Correlation in Accelerated Testing
加速测试中的相关性
Principles, Challenges, and Case Studies
原则、挑战和案例研究

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Q-Lab

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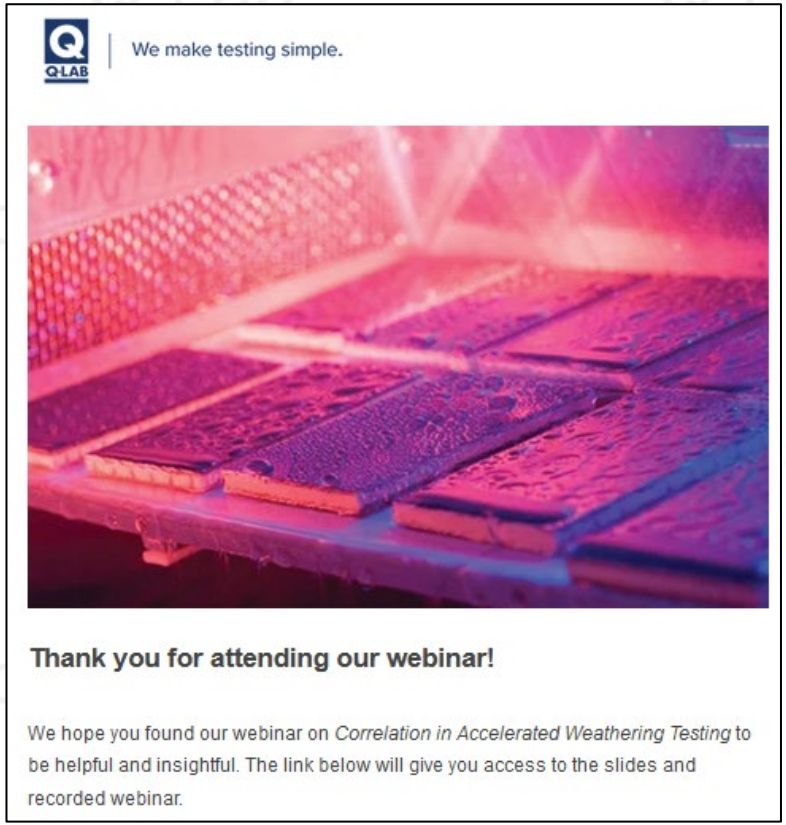


The Question 问题

- In weathering and corrosion, we encounter the same basic question over and over again …
- 在老化和腐蚀测试中，我们经常被问到同样的问题 …
- “How many hours in my accelerated test correlates to __ years of outdoor service?”
- 加速测试多少小时相当于户外几年？

The Hard Truth 残酷的事实

- There is no Universal Acceleration Factor, or “Magic Number,” between accelerated and outdoor testing
- 在加速测试和户外曝晒之间没有通用的加速因子，或 “魔法数字”
- Different materials in different service environments have different acceleration factors 不同的材料在不同的使用环境中有不同的加速因子
- Weathering and Corrosion Tests do not give quantitative predictions of Service Life 老化和腐蚀试验不能给出使用寿命的量化预测

Why is this such a challenge? 为什么这是一个挑战?

- The problem is not that we just haven't developed the perfect weathering tester yet.
- 问题不在于我们还没有开发出完美的老化试验箱
- 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固有的可变性和复杂性。考虑户外曝晒和加速测试之间的关系中的一些因素：

Outdoor factors 户外因素

1. Latitude 纬度
2. Altitude 海拔
3. Geography 地形地貌
4. Year-to-year variations 年份变化
5. Seasonal variations 季节变化
6. Specimen Orientation 样品曝晒角度
7. Environmental particulates 微环境

Laboratory factors 实验室因素

8. Specimen insulation 样品安装
9. Test cycle 测试循环
10. Water delivery 水的施加
11. Test temperatures 试验温度
12. Light source 光源

And of course...

13. The particular materials system tested 被测的特定材料体系

What Can Be Done 能做些什么

- Weathering and corrosion testing can have many goals other than determining acceleration factors and service life
- 除了确定加速因子和使用寿命，老化和腐蚀测试还有很多目标
- Define goals, set expectations, and from there select an appropriate test program
- 定义目标，设定期望，并选择一个合适的测试程序
- 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具有预测性，但它们通常具有相关性
- Weathering and corrosion tests are comparative, and comparative data can be powerful 老化和腐蚀测试是比较性的，比较性数据可能是强有力的

Accelerated Testing is a Tool for Decision Making
加速测试是一种决策工具

Accelerated tests can help you decide …

加速测试可以帮助你决定 …

- What ingredients to include or not include in a product 产品中的成分
- Whether a lot or batch is OK to ship to customers 这批产品是否可以运给客户
- What vendors to buy from 向哪些供应商采购
- What processing and manufacturing parameters should be selected
- 应该选择哪种工艺和制造参数
- Make better, faster decisions 做出更好、更快的决策

Accelerated Test Types 加速测试类型

What do we want to learn?

