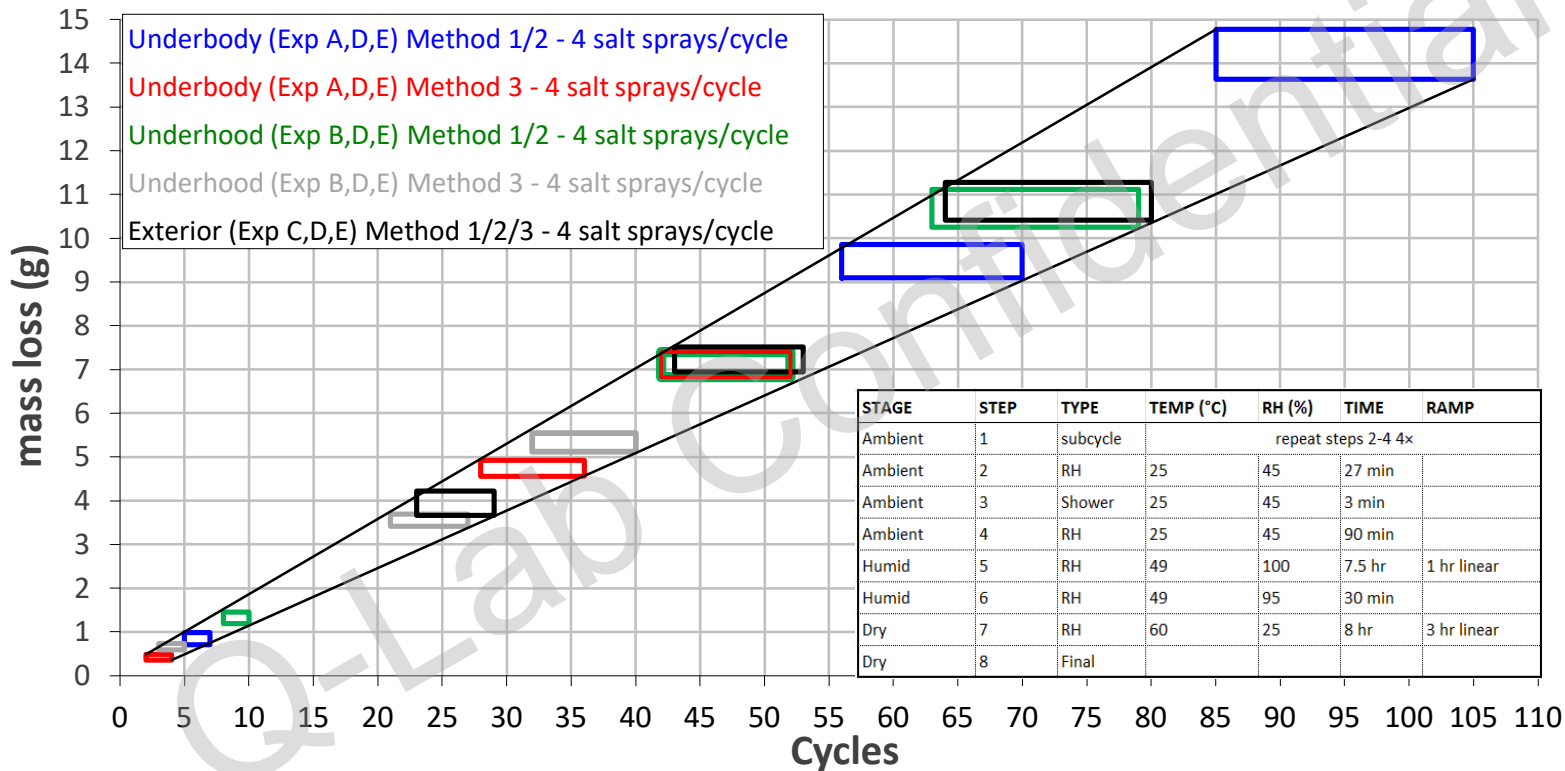
Reference Polystyrene yellowing validates tester performance in SAE J2527  
PS参比样板确保SAE J2527运行有效

# Corrosion Coupons



- Standardized metal specimens  
标准金属材质
- Mass loss due to corrosion is measured during a test  
在测试中测量腐蚀后的失重
- GMW 14872 requires a specific rate of mass loss throughout a test  
GMW 14872要求在测试中的失重曲线
- Ensures corrosion chamber is maintaining proper conditions and operator is running the test correctly  
确保盐雾箱维护正常，运行正常

# Mass Loss Tolerances in GMW 14872





# Control Material Guidelines

- Control materials must have known durability. This can be from:  
了解控制样的性能
  - Outdoor performance  
户外表现
  - Lab performance  
实验室表现
  - A combination of these
- Similar composition to test material  
和测试材料相似的成分
- Similar expected degradation mode to test material  
和测试材料类似的老化模式
- Best practice to include both weak- and strong-performing control materials  
测试中需要耐候性好和差的控制样

