NREL
Transforming ENERGY

Photovoltaic Cable Jackets: A Comparison of Representative Products Using Combined-Accelerated Stress Testing

David C. Miller*, Rachael L. Arnold, Peter L. Hacke, Aubrey Jackson, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy M. Newkirk, Greg Perrin, Laura T. Schelhas, Kent Terwilliger, Soňa Uličná

National Renewable Energy Laboratory (NREL), Golden, CO

*David.Miller@nrel.gov

Supplemental Slides
Tuesday, 2024/12/10

Details of the C-AST Runs

	C-AST RUN 1					C-AST RUN 2					C-AST RUN 3				
	SEQUENCE:					SEQUENCE:					SEQUENCE:				
NUMBER FAILURES:	Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert
CABLE ENDS	0	0	0	0	1	0	0	8	2	0	0	0	0	0	0
FIXTURE	0	0	0	0	1	0	0	3	1	1	0	0	0	0	4
DC±AC or DC CURRENT at HIGH IRRADIANCE {A}	0 0		9.0±5 9.0	9.0±5 9.0	24±10 24	0 0		24±10 24	15±8 15	10±6 10	0 0		10±6 10	10±6 10	10±6 10
DC±AC or DC CURRENT at LOW IRRADIANCE {A}	0	9.0±5 9.0	9.0±5 9.0	9.0±5 9.0	13±6 13	0 0	13±6 13	13±6 13	7.5±4 7.5	5±3 5	0 0	5±3 5	5±3 5	5±3 5	5±3 5
START DATE	2023/2/16	2023/2/17	2023/2/23	2023/3/17	2023/4/11	2023/4/24	2023/4/25	2023/5/03	2023/5/26	2023/6/26	2023/7/07	2023/7/10	2023/7/14	2023/9/13	2023/10/12

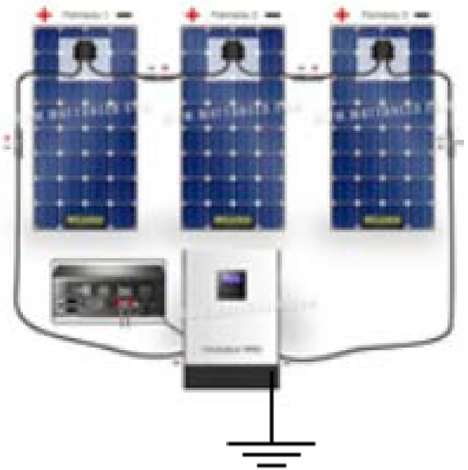
- Above: number of failed connectors and current settings for the D1 C-AST fixture cable specimens.

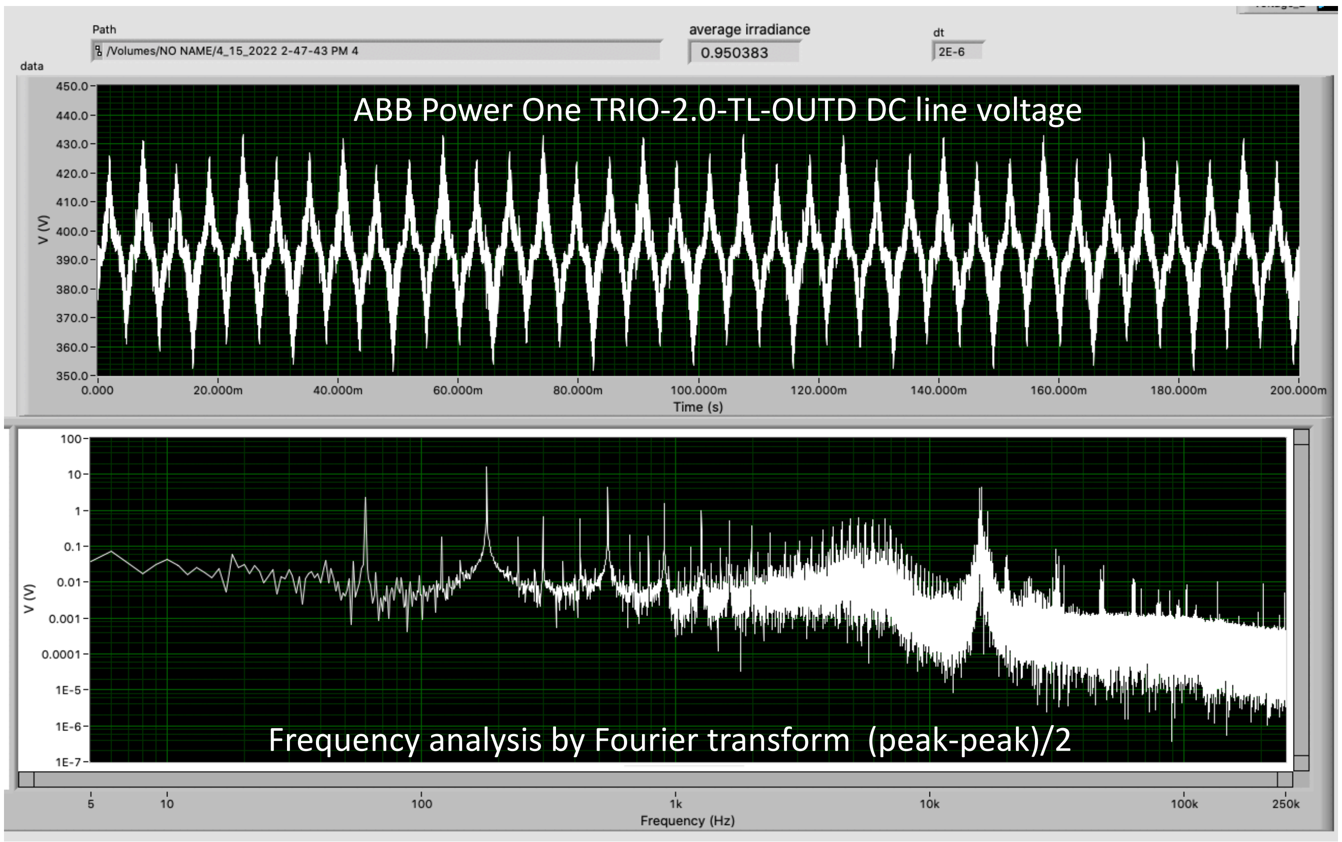
Details of the C-AST Runs

black	red	gray		
-29	-30	-30	AVG	WINTER
24	24	24	S.D.	
-81	-81	-81	CoV {%}	
28	30	29	MAX	
-45	-46	-46	MIN	
74	76	74	DIFF	
-11	-14	-11	AVG	SPRING
28	26	29	S.D.	
-262	-190	-261	CoV {%}	
29	26	29	MAX	
-45	-46	-46	MIN	
74	72	75	DIFF	
59	54	59	AVG	TROPICAL
26	23	27	S.D.	
100	100	100	CoV {%}	
85	79	87	MAX	
-26	-27	-27	MIN	
111	107	114	DIFF	
31	29	31	AVG	DESERT
36	35	36	S.D.	
100	100	100	CoV {%}	
86	83	87	MAX	
-26	-27	-27	MIN	
113	110	114	DIFF	

- Left: temperature of cables by color in the C-AST chamber for M2212-8000 (black), M2212-8011 (red), and M2212-8001 (gray).

Characterization of DC lines of module string





Measurement equipment

Verivolt IsoBlock V-4c

- •3 Way Galvanic isolation
- •1,500V sustained and 5,000V peak isolation (1 min)
- •DC to 100kHz Bandwidth
- •1500 V in/10 V out