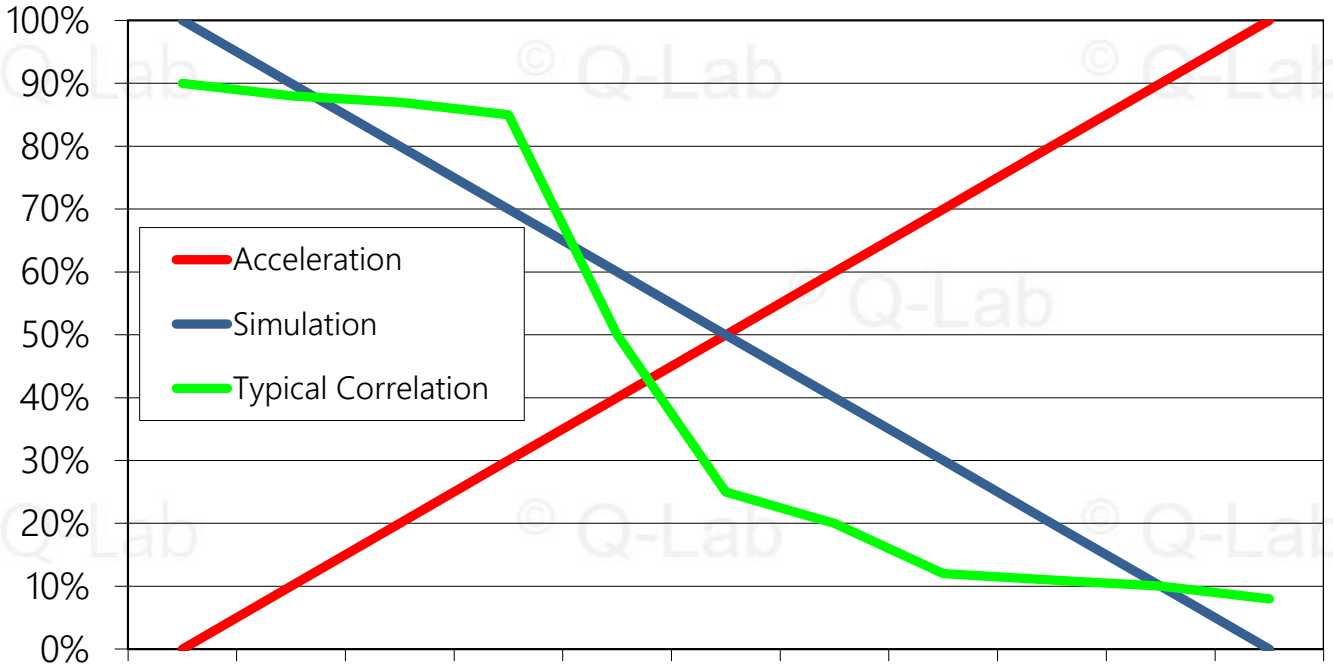
Accelerated Test Type	Result	Test Time	Results compared to
Quality Control 质量控制	Pass / fail 通过/失效	• Defined 确定的 • Short 短时间	Material specification 材料规格
Qualification / validation 验证	Pass / fail 通过/失效	• Defined 确定的 • Medium-long 中长	Reference material or specification 参照材料
Correlative 相关性	Rank-ordered data 排序相关	• Open-ended 不确定 • Medium 中等时间	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	• Open-ended 不确定 • Long 长时间	Natural exposure (Service environment) 自然曝晒（实际环境）

Accelerated Test Types 加速测试类型

What do we want to learn?

Accelerated Test Type	Result	Test Time	Results compared to
Quality Control	Pass / fail	• Defined • Short	Material specification
Qualification / validation	Pass / fail	• Defined • Medium-long	Reference material or specification
Correlative	Rank-ordered data	• Open-ended • Medium	Natural exposure (Benchmark site)
~~Predictive~~	~~Service life~~ ~~Acceleration factor~~	~~• Open-ended~~ ~~• Long~~	~~Natural exposure~~ ~~(Service environment)~~

Why is correlation such a challenge? 为什么相关性如此具有挑战性?



Correlation 相关性

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

不同测试的数据相互一致的程度

- Accelerated vs outdoor weathering 加速老化与户外曝晒
- One accelerated test method vs another 不同加速试验方法之间的比较
- One outdoor environment vs another 不同户外环境之间的比较

Why Correlation Matters 为什么相关性很重要

- Decision-making tools need to be validated 决策工具需要验证
- There is an inherent conflict between acceleration and realism
- 加速和现实之间存在着内在的冲突
- The only way to validate an accelerated weathering test is with outdoor/real world data
- 验证加速老化测试的唯一方法是使用户外/真实世界的数据
- In other words … Test the Test! 换句话说，测试你的测试！

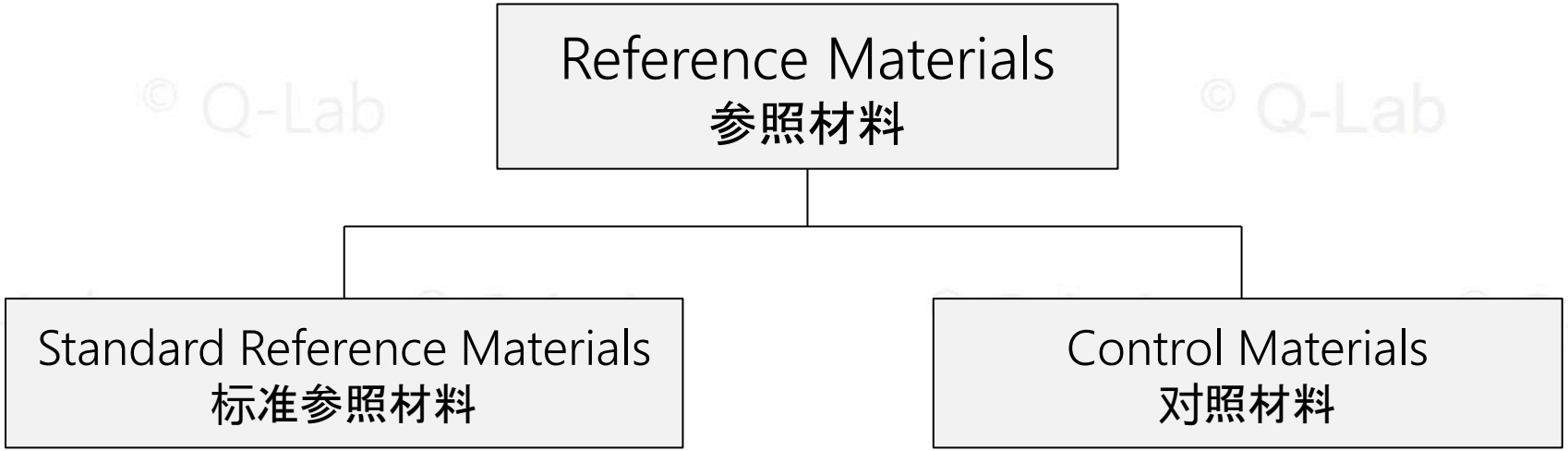
Methods for Establishing Correlation 得到相关性的方法