# Rank Order Correlation

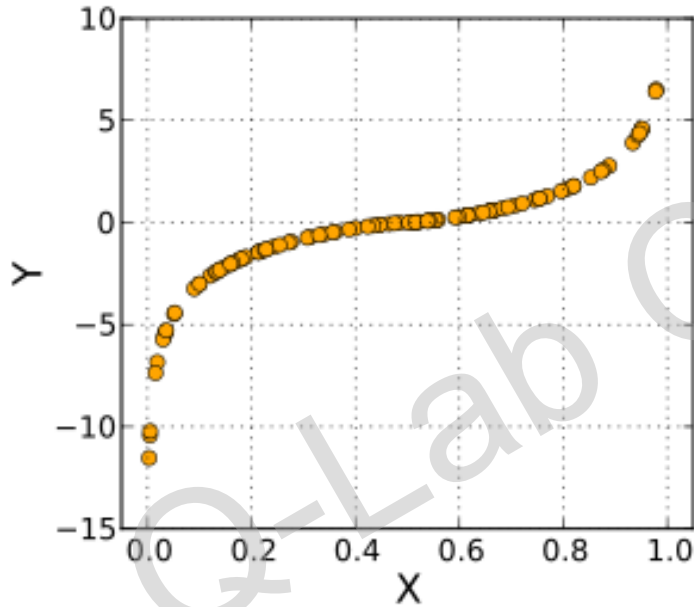
- Rank materials from best to worst outdoors and in lab test  
户外和实验室数据从好到差对样品进行排序
- Calculate correlation coefficient using Spearman's Rank Correlation Coefficient

## 使用斯皮尔曼相关系数计算

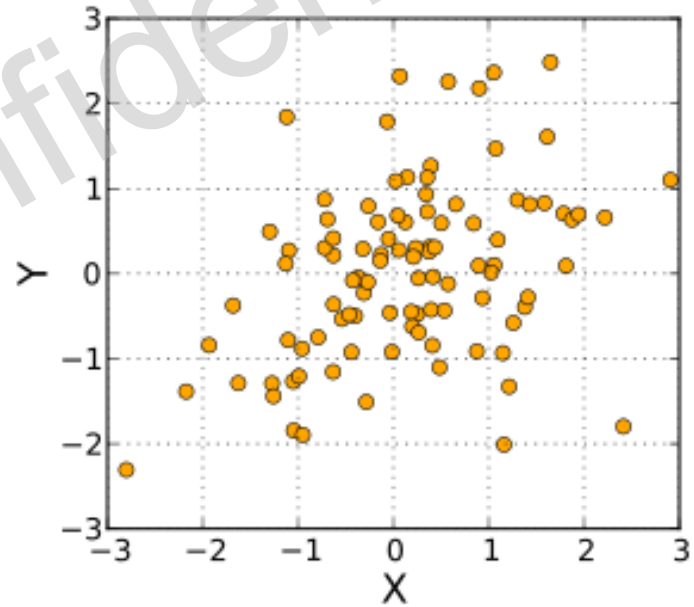
- Quantitative measure of how well the lab test matches outdoors  
定量计算出实验室数据和户外的匹配度
- Correlation of 1 is perfect (so is -1, in a way)  
相关系数1最好 ( -1是最差 )
- Correlation of 0 is random  
相关系数0为没有相关性

# Rank Ordering: Spearman Coefficient

Spearman coefficient:  
1.0



Spearman coefficient:  
0.35



# Rank Order Correlation Benefits

- Determines or confirm relationship between different exposure techniques

确认不同测试曝晒数据之间的关系

- Develops confidence in realism of lab techniques

增加实验室测试的可信度

- Provides a basis for directional decision-making in research and development

在研发过程中提供判断的基准依据

# Why not Pearson's Product-Moment Correlation?

- Pearson's compares two variables for fit  
(e.g. exposure length and degradation)

皮尔森比较两组变量是否匹配 (比如曝晒时间和老化)

- Since most degradation mechanisms are non-linear, Pearson's coefficient is usually poor

老化是非线性变化, 皮尔森系数通常比较差

- May still be useful in reformulation, once a test is verified with Rank Order Correlation!

排序相关计算之后皮尔森系数可能有效

# Perfect Correlation



Perfect correlation between Accelerated and Outdoor performance is rarely observed  
加速试验和户外之间完美的相关性是几乎不存在的

# Correlation Case Study #1

Flexible Intermediate Bulk Containers (FIBC)  
柔性集裝袋

# Flexible Intermediate Bulk Containers (FIBC)

## Situation

- FIBCs are used to carry goods. They need to survive at a job site for up to 12 months without losing tensile strength.

集装袋用来吊装货物。这些袋子需要连续使用12个月并且保证拉伸强度不损失

- Various test methods with Xenon and Fluorescent UV were compared to outdoor performance.