NI-9222

±10 V, 500 kS/s/ch, 16-Bit, Simultaneous Input, 4-Channel

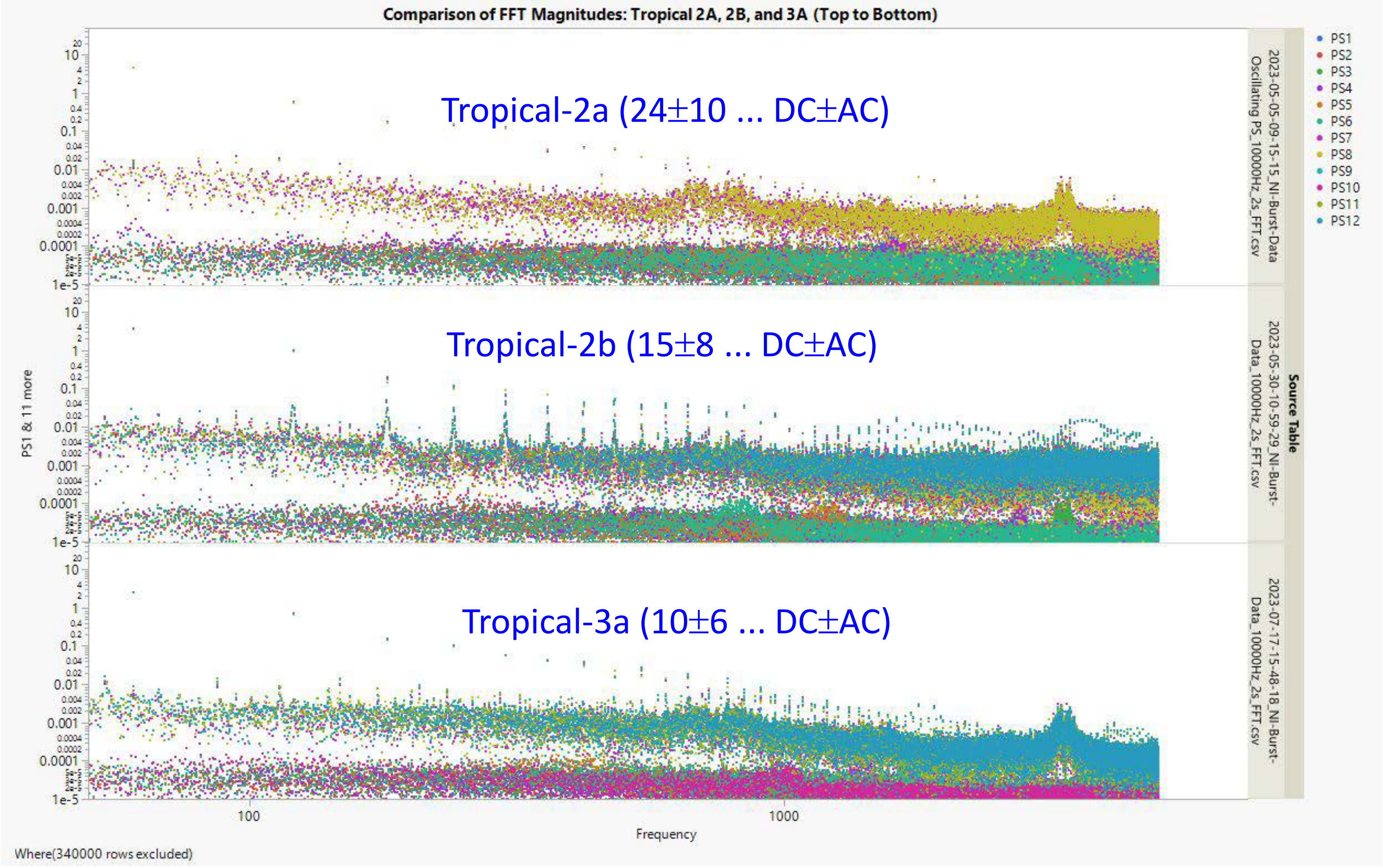
NI cDAQ 9178

Into Laptop running **LabVIEW**

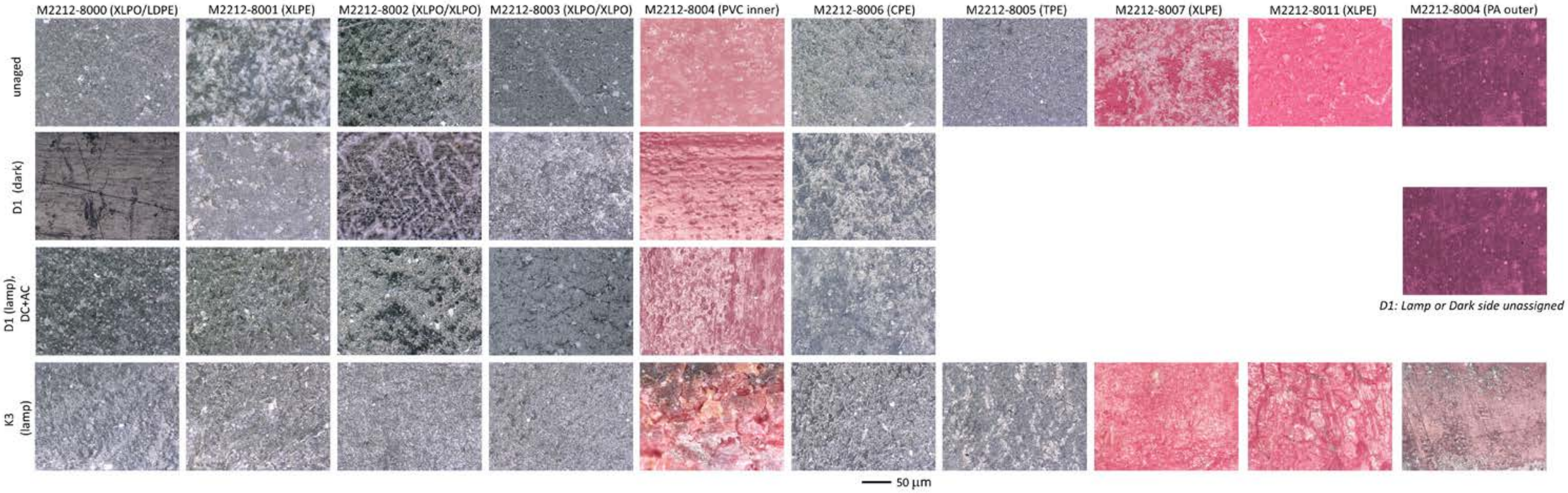
Overview of Inverter DC Strings Characterized

Inverter Maker	Inverter Model	Measured System voltage	Peak 120 Hz (V) (peak-peak)/2	Other significant peaks
SMA	SB 3000HFUS-30	328 V	0.2 V	48 kHz
SMA	SB 3000US-30	220 V	3 V	
SMA	SWR 1800U	208 V	3 V	
PV Powered	PVP 2000	162 V	5 V	10, 30, 50, 70 kHz
ABB Power One	TRIO-2.0-TL-OUTD	395 V	20 V	15 kHz
Proharvest OutBack Power	TS-480-8K	410 V	23 V	
Fronius	IG 5100	284 V	0.7 V	

DC+AC in C-AST D1 Experiment (Representative FFT's)



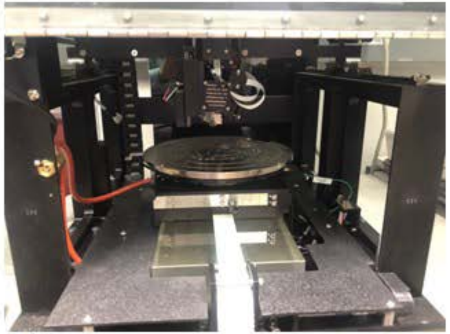
Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

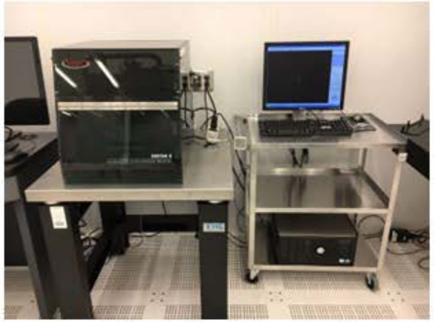


Surface Roughness (Profilometer) Methodology

Background:
Roughness Measurements Using Mechanical Profilometer

Dektak 8 (Veeco Instruments, Inc.)





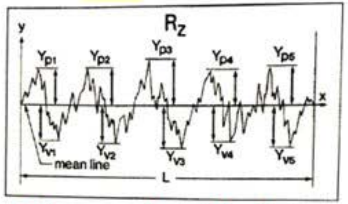
- Probe material: diamond
- 1.5 mm line scans
- Probe size: r=5 μm
- AVG[5-10 measurements], each sample

- Vertical resolution: 1 nm in 60 μm range
- Lateral resolution: scales with probe size
- z-measurement range: 0-260 μm
- Probe M/N 838-031-1
- Contact force: 3 mg

$$R_q = \sqrt{\frac{1}{L}\int_0^L y^2(x)dx}$$

R_q ~ rms (variation in) roughness.

$$R_{z\ (ISO)} = \frac{1}{10}\left(\sum_{i=1}^{10} Y_{pi} + \sum_{i=1}^{10} Y_{vi}\right)$$



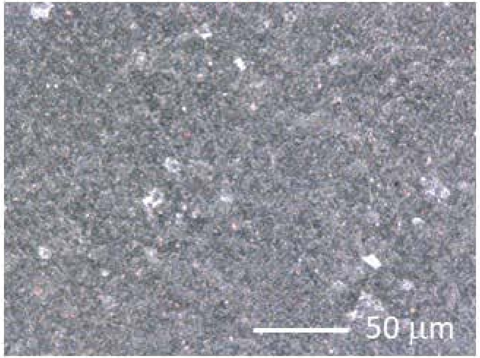
R_z focuses on largest sized features.

Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

Optical Microscopy – M2212-8000

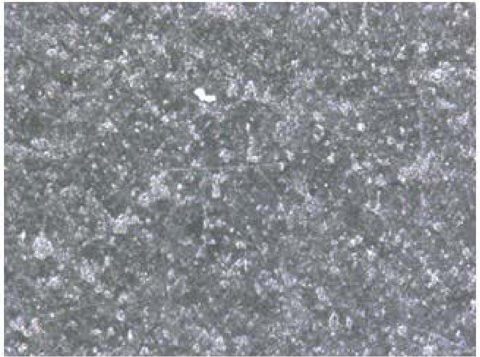
(black, XLPO outer/LDPE inner)

unaged

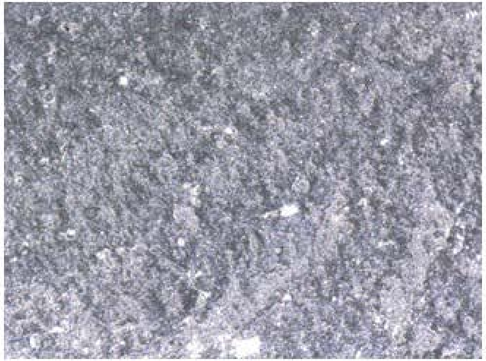


D1 (dark, at mandrel abrasion)

D1 (lamp)



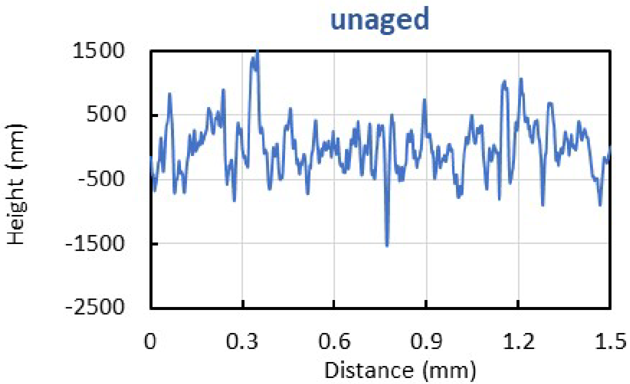
K3 (lamp)

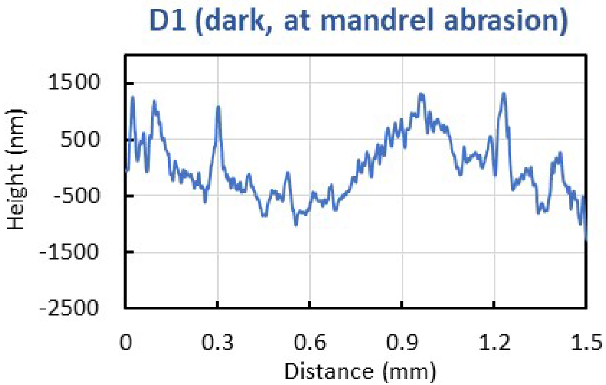


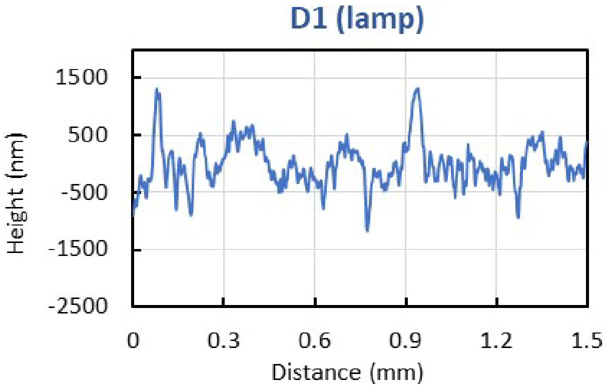
Roughness (Profilometer) of D1 and K3 C-AST Specimens

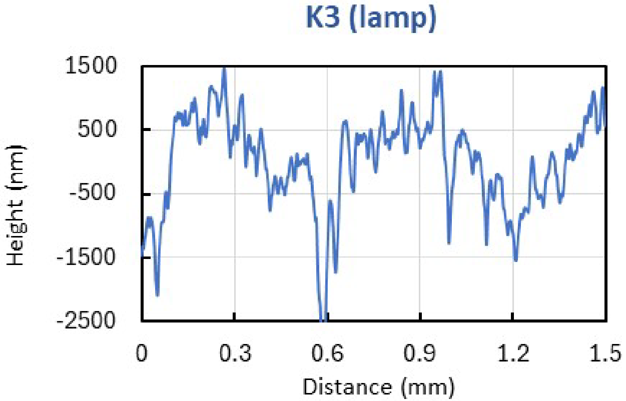
Roughness Profiles – M2212-8000

(black, XLPO outer/LDPE inner)