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

相关性测试（通常是户外和加速）的两种主要的方法

- Reference and Control Materials 参照和对照材料
- Rank Order Evaluation 等级排序评估

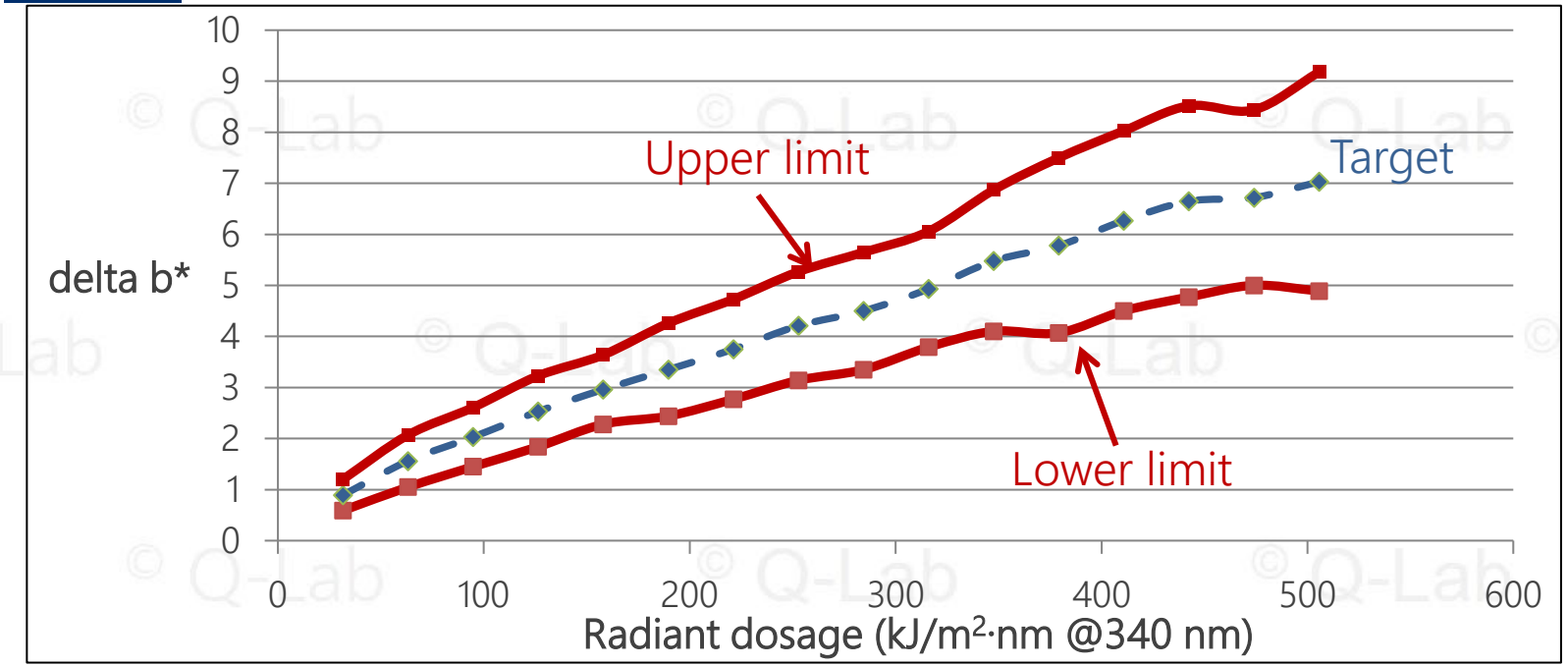
Reference and Control Materials 参照材料和对照材料



- Known performance in test environments 测试环境中性能已知
- Not necessarily similar to test specimens 不一定与试样相似
- Performance may not match test specimens 性能可能与试样不匹配
- Verify that lab tester is operating properly 验证试验箱运行正常

- Similar characteristics to test specimens 性能与试样相似
- May be your products or competitors'
- 可能是你的产品或竞争对手的产品
- Give confidence in lab exposure 给实验室测试信心

Weathering Reference Material (Polystyrene) 老化参照材料(PS板)



Reference Polystyrene yellowing validates tester performance in SAE J2527

Weathering Reference Material (Blue Wool L2) 老化参照材料L2

Association of Textile, Apparel & Materials Professionals

CERTIFICATE OF CONFORMITY

This is to certify that the **20 AFU & 5 AFU Blue Wool Lightfastness Standard, Item #08362** has been evaluated and found to be suitable for use in any AATCC Test Method in which it is mentioned.

The following end points have been confirmed by exposure of numerous specimens under conditions specified in AATCC Test Method 16.3, *Colorfastness to Light: Xenon-Arc.*

20 AFU & 5 AFU Blue Wool Lightfastness Standard L2, lot 9		
Exposure Period	Colorimetric End Point	
	ΔE^*_{CIELAB}	Gray Scale for Color Change
5 AATCC Fading Units (21 kJ/[m²nm] @ 420 nm)	3.2 ± 0.4	4
20 AATCC Fading Units (85 kJ/[m²nm] @ 420 nm)	7.5 ± 0.5	2 – 3

Control Material Guidelines 对照材料准则

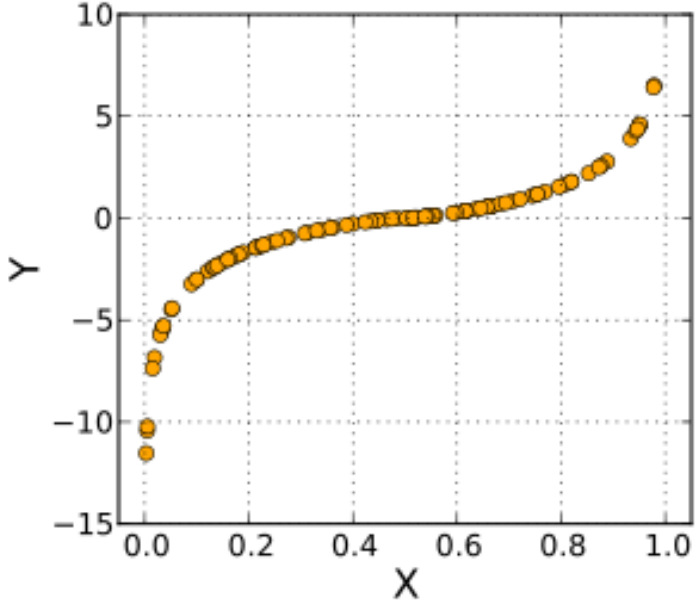
- Control materials must have known durability. This can be from:
- 对照材料的耐候性必须已知。这可能来自：
  - Outdoor performance 户外性能
  - Lab performance 实验室性能
  - A combination of these 户外和实验室性能的组合
- Similar composition to test material 与测试材料相似的成分
- Similar expected degradation mode to test material 与测试材料相似的预期降解模式
- Best practice to include both weak- and strong-performing control materials
- 最佳试验方案包括性能差的和性能好的对照材料