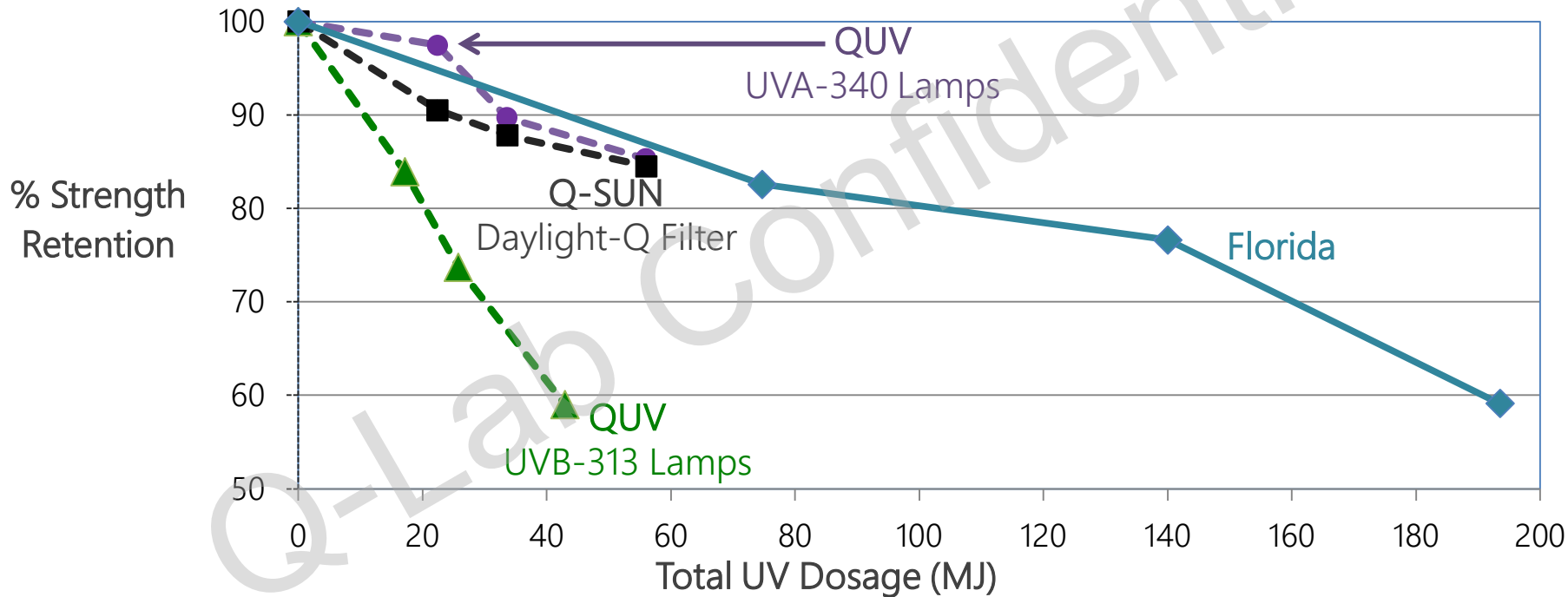
各种氙灯和紫外的测试与户外的表现相比较



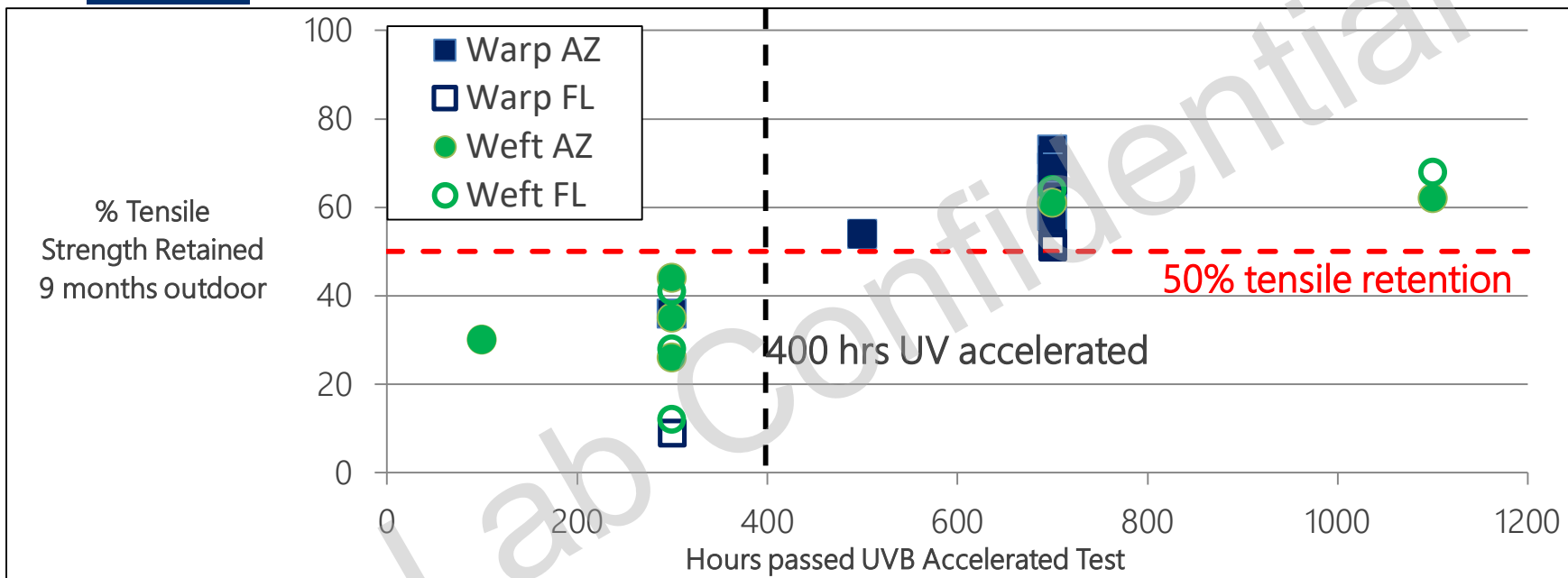


# FIBC Correlative Testing

## Accelerated and Outdoor testing – Radiant Dosage 辐照量



# FIBC results: Outdoor/Accelerated Correlation



Very good pass/fail correlation between accelerated and outdoor weathering  
加速试验和户外很好的pass/fail相关性  
Every specimen that survived >400 hours accelerated survived 9 mo outdoors  
能过400小时UVB的样品也能过9个月的户外曝晒

# FIBC Correlation Conclusions

- Xenon arc and fluorescent accelerated testing both provided good correlation to outdoor evaluation

氙灯和紫外加速测试都提供了和户外好的相关性

- Realistic light sources (UVA fluorescent, Daylight filtered xenon arc) gave strength retention results that can be correlated to outdoor exposure on a radiant dosage basis

模拟性好的光源（UVA·氙灯使用日光过滤片），在同样的辐照量水平下，和户外的相关性较好

- Acceleration factor ~7: >250 hours xenon testing correlated to 2.5 months in Florida

加速因子~7: 250小时以上的氙灯测试和佛罗里达2.5个月相关性较好

- Pass/fail behavior of FIBC over 6-9 months predicted well by UVB-313 fluorescent test

UVB313方法可以很好预测6-9个月的集装袋pass和fail的情况

- Acceleration factor ~16: >400 hours lab testing correlated to 9 months outdoors. Pass/fail testing can often be faster!

加速因子~16: 大于400小时的UVB和9个月的户外相关性较好. Pass/fail测试可以很快

# Correlation Case Study #2:

Artists' Colored Pencils  
彩色铅笔

# Colored Pencils Correlation Study

## Background

- There was no standard to distinguish colored pencils' light stability  