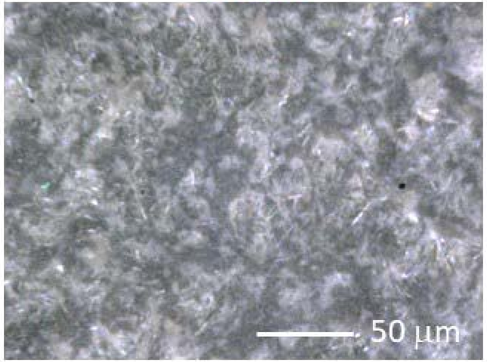


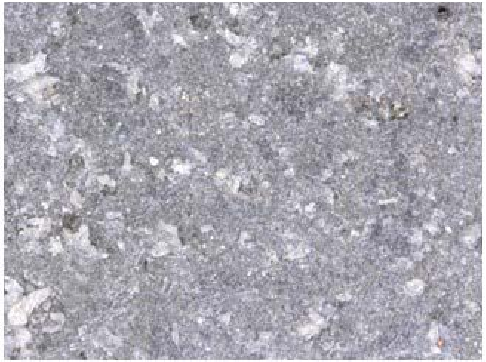
Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

Optical Microscopy – M2212-8001

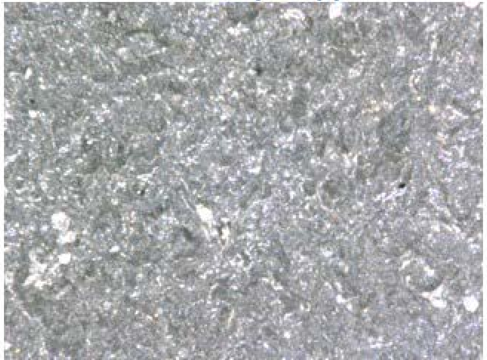
(black, XLPE)

unaged





D1 (lamp)

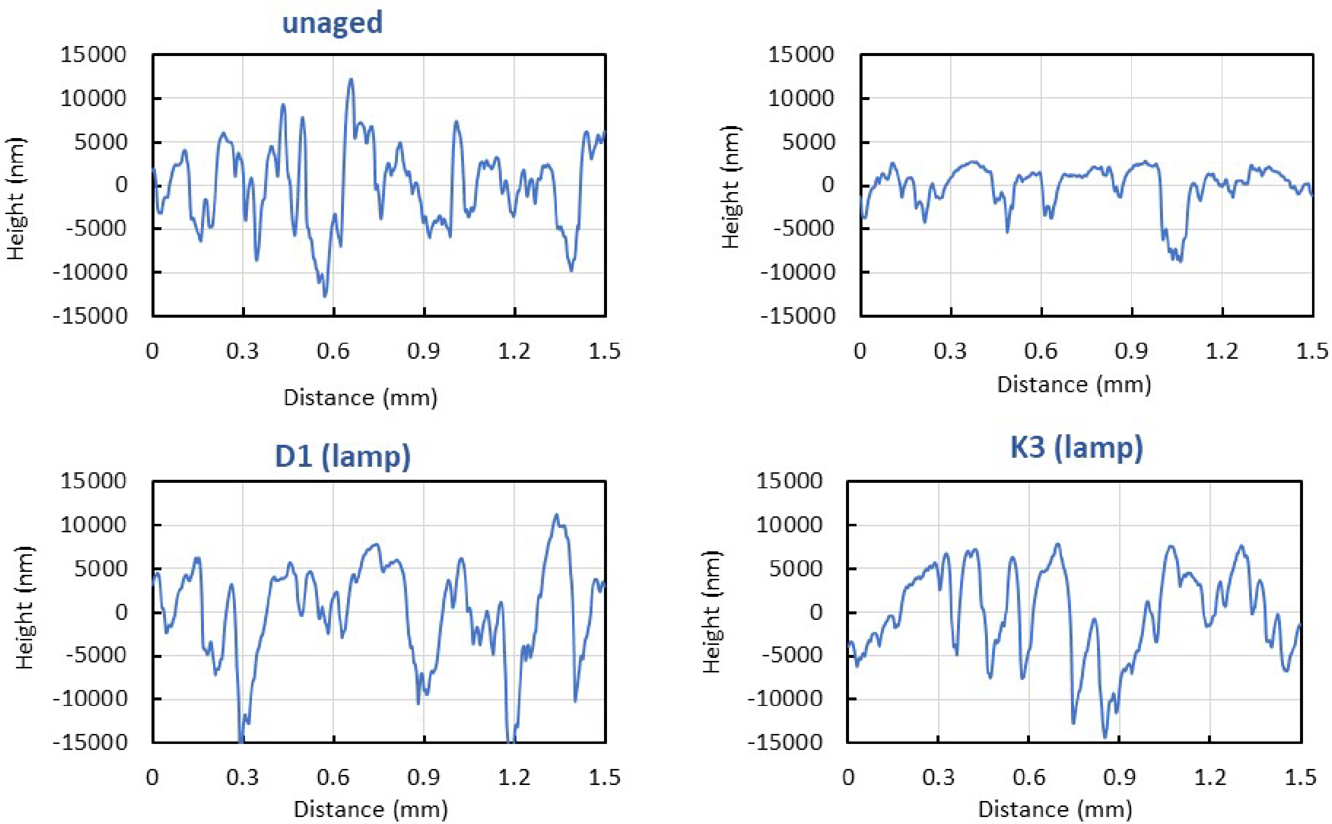


K3 (lamp)

Roughness (Profilometer) of D1 and K3 C-AST Specimens

Roughness Profiles – M2212-8001

(black, XLPE)

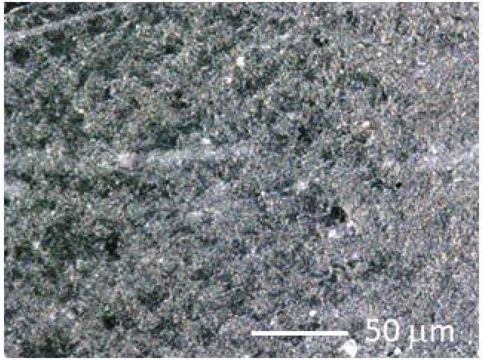


Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

Optical Microscopy – M2212-8002

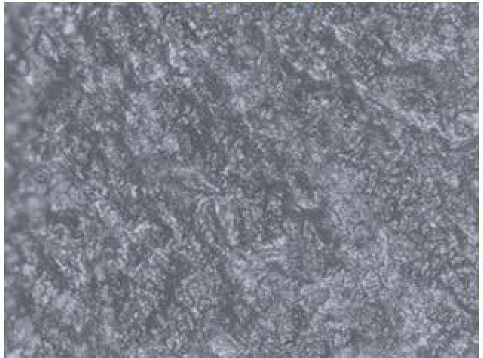
(black, XLPO outer/XLPO inner)

unaged



D1 (dark, at mandrel abrasion)

D1 (lamp)

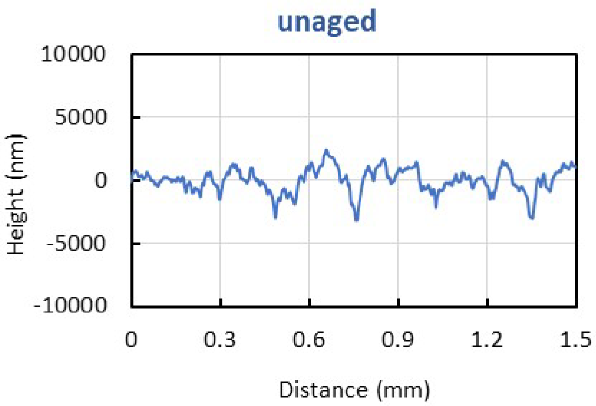


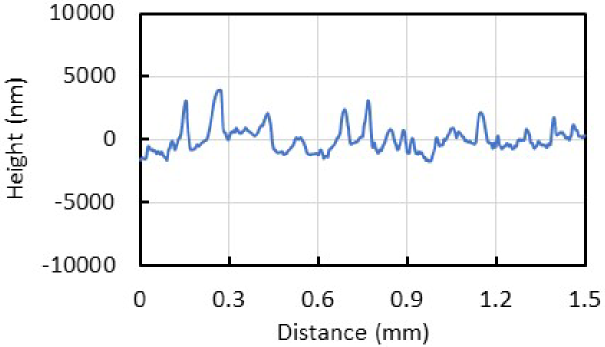
K3 (lamp)

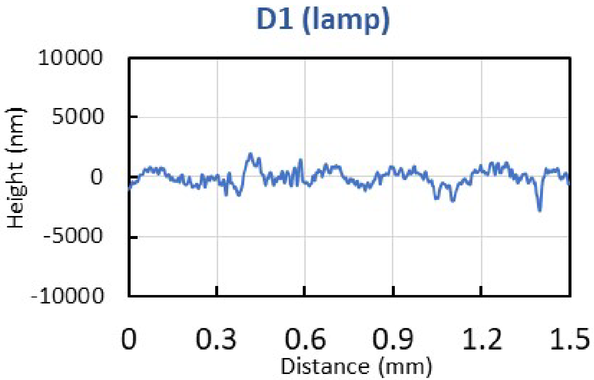
Roughness (Profilometer) of D1 and K3 C-AST Specimens

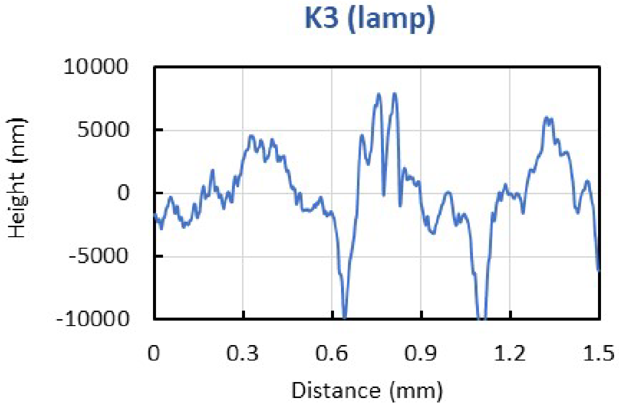
Roughness Profiles – M2212-8002

(black, XLPO outer/XLPO inner)







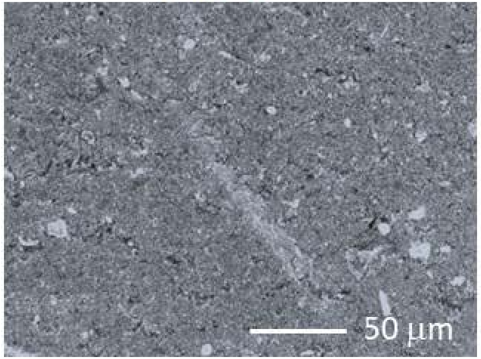


Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

Optical Microscopy – M2212-8003

(black, XLPO outer/XLPO inner)

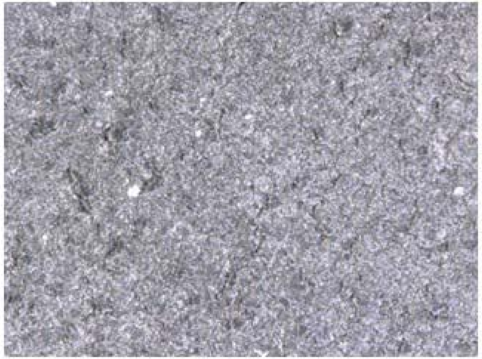
unaged



D1 (dark, at mandrel abrasion)