Rank Order Correlation 排序相关性

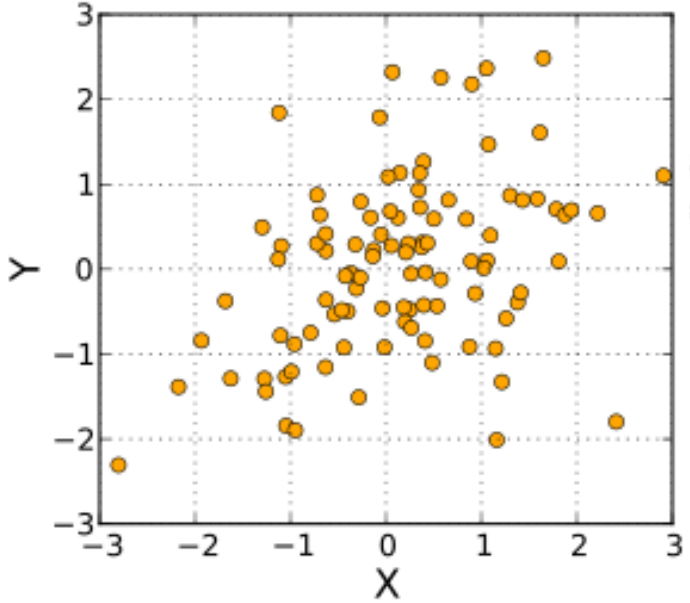
- Rank materials from best to worst outdoors and in lab test
- 在户外和实验室测试中，把材料按照从好到差进行排序
- Calculate correlation coefficient using 计算相关系数
  Spearman's Rank Correlation Coefficient 使用斯皮尔曼排序相关系数
  - Quantitative measure of how well the lab test matches outdoors
  - 定量衡量实验室测试与户外曝晒的匹配程度
  - Correlation of 1 is perfect (so is -1, in a way) 相关系数为1是正相关，是最好
  - Correlation of 0 is random 相关系数为0是随机的，不存在相关性

Rank Ordering: Spearman Coefficient 排序：斯皮尔曼相关系数

Spearman coefficient:
1.0



Spearman coefficient:
0.35



Rank Order Correlation Benefits 排序相关性的优势

- Determines or confirm relationship between different exposure techniques
- 确定或确认不同测试技术之间的关系
- Develops confidence in realism of lab techniques
- 开发对实验室测试技术真实性的信心
- Provides a basis for directional decision-making in research and development
- 为研发中的方向性决策提供基础

Why not Pearson's Product-Moment Correlation?
为什么不是皮尔逊积矩相关性?

- Pearson's compares two variables for fit 皮尔逊比较两个变量的适合度
  (e.g. exposure length and degradation)（比如：曝晒时长和降解)

- Since most degradation mechanisms are non-linear, Pearson's coefficient is usually poor 由于大多数降解机制是非线性的，皮尔逊相关系数通常较差

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

- 一旦用等级排序相关性验证了一个测试，材料改变配方后可能仍然有用!

Perfect Correlation 完全相关

Perfect correlation between Accelerated and Outdoor performance is rarely observed

加速性能与户外性能之间很少会出现完全相关

Correlation Case Study #1
相关性案例研究 #1

Flexible Intermediate Bulk Containers (FIBC)
集装袋 (FIBC)

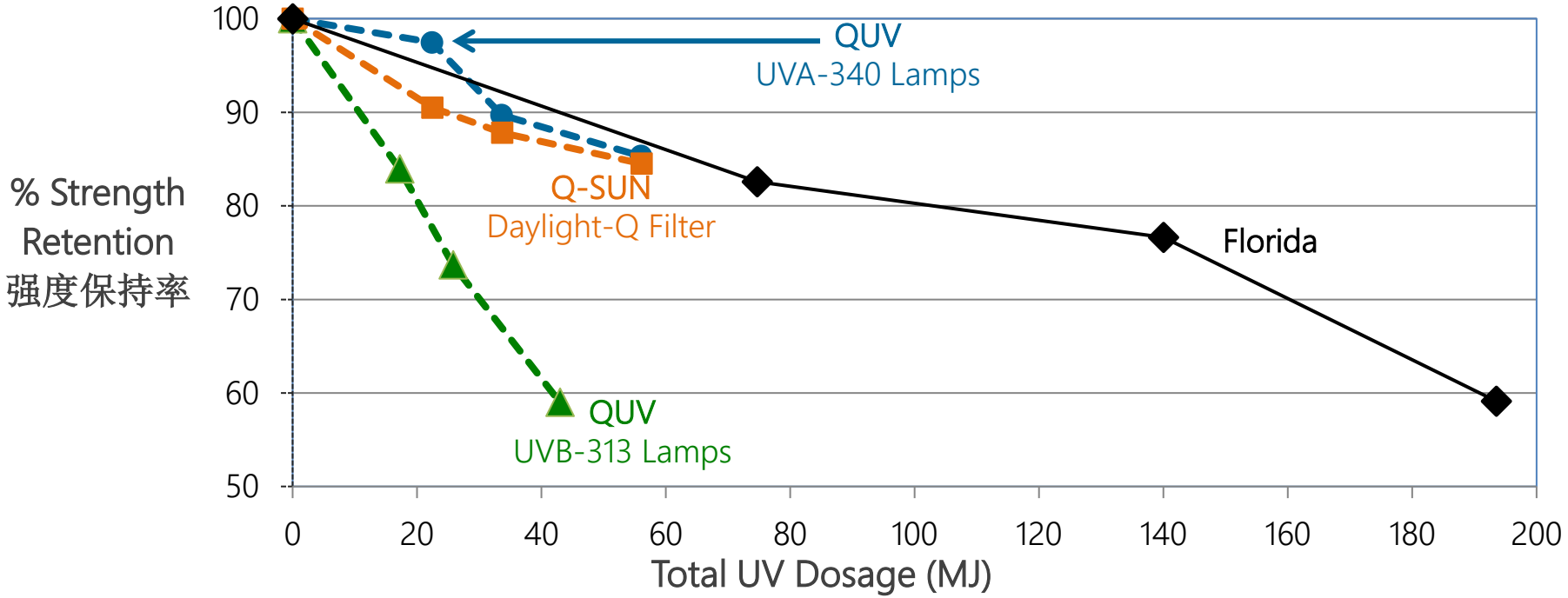
Flexible Intermediate Bulk Containers (FIBC) 集装袋