没有标准来区分彩色铅笔的耐光稳定性

## Objective

- Develop standard and determine correlation between natural and accelerated exposures  
建立标准，研究自然和加速试验的相关性
- Property measured is delta E – total color change  
评估指标为色差

# Colored Pencils Correlation Study

## Xenon accelerated test data

Color	delta E	Color	delta E	Color	delta E
Red-1	5.7	Yellow	45.6	Blue-1	10.9
Red-1	5.7	Yellow	45.9	Blue-1	11.2
Red-2	26.7	Green-1	6.1	Blue-2	26.8
Red-2	28.5	Green-1	7.0	Blue-2	28.2
Orange-1	79.7	Green-2	5.8	Purple-1	23.0
Orange-1	79.3	Green-2	7.9	Purple-1	22.3
Orange-2	34.8	Green-3	19.3	Purple-2	23.1
Orange-2	34.8	Green-3	19.9	Purple-2	22.9
Beige	19.7	Aqua	5.8	Black	2.7
Beige	19.7	Aqua	5.7	Black	2.1

15 materials – a minimum of 10 (better if 20!) needed for correlation

15种材料 – 最少10种(20种更好)用来做相关性研究

# Colored Pencil Correlation Study

## Comparison of accelerated to outdoor

Specimen	Arizona Under Glass		Florida Under Glass		Xenon	
	$\Delta E$	Rank	$\Delta E$	Rank	$\Delta E$	Rank
Red Pigment A	10.9	1	1.3	1	5.7	1
Red Pigment B	45.8	2	36.6	2	27.6	2
Orange Pigment	79.9	3	80.4	3	79.5	3

# Results - Rank Order Correlation

Test Rankings Being Compared	Spearman's Rank Coefficient
Arizona – Florida	0.94
Xenon – Arizona	0.95
Xenon – Florida	0.93

Excellent rank order correlation between natural and accelerated exposure results of all of the specimens