D1 (lamp)

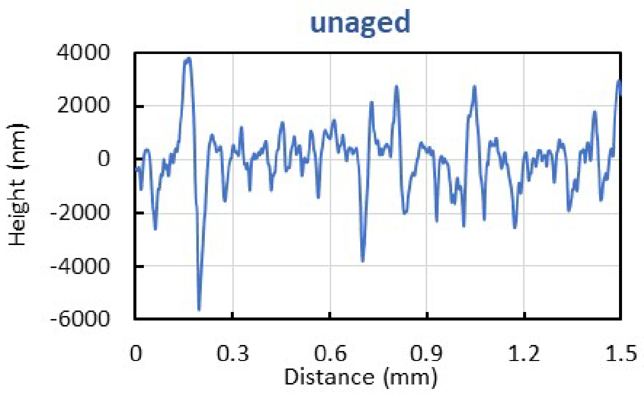
K3 (lamp)

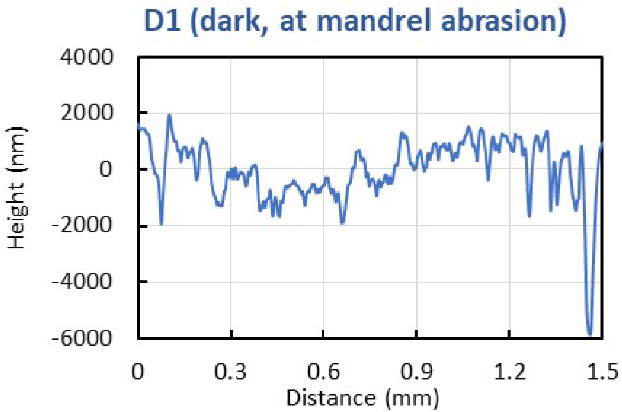


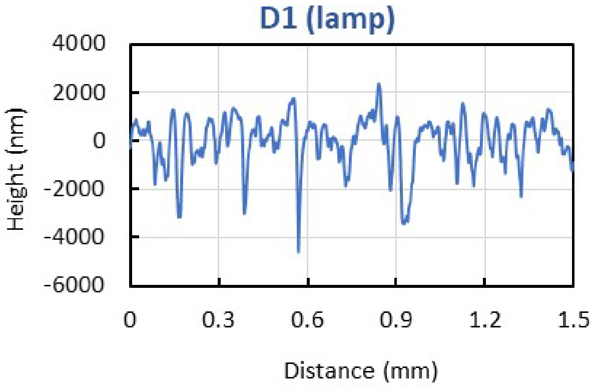
Roughness (Profilometer) of D1 and K3 C-AST Specimens

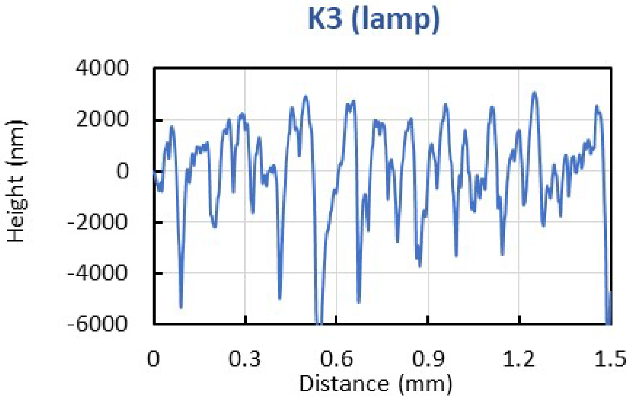
Roughness Profiles – M2212-8003

(black, XLPO outer/XLPO inner)







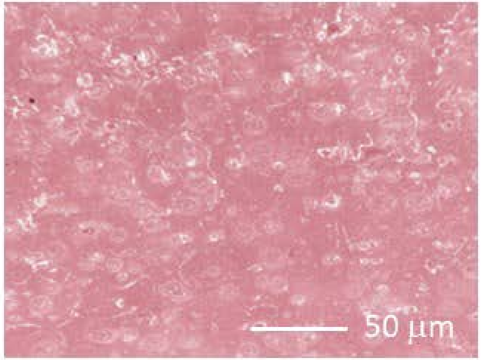


Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

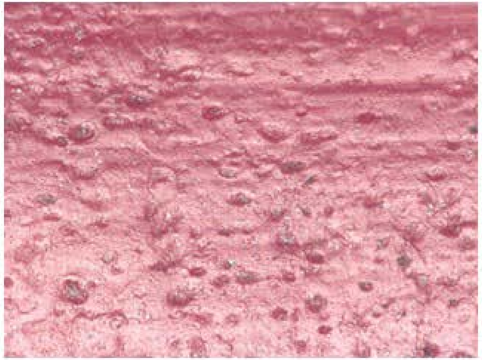
Optical Microscopy – M2212-8004 (PVC Inner)

(red, for PVC inner)

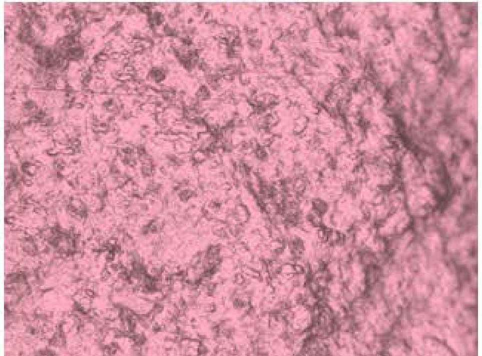
unaged



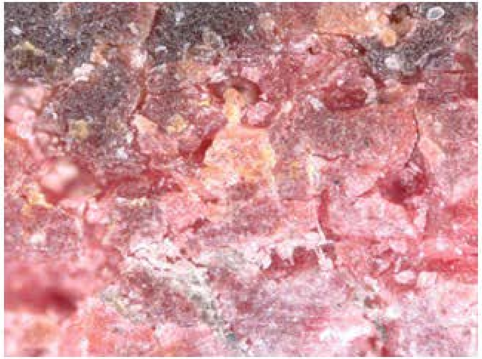
D1 (dark, at mandrel abrasion)



D1 (lamp)



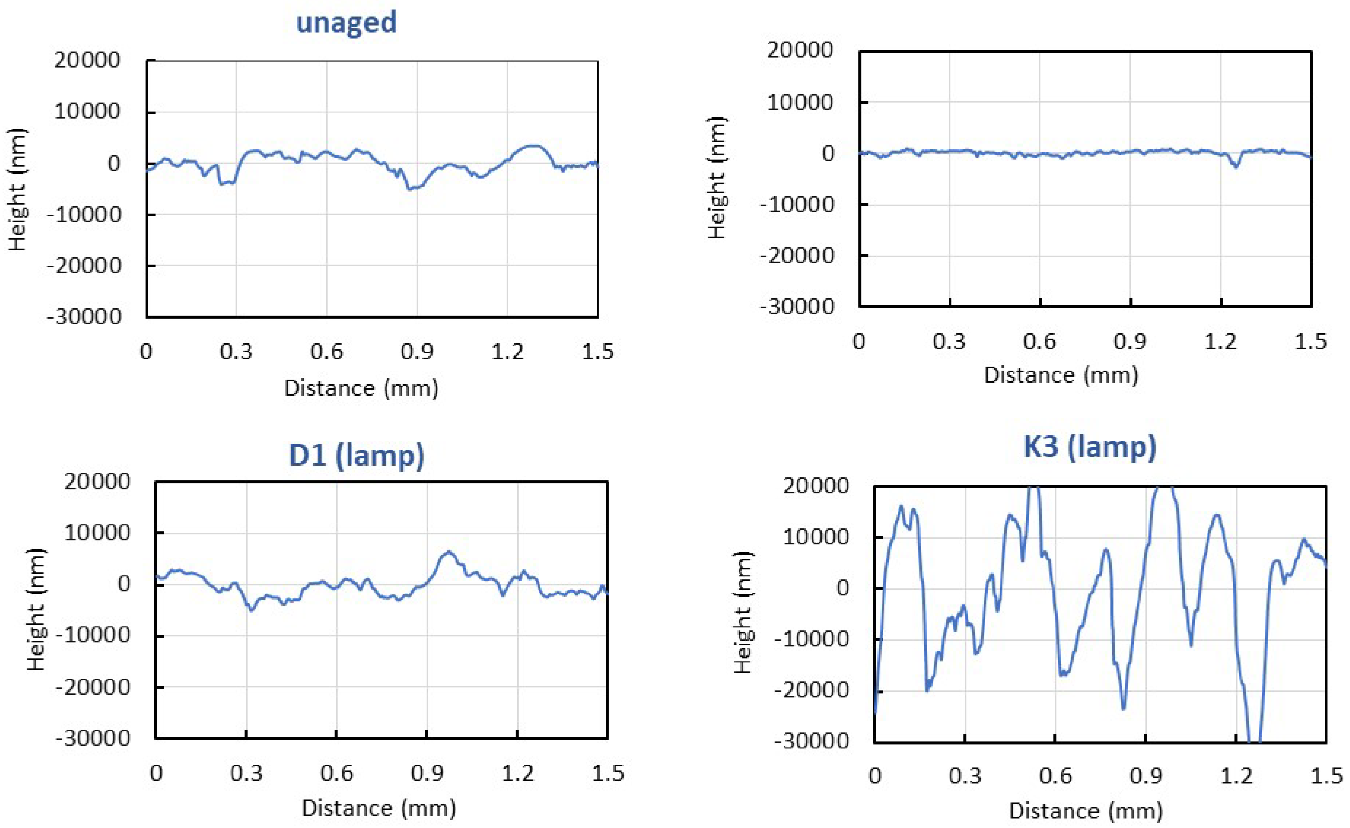
K3 (lamp)



Roughness (Profilometer) of D1 and K3 C-AST Specimens

Roughness Profiles – M2212-8004 (PVC Inner)

(red, for PVC inner)

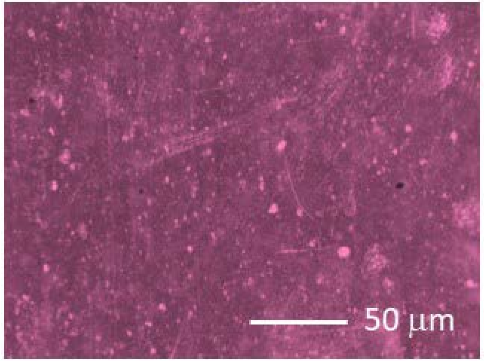


Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

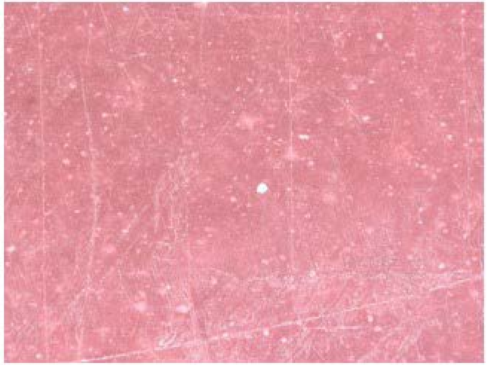
Optical Microscopy --- 8004, PA Outer

(red, for PA outer)