Situation 现状

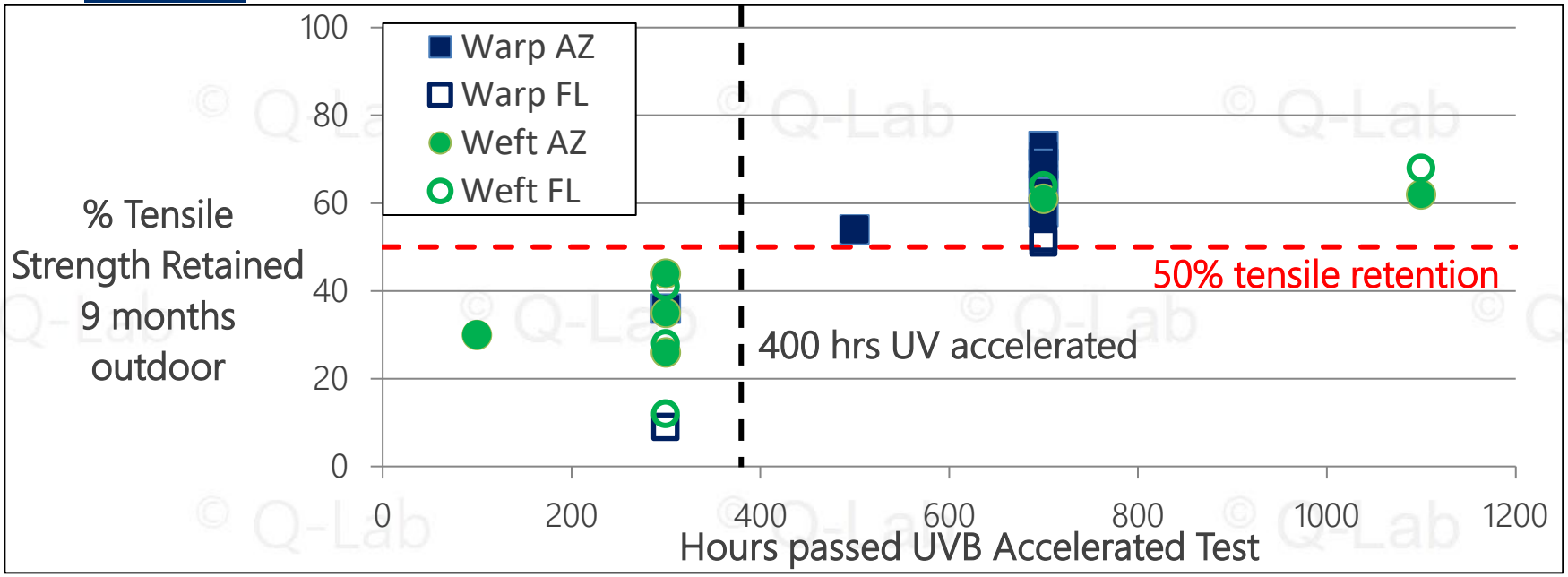
- FIBCs are used to carry goods. They need to survive at a job site for up to 12 months without losing tensile strength.
- 集装袋用来运载货物，它们需要在工作场所长达12个月，而不丧失拉伸强度
- Various test methods with Xenon and Fluorescent UV were compared to outdoor performance.
- 氙灯和紫外的各种测试方法与户外性能进行了比较

FIBC Correlative Testing 集装袋相关性测试

Accelerated and Outdoor testing – Radiant Dosage 辐照量



FIBC results: Outdoor/Accelerated Correlation



Very good pass/fail correlation between accelerated and outdoor weathering

Every specimen that survived >400 hours accelerated survived 9 mo outdoors

FIBC Correlation Conclusions 集装袋相关性总结

- Xenon arc and fluorescent accelerated testing both provided good correlation to outdoor evaluation
- 氙灯和荧光紫外加速试验都与户外评估的相关性较好
- 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
- 真实光源（UVA紫外灯管，配备日光过滤片的氙灯）给出的强度保持率结果与户外曝晒结果相关
  - Acceleration factor ~7: >250 hours xenon testing correlated to 2.5 months in Florida
  - 加速因子大概为7：氙灯测试超过250小时与Florida户外曝晒2.5个月相关
- Pass/fail behavior of FIBC over 6-9 months predicted well by UVB-313 fluorescent test
- 通过UVB-313荧光紫外测试很好地预测了集装袋在6到9个月内的合格/失效性能
  - Acceleration factor ~16: >400 hours lab testing correlated to 9 months outdoors. Pass/fail testing can often be faster!
  - 加速因子大概为16：实验室测试超过400小时与户外9个月相关，合格/失效测试通常会更快！

Correlation Case Study #2
相关性案例研究 #2

Artists' Colored Pencils
画家的彩色铅笔

Colored Pencils Correlation Study 彩色铅笔相关性研究

Background 背景

- There was no standard to distinguish colored pencils' light stability
- 彩色铅笔的光稳定性测试没有相关标准

Objective 目标

- Develop standard and determine correlation between natural and accelerated exposures
- 制定标准并确定自然曝晒与加速测试之间的相关性
- Property measured is delta E (total color change)
- 测量指标是delta E (总的颜色变化)

Colored Pencils Correlation Study 彩色铅笔相关性研究

Xenon accelerated test data 氙灯加速测试数据

Color 颜色	delta E	Color 颜色	delta E	Color 颜色	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

Colored Pencils Correlation Study 彩色铅笔相关性研究

Comparison of accelerated to outdoor 加速与户外的比较

	Arizona Under Glass		Florida Under Glass		Xenon	
Specimen	ΔE	Rank	ΔE	Rank	ΔE	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 结果 - 排序相关性