所有样品都体现了自然和实验室很好的相关性



# Correlation Case Study #3:

Lithographic Inks  
平板印刷油墨

# Printing Ink Correlative Study

## Purpose

- Evaluate the light stability of lithographic inks

评估平板印刷油墨的光稳定性



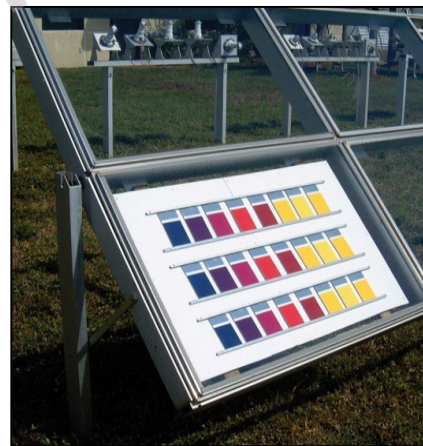
## Test Program

- Natural outdoor tests

自然曝晒

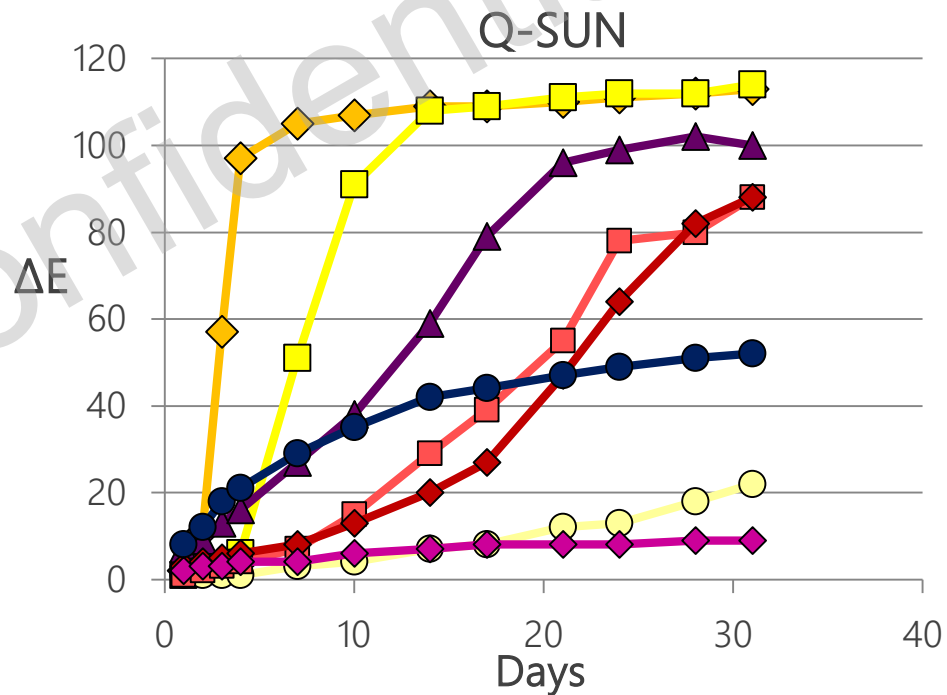
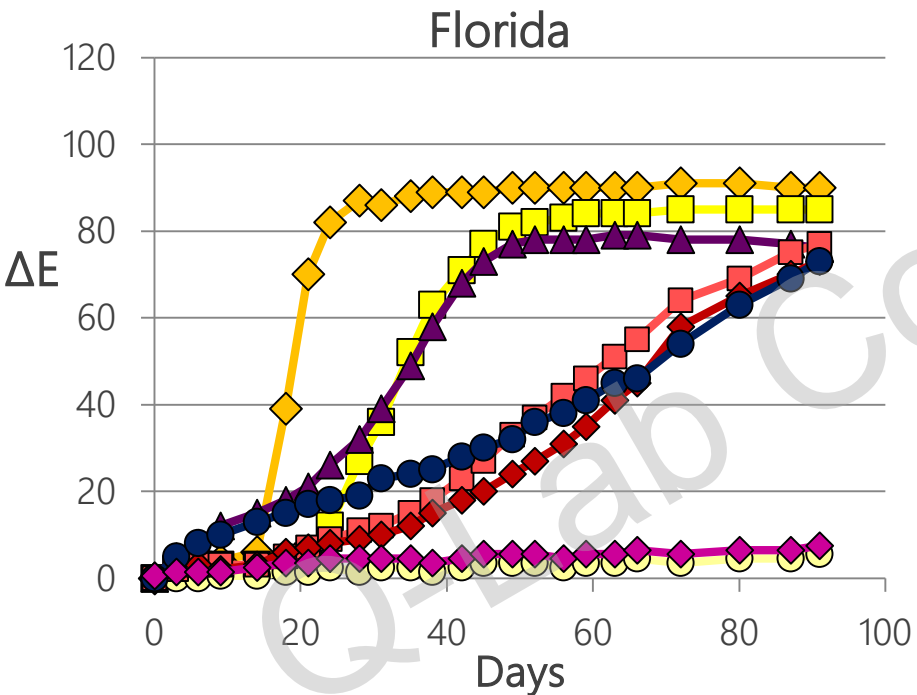
- Q-SUN Xenon Arc tests