Unaged



D1, Lamp or Dark side unassigned

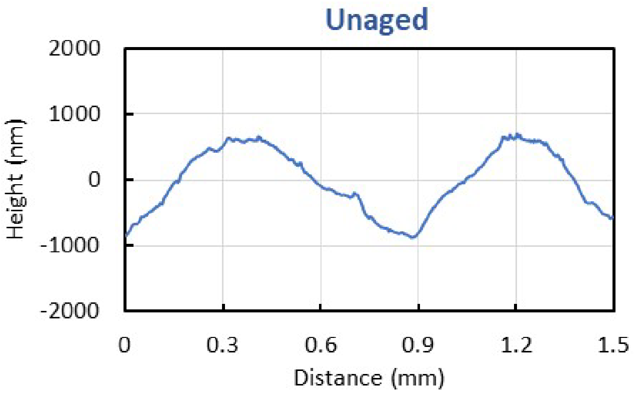


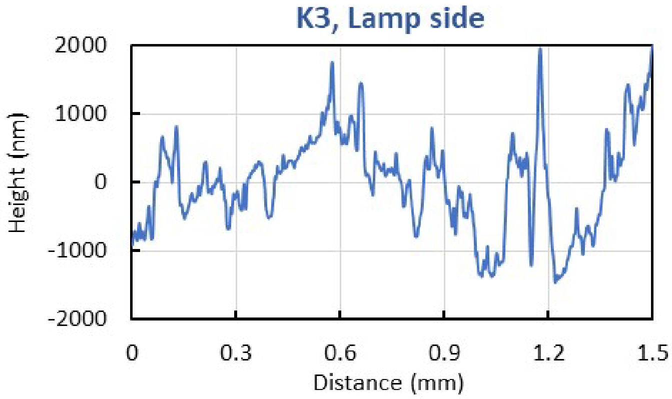
K3, Lamp side

Roughness (Profilometer) of D1 and K3 C-AST Specimens

Roughness profiles --- 8004, PA Outer

(red, for PA outer)



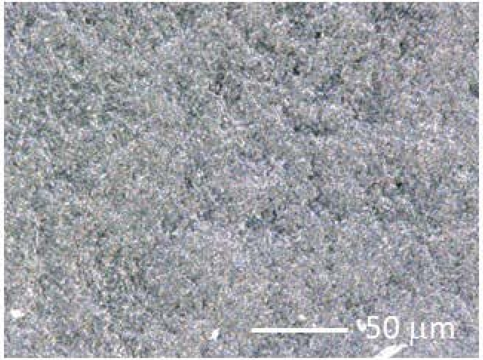


Morphology (Optical Microscope) of D1 and K3 C-AST Specimens

Optical Microscopy – M2212-8006

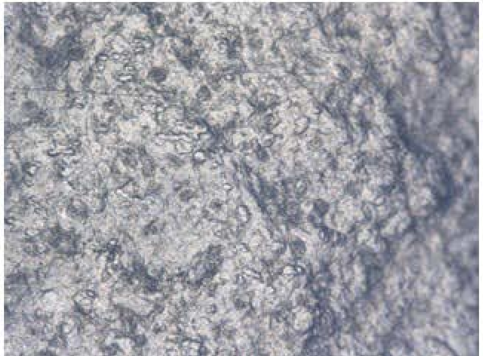
(black, CPE)

unaged

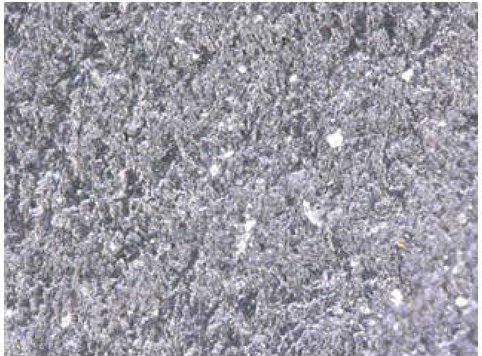


D1 (dark, at mandrel abrasion)

D1 (lamp)



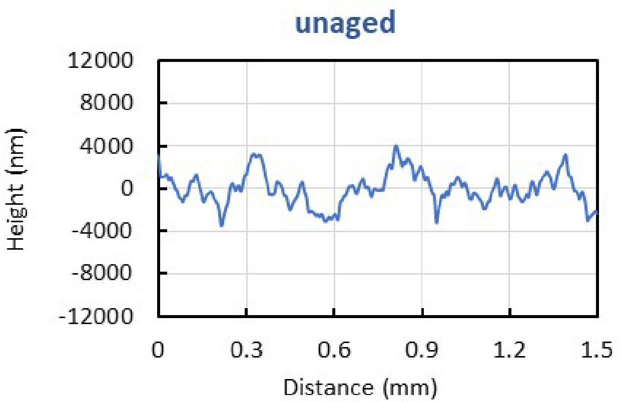
K3 (lamp)

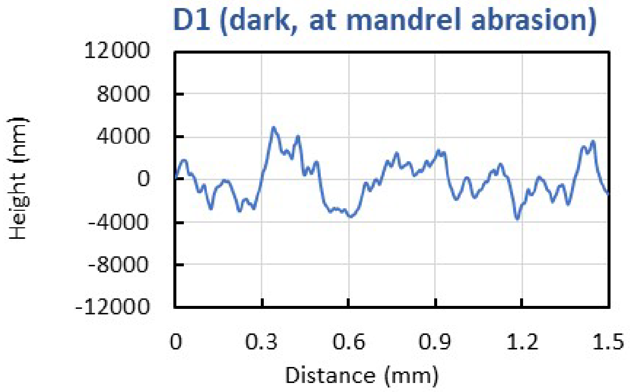


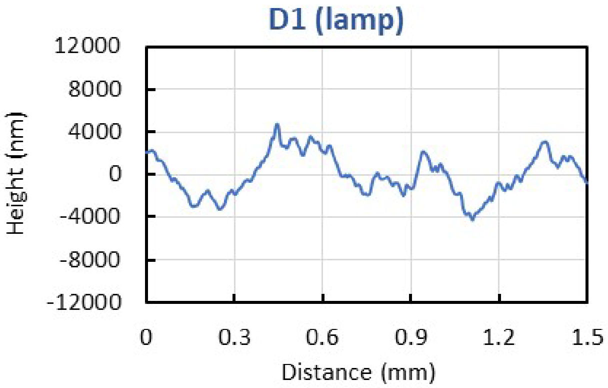
Roughness (Profilometer) of D1 and K3 C-AST Specimens

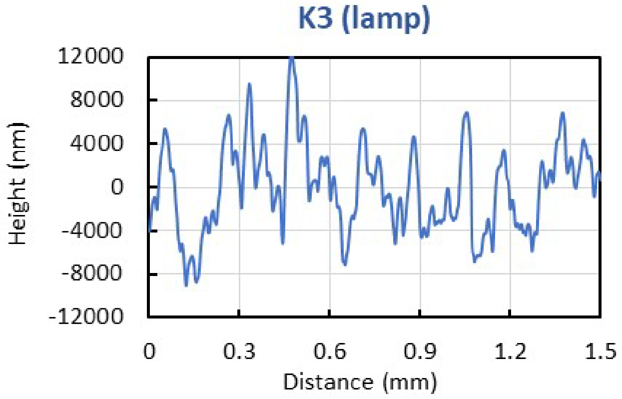
Roughness Profiles – M2212-8006

(black, CPE)







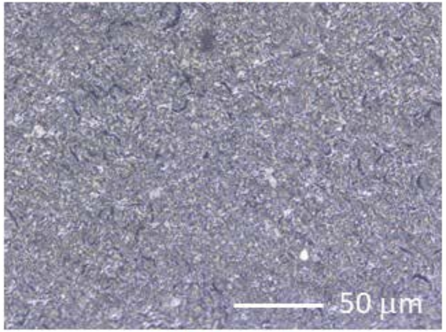


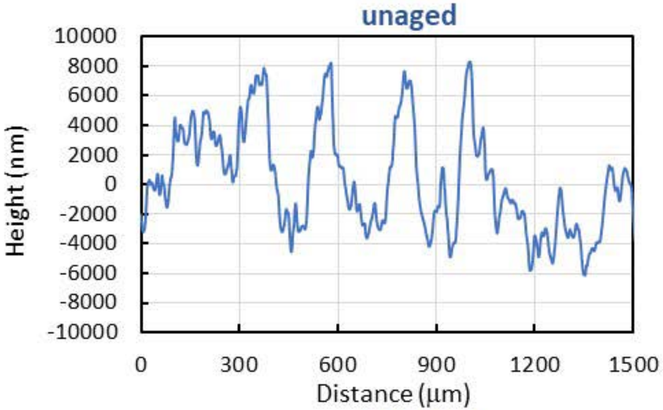
Morphology (Optical Microscope) and Roughness (Profilometer) of D1 and K3 C-AST Specimens

Optical Microscopy and Roughness Profiles – M2212-8005

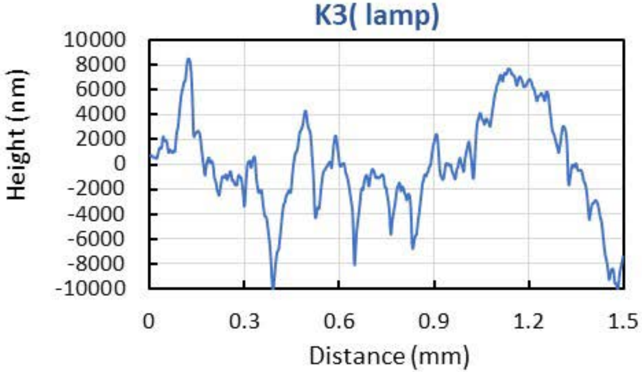
(black, TPE)

unaged





K3 (lamp)

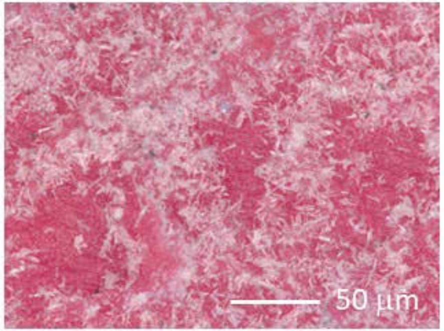


Morphology (Optical Microscope) and Roughness (Profilometer) of D1 and K3 C-AST Specimens

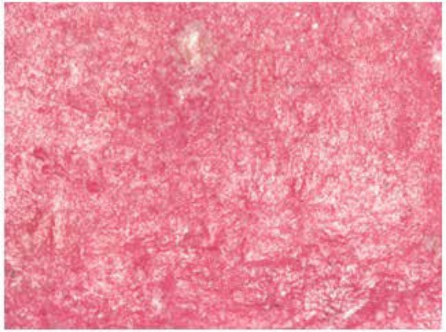
Optical Microscopy and Roughness Profiles – M2212-8007

(red, XLPE)