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

所有样品的自然曝晒和加速测试结果之间具有非常好的等级排序相关性

Correlation Case Study #3
相关性案例研究 #3

Lithographic Inks
平版油墨

Printing Ink Correlative Study 印刷油墨相关性研究

Purpose 目的

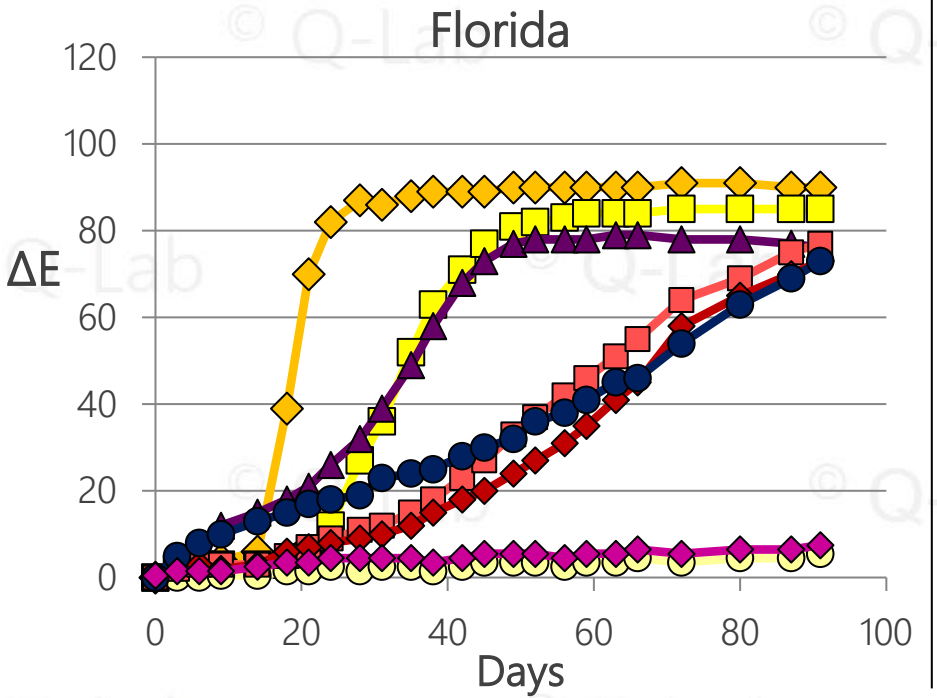
- Evaluate the light stability of lithographic inks
- 评估平版油墨的光稳定性

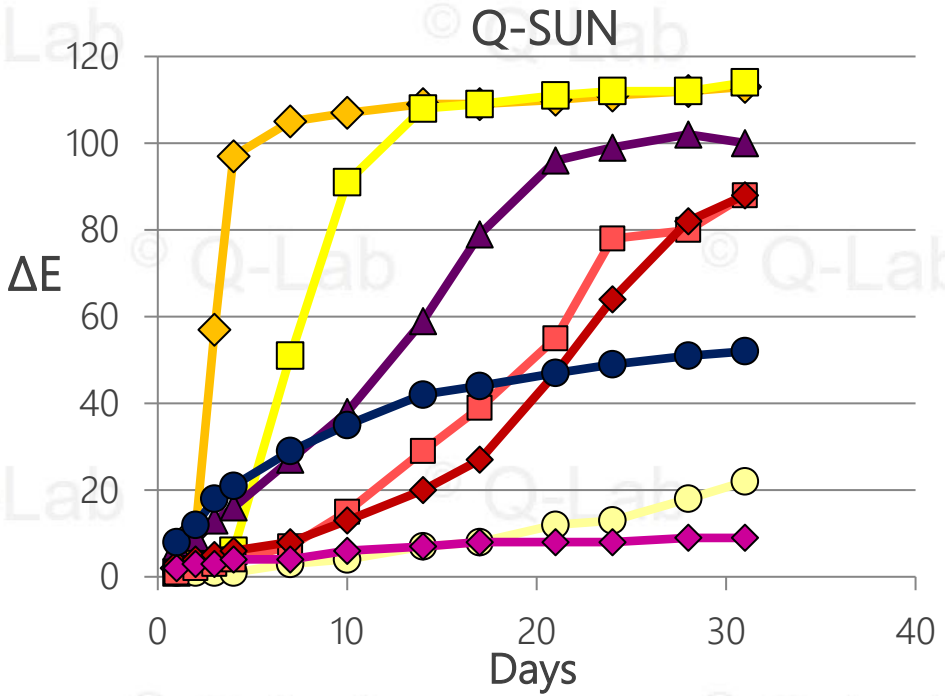
Test Program 测试程序

- Natural outdoor tests
- 自然户外曝晒
- Q-SUN Xenon Arc tests
- 氙灯加速测试

Printing Ink Correlation Study 印刷油墨相关性研究

delta E Color Fade Measurements 颜色测量

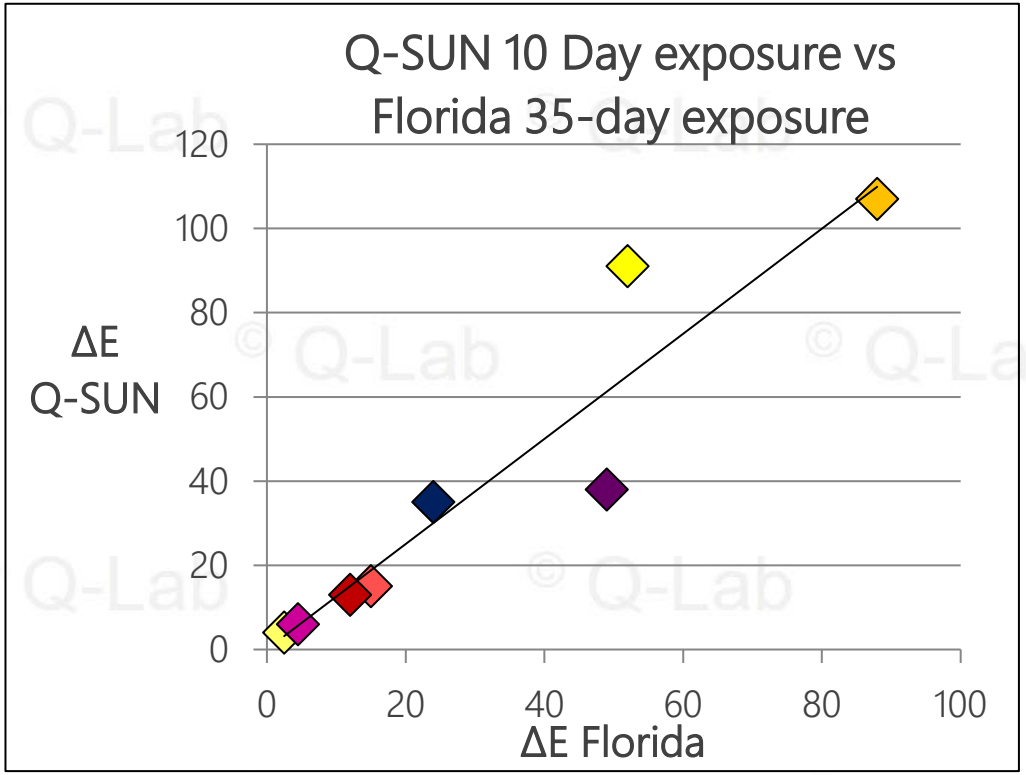




Printing Ink Correlation Study 印刷油墨相关性研究

Conclusions 结论

- Excellent **rank order correlation** between outdoor & lab results
- 户外和实验室结果之间的相关性很好
- Test technique can be applied to any ink, ink/substrate combination
- 测试技术可应用于任何油墨及组合
- Acceleration factor ~3.5 for these materials under these test conditions
- 在这些试验条件下，这些材料的加速因子约为3.5