氙灯测试



# Printing Ink Correlation Study

## delta E Color Fade Measurements



# Printing Ink Correlation Study

## Conclusions

- Excellent rank order correlation between outdoor & lab results

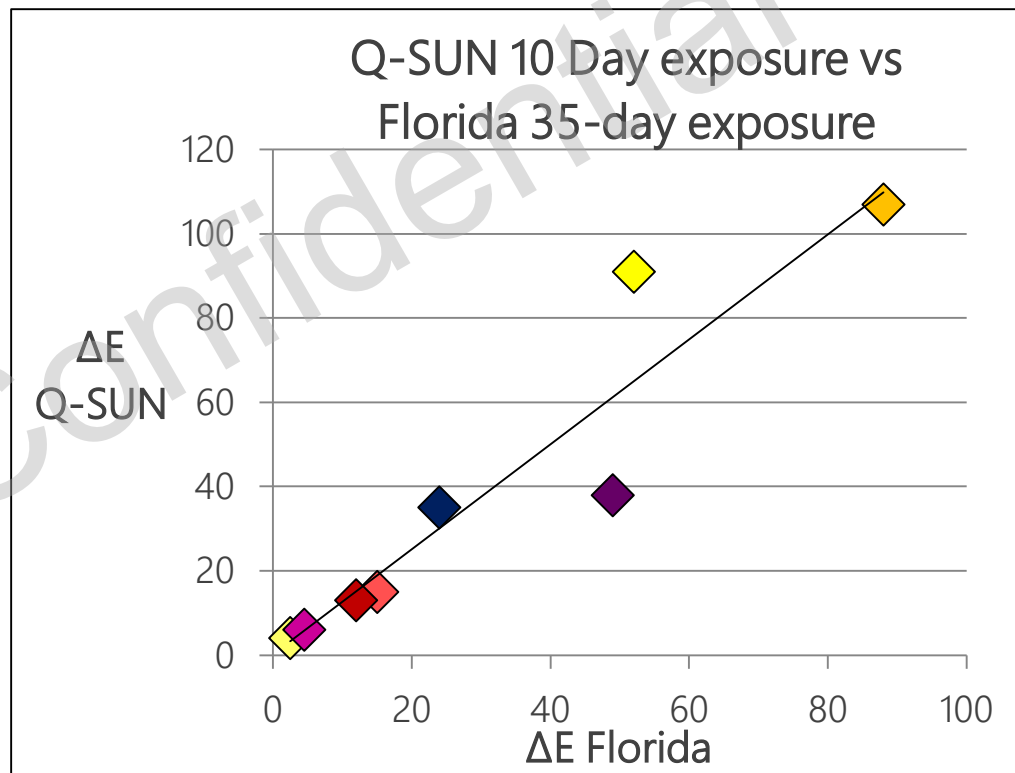
实验室和户外很好的相关性

- Test technique can be applied to any ink, ink/substrate combination

测试方法可以引申到其他油墨或者成品

- Acceleration factor ~3.5 for these materials under these test conditions

加速因子~3.5 (对于这些材料在这样的测试条件下)



# Correlation Case Study #4:

Colored Plastics  
塑料片

# Colored Plastics Correlation Study

## Situation

- Inorganic color additives in plastics like PVC are increasingly being replaced by organic additives.  
PVC中有机颜料替代无机颜料
- Better safety, decreased lightfastness performance.  
安全性更好但是耐候性下降
- Need to understand better outdoor light / colorfastness  
需要理解户外日晒环境

## Test Program

- Accelerated weathering testing of colored PVC plastics performed, color change ( $\Delta E$ ) measured  
PVC材料实验室加速测试·评估delta E
- Outdoor exposures for 2 months (Florida)  
佛罗里达户外曝晒2个月
- Accelerated lab for 200 hours (UV fluorescent and xenon arc)  
紫外和氙灯加速测试各200小时

# PVC Weathering Test Program

- Outdoor Exposures 户外曝晒
  - Florida
  - Unbacked specimens, 45° south facing
  - 57 days
- Fluorescent UV 荧光紫外
  - UVA-340 and UVB-313 lamps
  - 4h light, 0.72 W/m<sup>2</sup>/nm, 45 °C
  - 4h condensation, 40 °C
  - 200 hours
- Xenon arc 氙弧灯
  - Daylight-Q and Extended UV-Q/B filters
  - 5h light, 0.68 W/m<sup>2</sup>/nm, 35-45 °C
  - 20 min spray, 40 °C
  - 200 hours