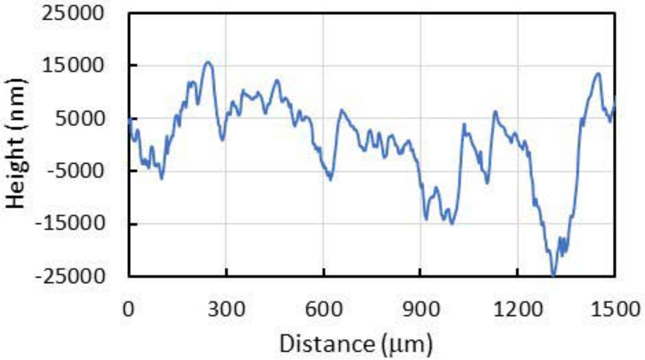
unaged



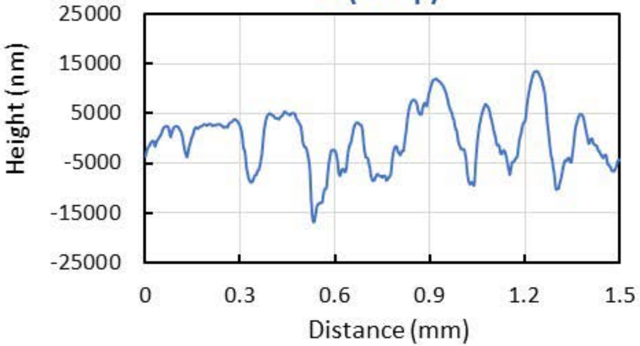
K3 (lamp)



unaged



K3(lamp)

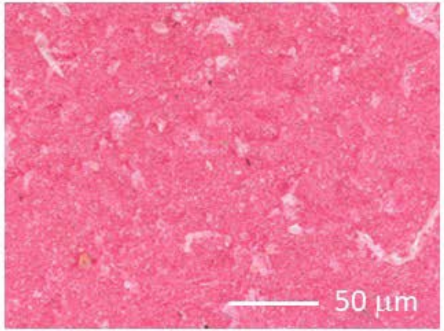


Morphology (Optical Microscope) and Roughness (Profilometer) of D1 and K3 C-AST Specimens

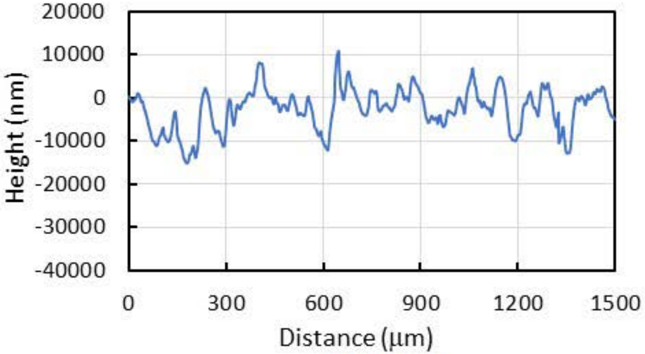
Optical Microscopy and Roughness Profiles – M2212-8011

(red, XLPE)

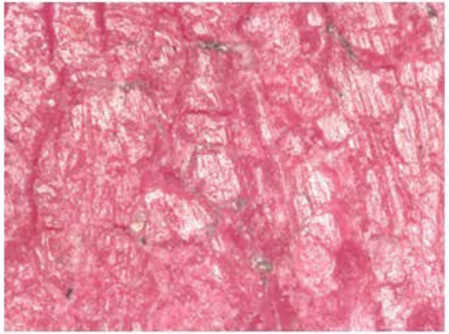
unaged



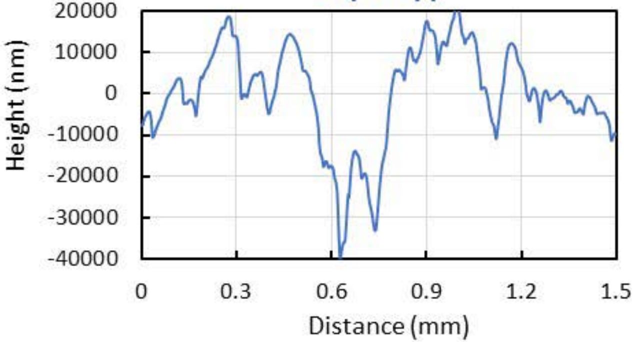
unaged



K3 (lamp)

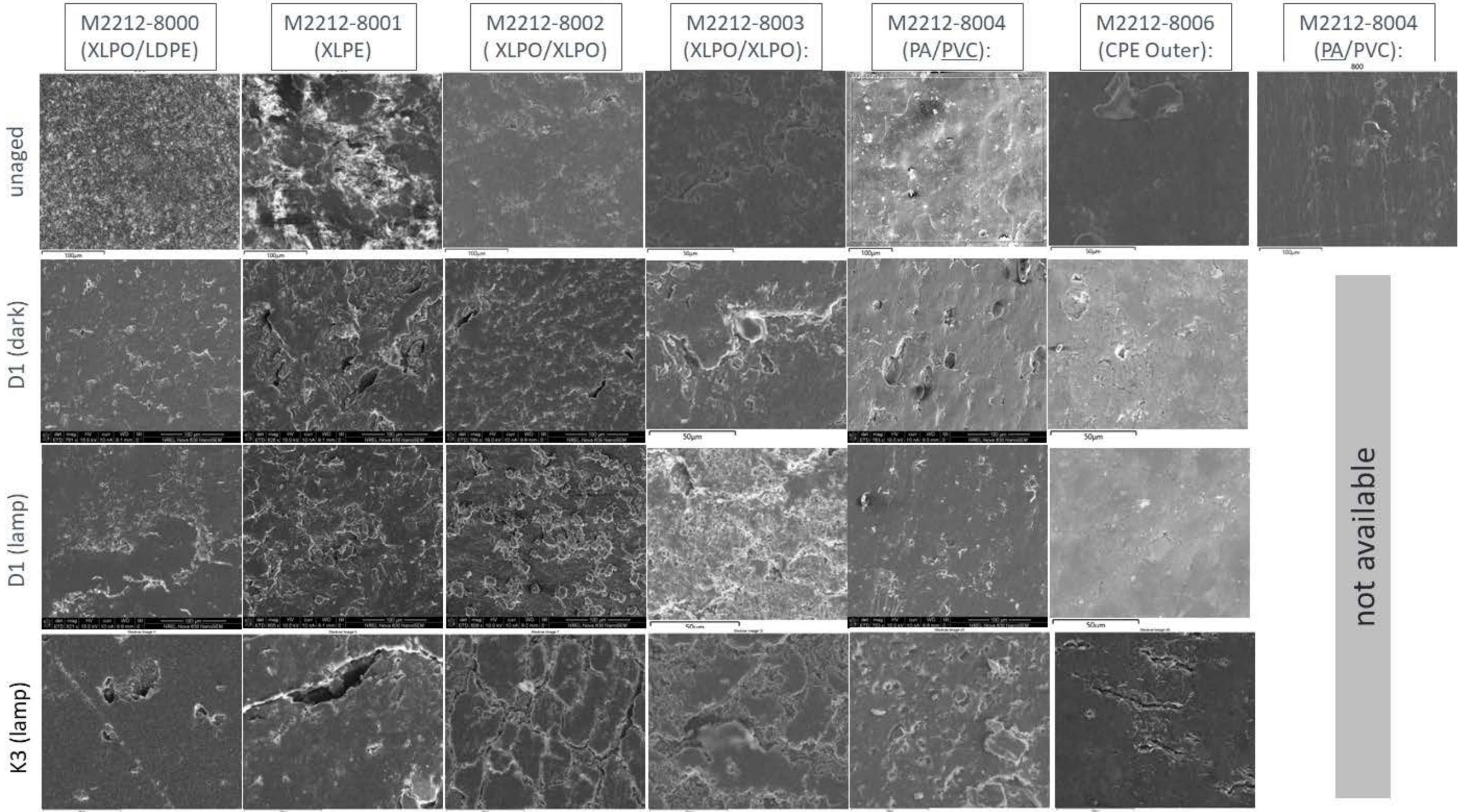


K3(lamp)