Correlation Case Study #4
相关性案例研究 #4

Colored Plastics
彩色塑料

Colored Plastics Correlation Study 彩色塑料相关性研究

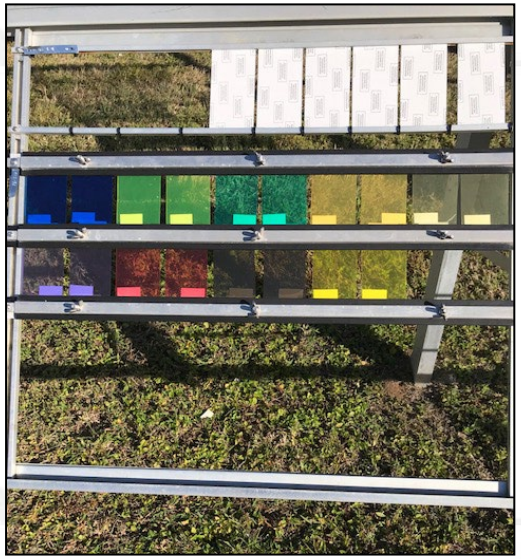
Situation 现状

- Inorganic color additives in plastics like PVC are increasingly being replaced by organic additives
- PVC等塑料中的无机彩色添加剂越来越多地被有机添加剂所取代
- Better safety, decreased lightfastness performance 安全性更好，但耐光性能下降
- Need to understand better outdoor light / colorfastness 需要更好地了解户外耐光性

Test Program 测试程序

- Accelerated weathering testing of colored PVC plastics performed, color change (ΔE) measured
- 对彩色PVC塑料进行加速老化试验，测量颜色变化(ΔE)
- Outdoor exposures for 2 months (Florida) 户外曝晒2个月(Florida)
- Accelerated lab for 200 hours (UV fluorescent and xenon arc)
- 实验室加速测试200小时 (荧光紫外和氙灯)

PVC Weathering Test Program 老化测试程序



- 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^2/nm, 45 °C
  - 4h condensation, 40 °C
  - 200 hours
- Xenon arc 氙灯
  - Daylight-Q and Extended UV-Q/B filters
  - 5h light, 0.68 W/m^2/nm, 35-45 °C
  - 20 min spray, 40 °C
  - 200 hours

Results 结果

Green 绿色

Results 结果

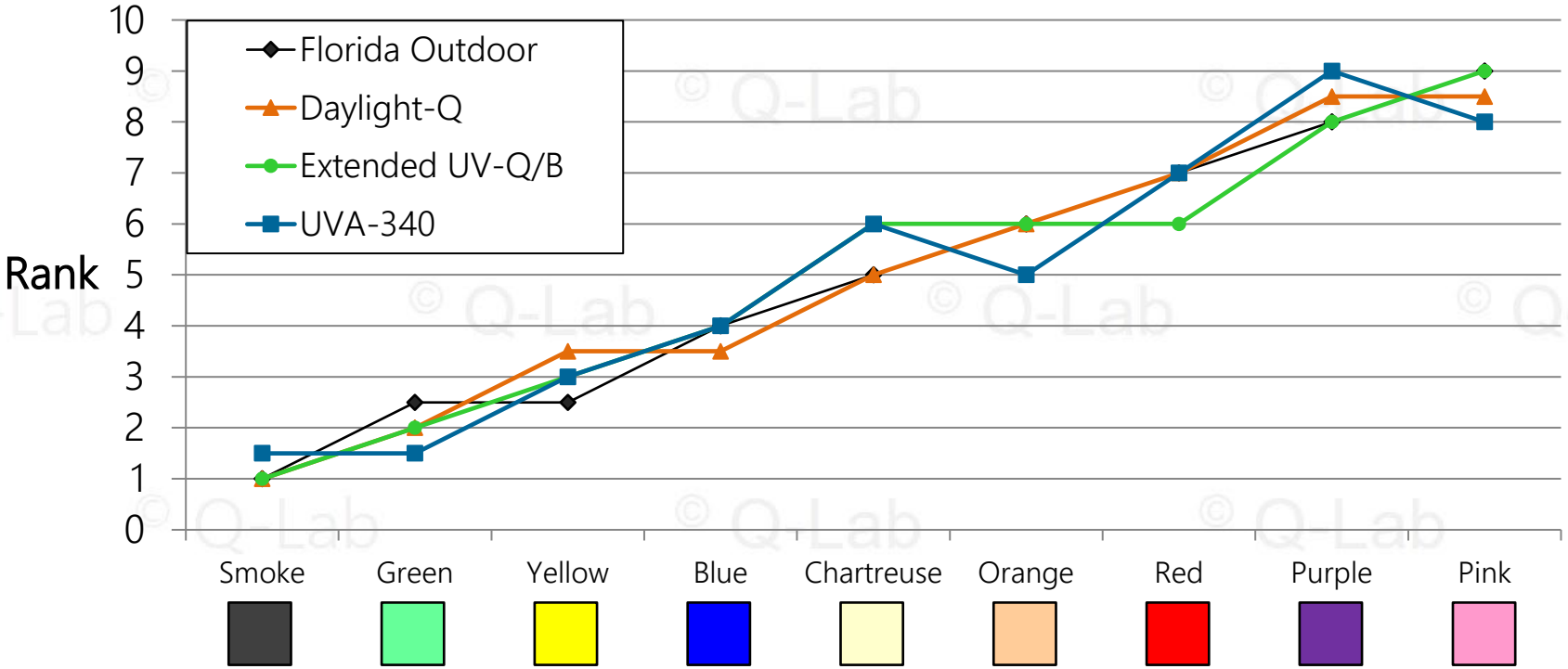
Purple 紫色

Correlation: Accelerated vs Outdoor 相关性：加速与户外

Color	Florida Outdoor ΔE	Florida Outdoor Rank	Daylight ΔE	Daylight Rank	Extended UV ΔE	Extended UV Rank	UVA-340 ΔE	UVA-340 Rank	UVB-313 ΔE	UVB-313 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 --->			**0.98**		**0.96**		**0.95**		**0.54**	