# Results

## Green





# Results

## Purple

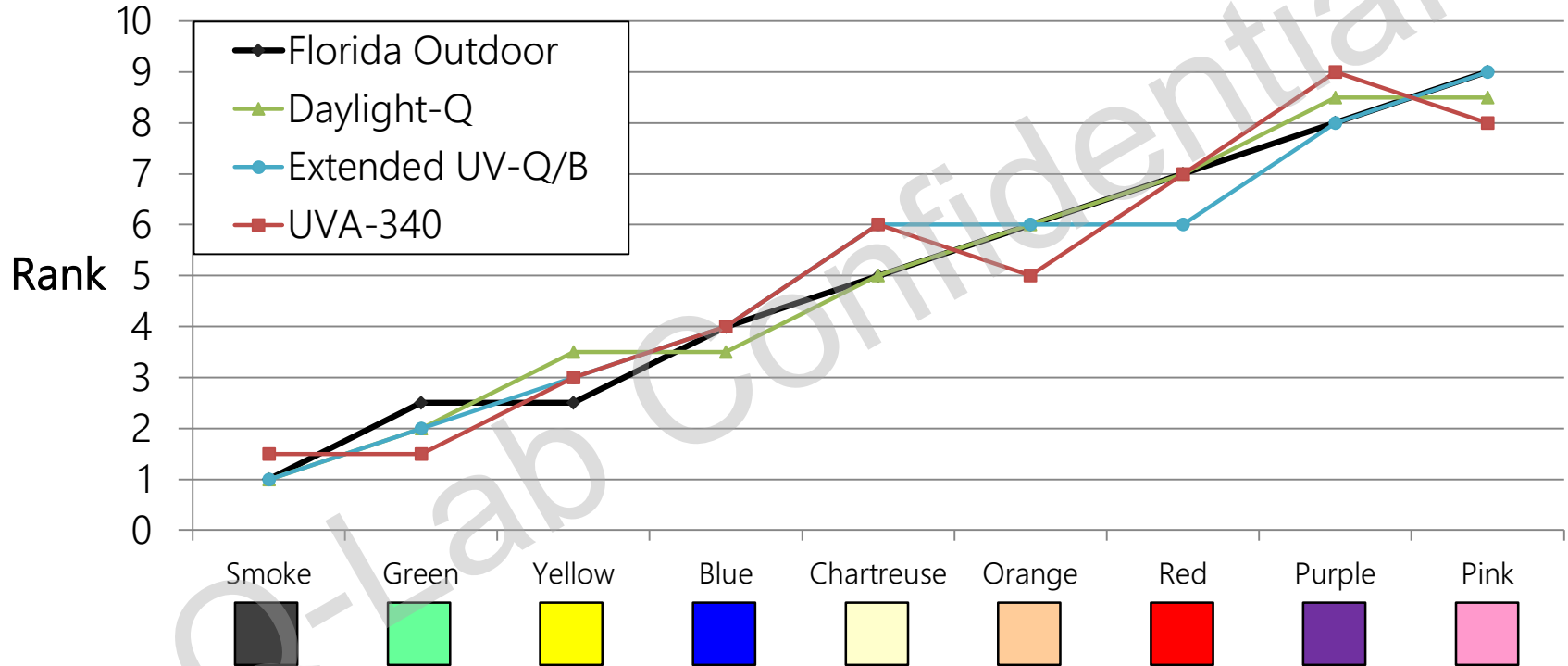


# Correlation: Accelerated vs Outdoor

Color	Florida Outdoor		Daylight		Extended UV		UVA-340		UVB-313	
	$\Delta E$	Rank	$\Delta E$	Rank	$\Delta E$	Rank	$\Delta E$	Rank	$\Delta E$	Rank
Smoke	0.6	1	1.0	1	1.8	1	1.3	1	3.6	1
Green	2.0	2.5	2.0	2	5.6	2	1.8	1	16.7	3.5
Yellow	2.5	2.5	5.0	3.5	6.3	3	4.7	3	43.0	7
Blue	4.7	4	5.2	3.5	7.2	4	5.7	4	21.0	5
Chartreuse	5.6	5	7.7	5	11.0	6	11.9	6	25.5	6
Orange	8.6	6	11.2	6	11.4	6	10.2	5	17.7	3.5
Red	14.0	7	35.0	7	11.8	6	16.8	7	14.3	2
Purple	39.0	8	42.0	8.5	40.7	8	26.6	9	50.7	8.5
Pink	71.9	9	41.3	8.5	65.3	9	19.7	8	49.7	8.5
Rank order correlation with Outdoors --->			<b>0.98</b>		<b>0.96</b>		<b>0.95</b>		<b>0.54</b>	

*Excellent color change correlation between FL outdoors and accelerated (except UVB-313)*

# Rank Order Correlation: Accelerated vs Outdoor



# Conclusions

- Correlation for color change between accelerated and outdoor tests  
加速实验和户外颜色变化的相关性
  - Excellent rank order correlation for xenon (Daylight or Extended UV filter) and UV fluorescent (UVA-340 lamps) 氙灯 (日光或紫外延展过滤器) 和荧光紫外 (UVA-340灯管) 和户外很好的相关性
  - Acceleration factor for 57 days outdoor and 200 h accelerated (7:1)  
57天户外 : 200小时实验室加速 = 7 : 1
  - Poor correlation for UV fluorescent UVB-313 lamps  
UVB313方法和户外相关性较差
- Different degradation observed for pigments and base plastics  
颜料和底材出现不同的老化
  - Darkening from plastic yellowing from shortwave UV  
塑料基材在短波紫外光下黄变变暗
  - Fade from breakdown of pigments from visible light  
颜料在可见光下分解褪色
  - Differences most pronounced for pink and red specimens  
粉色和红色样品差异最显著
  - Illustrates the need for thorough color characterization beyond  $\Delta E$   
除 $\Delta E$ 之外进行全面颜色表征分析的必要性