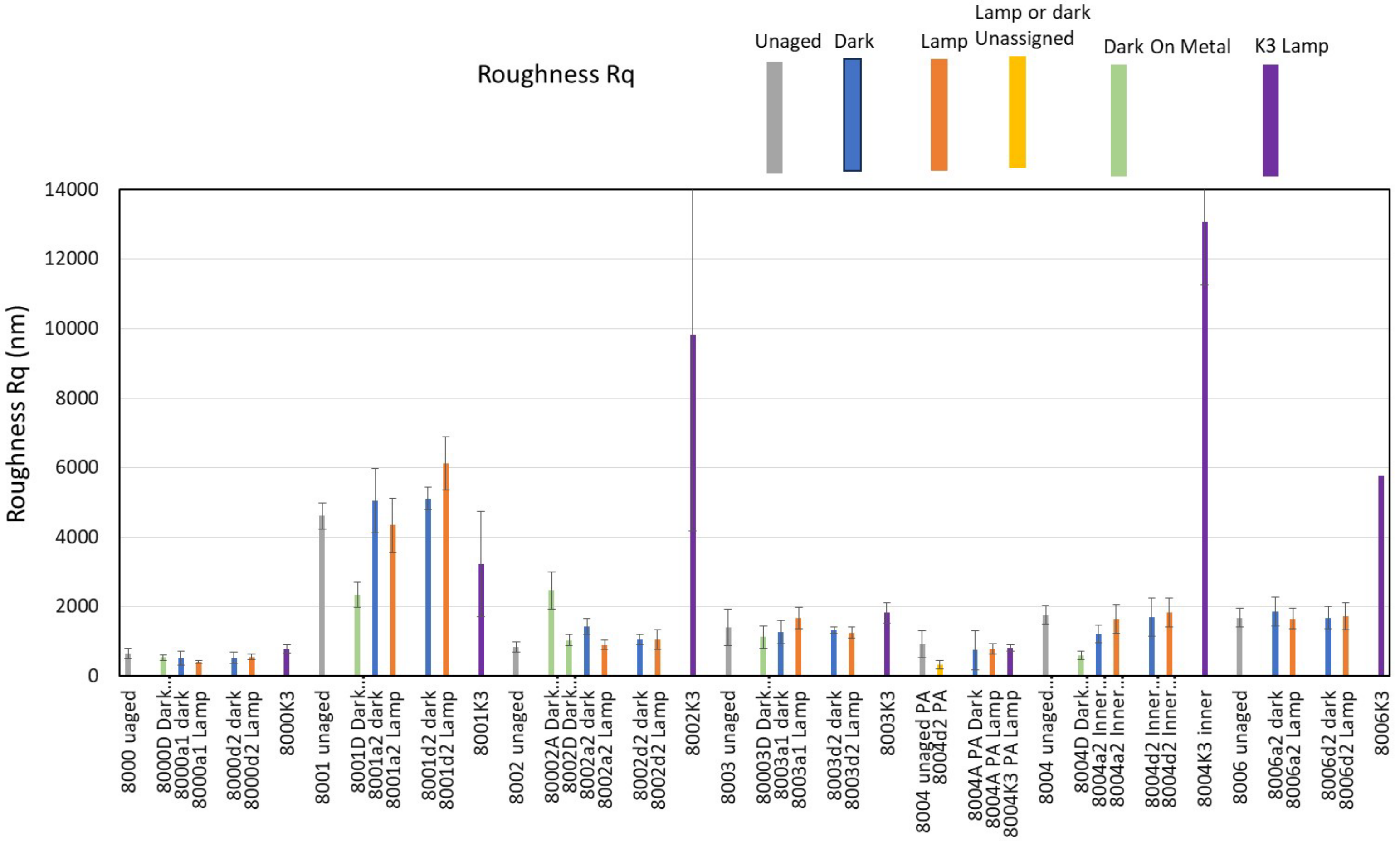


Morphology (SEM) of D1 and K3 C-AST Specimens

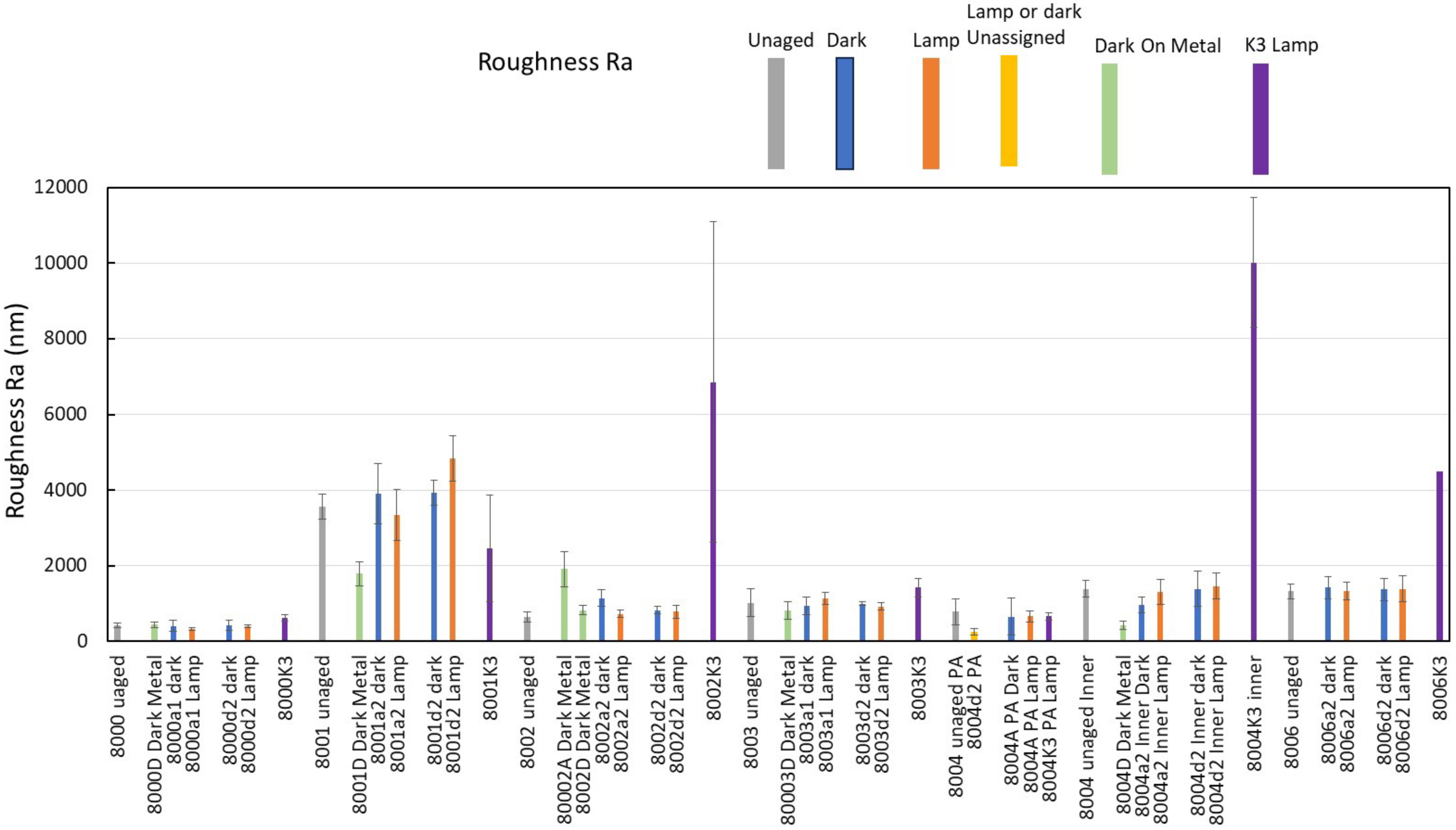
Select D1 Cables: Qualitative Morphology



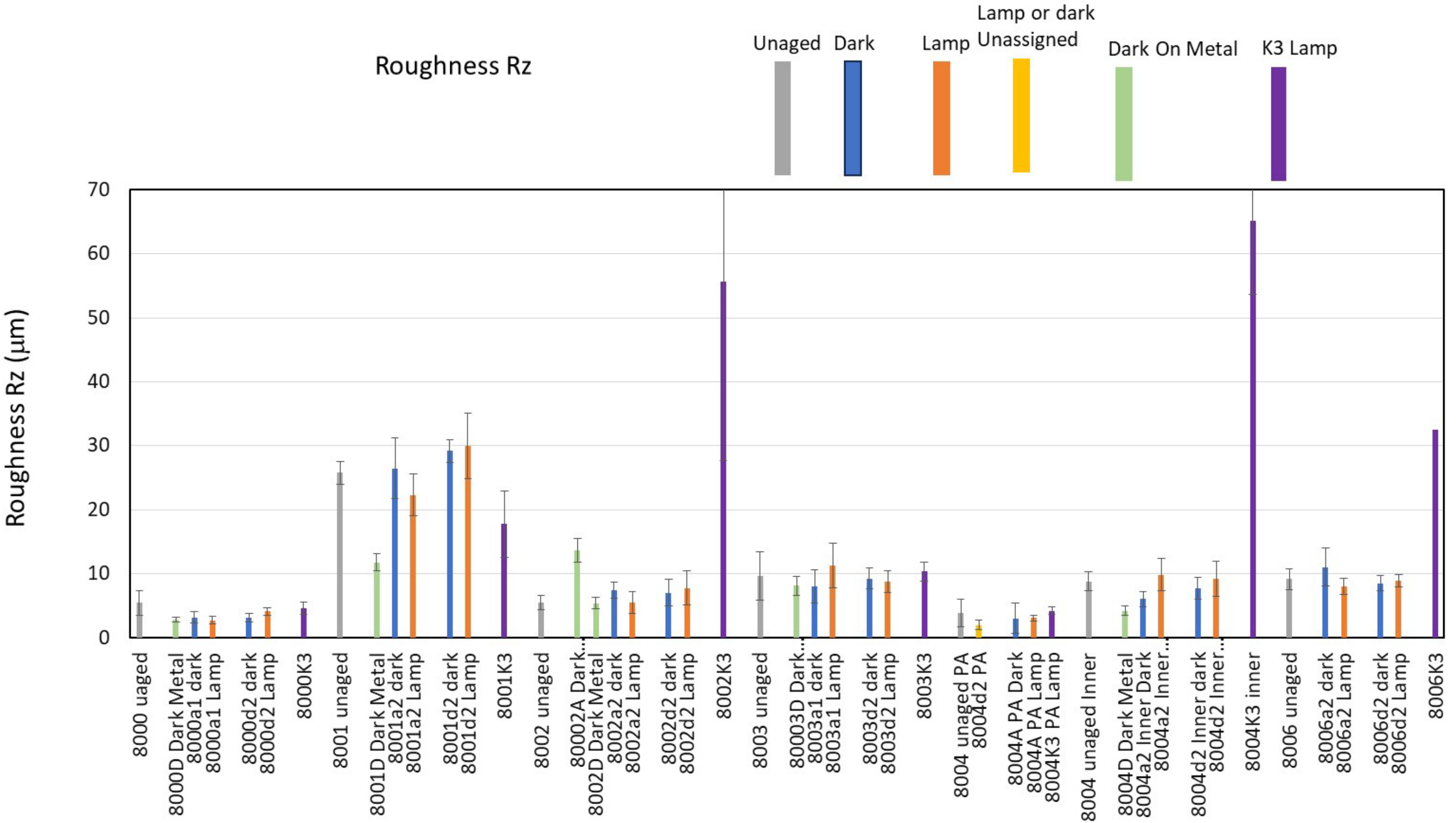
Roughness (root mean square) of D1 and K3 C-AST Specimens



Roughness (average) of D1 and K3 C-AST Specimens



Roughness (maximum peak to valley height) of D1 and K3 C-AST Specimens



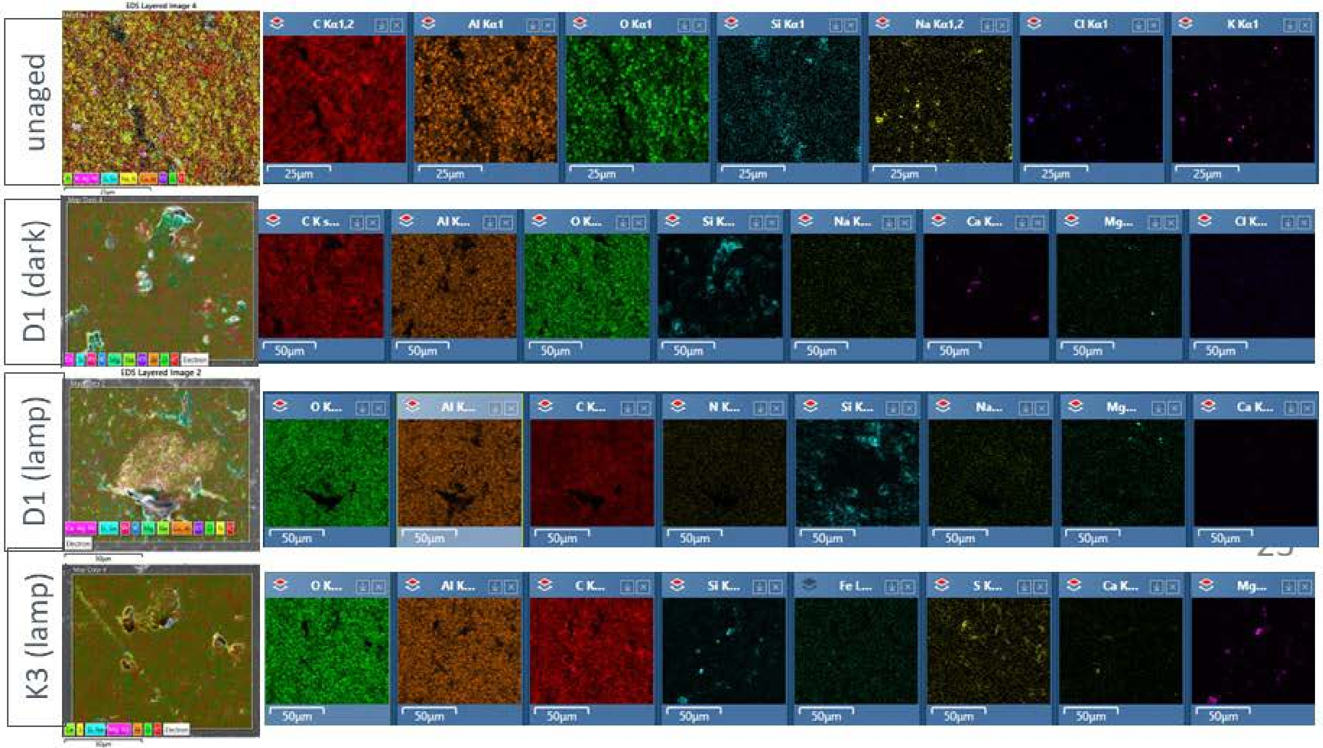
Composition (EDS) of D1 and K3 C-AST Specimens

M2212-8000 (IEC, XLPO/LDPE): Quantitative Composition

Left:
greatest concentration

- Al, Si observed in addition to C, O + Si agglomeration
- Trace elements: Na, Cl, K, e.g., salts.