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

Rank Order Correlation: Accelerated vs Outdoor 相关性：加速与户外



Conclusions 结论

- Correlation for color change between accelerated and outdoor tests
- 加速测试与户外曝晒之间颜色变化的相关性
  - 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片)和荧光紫外灯(UVA-340 灯管)具有极好的等级排序相关性
  - Acceleration factor for 57 days outdoor and 200 h accelerated (7:1) 加速因子为7:1，户外57天对应加速200小时
  - Poor correlation for UV fluorescent UVB-313 lamps 荧光紫外UVB-313灯管的相关性不好

- Different degradation observed for pigments and base plastics
- 观察到颜料和塑料的不同降解
  - Darkening from plastic yellowing from shortwave UV 短波紫外线导致塑料发黄而变暗
  - Fade from breakdown of pigments from visible light 因可见光引起的色素分解而褪色
  - Differences most pronounced for pink and red specimens 粉色和红色样品的差异最为明显
  - Illustrates the need for thorough color characterization beyond ΔE 说明了除ΔE之外的全面颜色表征的必要性

Correlation Case Study #5
相关性案例研究 #5

Vinyl Siding
乙烯基外墙板

What is Vinyl Siding? 什么是乙烯基外墙板?

- Co-extruded building cladding material 共挤建筑包覆材料
  - Manufactured mostly from Polyvinyl Chloride (PVC) 主要由聚氯乙烯制成
  - Top layer (capstock) is durable and UV-stabilized 表层(耐候强化树脂)经久耐用，防紫外线
  - Also known as uPVC Weatherboarding in some regions 在某些地区也称为PVC挡风板
- Developed in the 1960's, became popular in the 1970's **始于20世纪60年代，流行于20世纪70年代**
- Most common residential exterior cladding material in US & Canada – about 20 million m^2 used per year
- **美国和加拿大最常见的住宅外墙材料**

Vinyl Siding Institute 乙烯基外墙板研究所

Outdoor test program 户外测试程序

- Large-scale, long-term study 大规模长期研究
- Outdoor data collection ongoing since 1984
- 自1984年以来一直收集户外数据
- New tests started every 5 years; thousands of specimens and replicates tested
- 每5年开始新的测试，测试了数千种样品
- Long-term material degradation mechanisms are now well understood
- 长期的材料降解机制现在已经很好了解了

Correlation here is between short- and long-term outdoor testing
这里的相关性是指短期和长期户外测试之间的相关性

Vinyl Siding Institute 乙烯基外墙板研究所

Service Life Certification 使用寿命认证

- Accurate service life estimate based on 2-year outdoor testing
- 基于2年户外测试的准确的使用寿命预测
  - If after 2 years of exposure, color change is <1, then after 25 years it has a high probability of color change <4 如果曝晒2年，颜色变化<1，那么25年后颜色变化<4的概率很高
  - Acceleration for service life prediction of 12:1 使用寿命预测为12:1

- 2 year outdoor certification program 两年户外认证项目
  - Administered by ISO 17025-accredited, independent 3rd party 由ISO 17025认可的独立第三方管理
  - Exposures in FL, AZ, OH 在佛罗里达，亚利桑那和俄亥俄州进行户外曝晒
  - Tests performed in accordance with ASTM test standards 根据ASTM标准进行测试
  - Receive a VSI stamp, gives credibility to a 25-year warranty 获得VSI盖章，让25年质保变得可信

Qualification / Correlation Case Study 认证/相关性案例

Vinyl Siding Institute (VSI)

- New Goal: Correlate accelerated test to 2-year outdoor results
- 新目标：将加速测试与2年户外结果相关联
  - Six rounds of accelerated testing conducted by multiple labs – examined test cycles of both UV fluorescent and xenon
  - 由多个实验室进行的六轮加速测试 – 评估了荧光紫外和氙灯的测试循环
- Unique Fluorescent UV cycle provided best correlation for PVC siding material
- 独特的荧光紫外测试循环为PVC材料提供了最佳相关性
  - Hot condensation best for accelerating realistic moisture attack synergistically with UV
  - 冷凝与紫外光协同最适合加速真实的水分侵蚀
  - Long wave and visible had little impact 长波紫外线和可见光几乎没有影响
  - Reduced UV temps and increase condensation temps gave better results
  - 降低紫外光测试循环温度，并提高冷凝测试循环温度，得到了更好的结果
- UV fluorescent test not adopted for certification program, but used by members for product development
- 荧光紫外测试不用于认证，但被成员用于产品开发

Summary of Correlative Testing
相关性测试总结

Accelerated Test Types

Accelerated Test Type	Result	Test Time	Results compared to
Quality Control	Pass / fail	• Defined • Short	Material specification
Qualification / validation	Pass / fail	• Defined • Medium-long	Reference material or specification
Correlative	Rank-ordered data	• Open-ended • Medium	Natural exposure (Benchmark site)
~~Predictive~~	~~Service life Acceleration factor~~	~~• Open-ended~~ ~~• Long~~	~~Natural exposure (Service environment)~~

What did we learn from those correlation case studies?
我们从这些相关性案例研究中学到了什么?

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

所有的加速因子都不一样！它们不是通用的或普遍的，它们取决于：

- The specific material tested 测试材料
- The type of test being correlated to natural outdoor results – fluorescent UV, xenon, accelerated outdoors
- 与自然户外结果相关的测试类型 – 荧光紫外，氙灯，加速户外
- The specific set of lab tester time cycles and temperature 实验室测试设备时间周期和温度的特定设置
- The specific outdoor exposure site and sample mounting procedure 特定的户外曝晒场和样品安装方式
- The failure mechanism(s) being evaluated 需要评估的失效模式

Correlation between accelerated and outdoor testing

加速测试和户外测试之间的相关性

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

对于各种材料系统，可以确定户外测试和加速测试之间的相关性。然而…

- Acceleration factors are not general and often only valid for one type of degradation
- 加速因子不是通用的，通常只对一种失效模式有效
- Comparative testing usually gives rank-ordered data, which can be powerful data
- 比对测试通常给出等级排序数据，这可能是强有力的数据
- It is critical to perform outdoor testing to validate accelerated testing - “Test the Test”
- 进行户外曝晒以验证加速测试非常重要 – “测试你的测试”

Thank you for your attention!

Questions?

Send your inquiry to:
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