# Correlation Case Study #5:

Vinyl Siding  
乙烯基壁板

# What is Vinyl Siding?

- Co-extruded building cladding material  
共挤建筑覆层材料
  - Manufactured mostly from Polyvinyl Chloride (PVC)  
大部分是PVC材质
  - Top layer (capstock) is durable and UV-stabilized  
最上层很耐候·抗紫外
  - Also known as uPVC Weatherboarding in some regions  
在一些地区也叫做uPVC耐候板
- Developed in the 1960's, became popular in the 1970's  
1960年开发, 70年代流行
- Most common residential exterior cladding material in US & Canada – about 20 million m<sup>2</sup> used per year  
北美最常用的住所外包覆材料-每年2千万m<sup>2</sup>的用量



# Vinyl Siding Institute

## Outdoor test program

- Large-scale, long-term study  
大量的、长时间的研究
- Outdoor data collection ongoing since 1984  
1984年以来一直收集户外数据
- New tests started every 5 years; thousands of specimens and replicates tested  
新的测试每5年开始，数以千计的样品被测试
- Long-term material degradation mechanisms are now well understood  
长期材料老化机制被很好地掌握



Correlation here is between short- and long-term outdoor testing  
这里的相关性研究对象是短期和长期户外测试



# Vinyl Siding Institute

## Service Life Certification

- Accurate service life estimate based on 2-year outdoor testing  
正确的寿命预测建立在2年的户外曝晒
  - If after 2 years of exposure, color change is  $<1$ , then after 25 years it has a high probability of color change  $<4$   
如果2年曝晒后·色差小于1·那么25年之后很可能色差小于4
  - Acceleration for service life prediction of 12:1  
加速比例为12:1
- 2 year outdoor certification program  
2年的户外认证项目
  - Administered by ISO 17025-accredited, independent 3rd party  
有ISO 17025认证的第三方操作
  - Exposures in FL, AZ, OH  
在FL,AZ,OH曝晒
  - Tests performed in accordance with ASTM test standards  
实验室做ASTM标准
  - Receive a VSI stamp, gives credibility to a 25-year warranty  
接受一个VSI章-保证25年的寿命



# Qualification / Correlation Case Study

## Vinyl Siding Institute (VSI)

- New Goal: Correlate accelerated test to 2-year outdoor results  
新目标：实验室加速和2年户外数据相关性
  - Six rounds of accelerated testing conducted by multiple labs – examined test cycles of both UV fluorescent and xenon  
六轮实验室测试- 紫外和氙灯
- Unique Fluorescent UV cycle provided best correlation for PVC siding material  
荧光紫外测试提供了最好的相关性对于PVC材料
  - Hot condensation best for accelerating realistic moisture attack synergistically with UV  
热冷凝伴随紫外光照是最好地对材料进行潮湿侵袭
  - Long wave and visible had little impact  
长波段和可见光影响很小
  - Reduced UV temps and increase condensation temps gave better results  
降低紫外光照时的温度 · 升高冷凝温度可以得到更好的结果
- UV fluorescent test not adopted for certification program, but used by members for product development  
荧光紫外测试不被认证 · 但是PVC行业用紫外方法做材料的开发

# Summary of Correlative Testing

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# Accelerated Test Types

Accelerated Test Type	Result	Test Time	Results compared to
Quality Control	Pass / fail	<ul style="list-style-type: none"> <li>• Defined</li> <li>• Short</li> </ul>	Material specification
Qualification / validation	Pass / fail	<ul style="list-style-type: none"> <li>• Defined</li> <li>• Medium-long</li> </ul>	Reference material or specification
Correlative	Rank-ordered data	<ul style="list-style-type: none"> <li>• Open-ended</li> <li>• Medium</li> </ul>	Natural exposure (Benchmark site)
Predictive	<del>Service life</del> <del>Acceleration factor</del>	<del>• Open-ended</del> <del>• Long</del>	<del>Natural exposure</del> <del>(Service environment)</del>

# What did we learn from those correlation case studies?

All of the acceleration factors were different! They are not general or universal and they depend on:

没有统一的加速因子，因为以下：

- The specific material tested  
具体的材料特性
- The type of test being correlated to natural outdoor results – fluorescent UV, xenon, accelerated outdoors  
实验室的测试方法- 荧光紫外，氙灯，户外加速
- The specific set of lab tester time cycles and temperature  
测试循环和温度
- The specific outdoor exposure site and sample mounting procedure  
具体的户外曝晒地点和样品安装
- The failure mechanism(s) being evaluated  
失效模式

# Correlation between accelerated and outdoor testing

Correlation between outdoor and accelerated testing can be determined for a variety of materials systems. However...

实验室加速测试和户外的相关性由不同的材料特性决定，然而。。

- Acceleration factors are not general and often only valid for one type of degradation  
加速因子不是唯一的而且通常只适用于一种失效模式
- Comparative testing usually gives rank-ordered data, which can be powerful data  
排序数据很有用
- It is critical to perform outdoor testing to validate accelerated testing - "Test the Test"  
户外测试很重要，用来验证实验室加速测试

# Question?



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