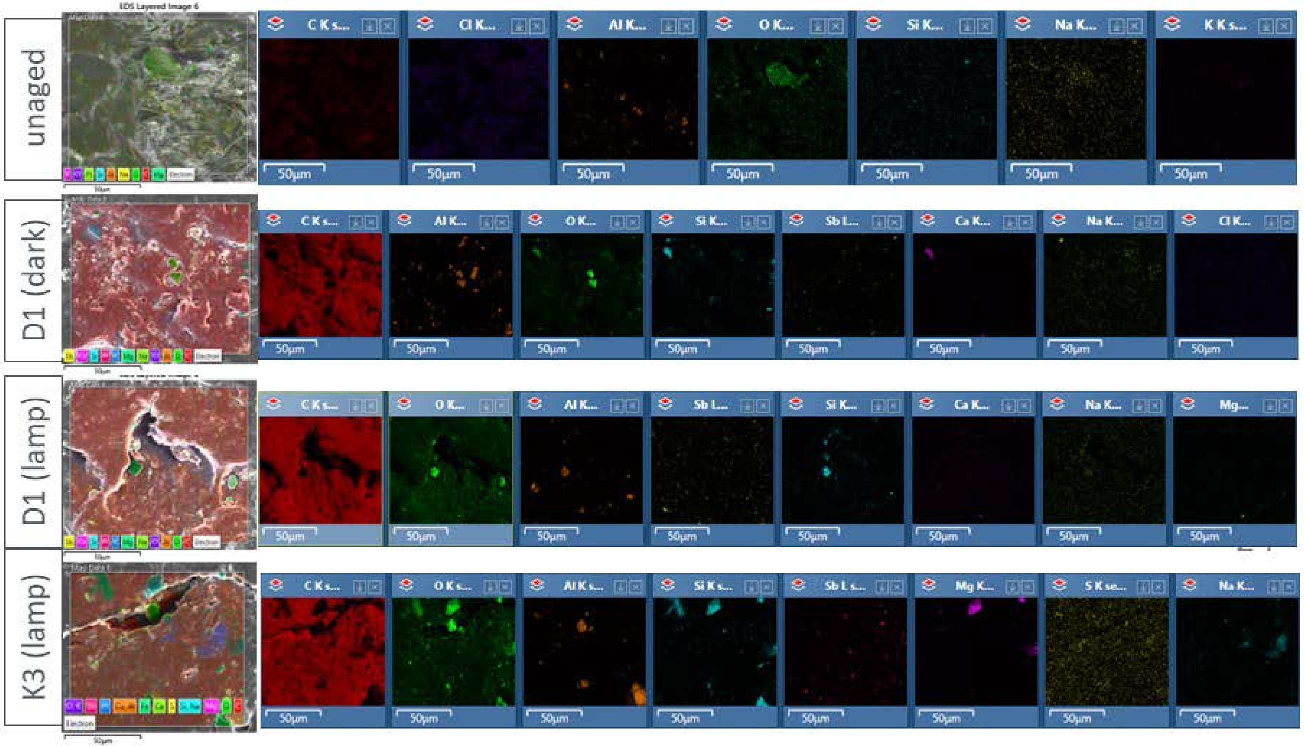
Right:
least concentration



Composition (EDS) of D1 and K3 C-AST Specimens

M2212-8001 (NEC, XLPE): Quantitative Composition

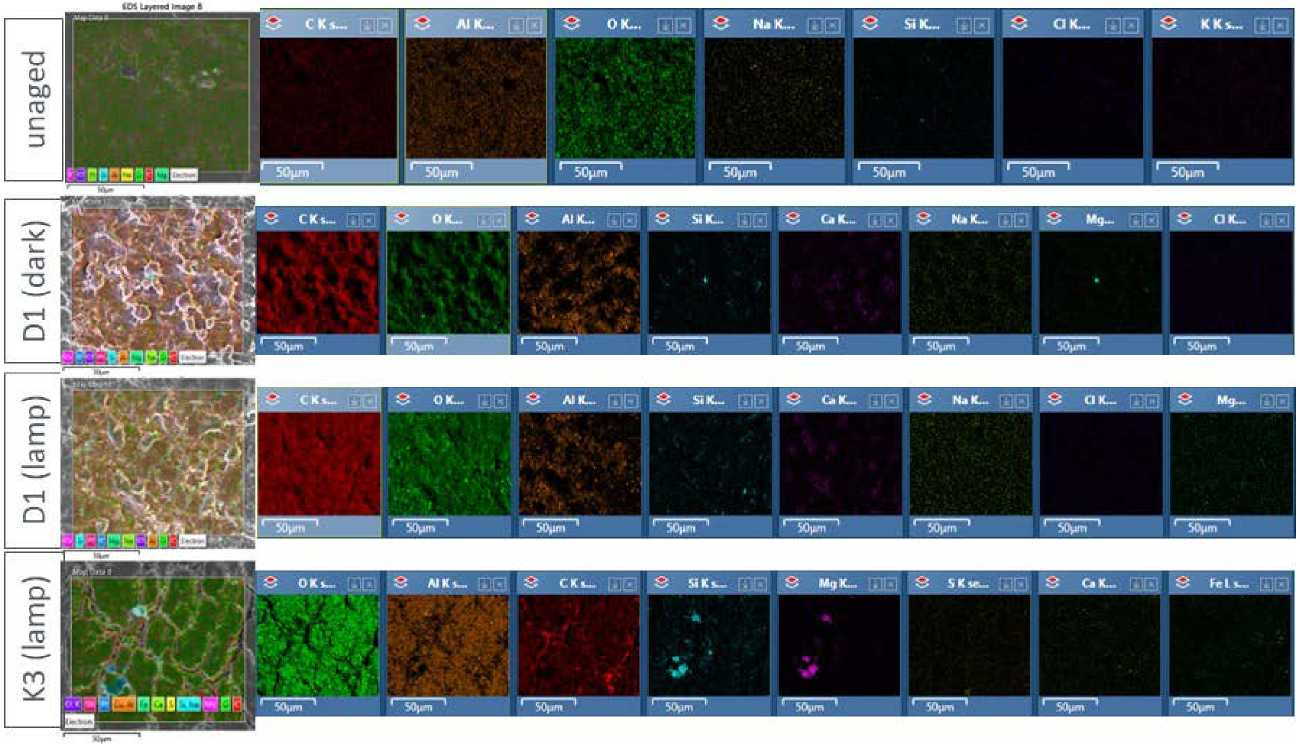
- Unaged: fibrous surface texture.
- Al, Si observed (including composition clusters) in addition to C, O.



Composition (EDS) of D1 and K3 C-AST Specimens

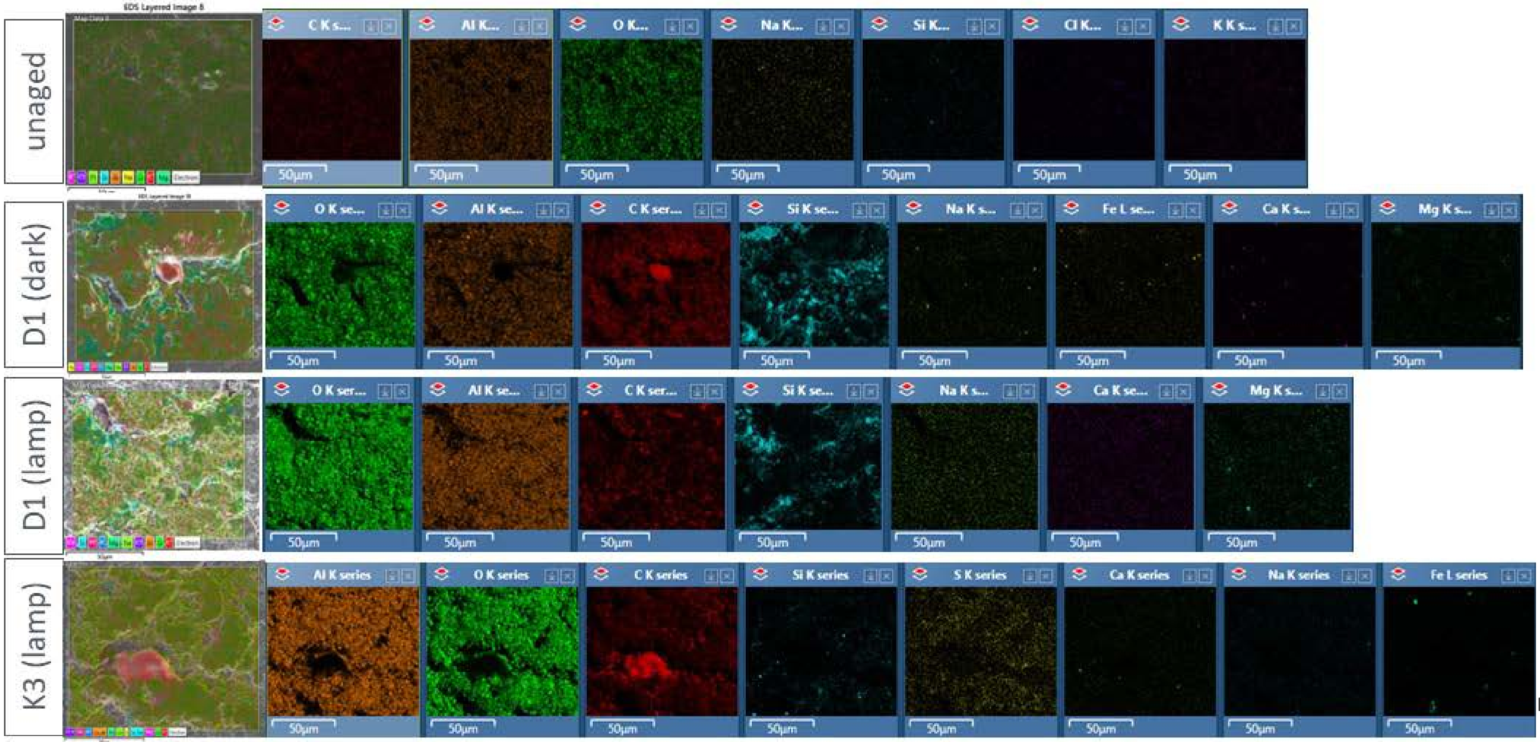
M2212-8002 (IEC, XLPO/XLPO): Quantitative Composition

- Al observed in addition to C, O.
- Trace elements: Si, Na, Mg.



Composition (EDS) of D1 and K3 C-AST Specimens

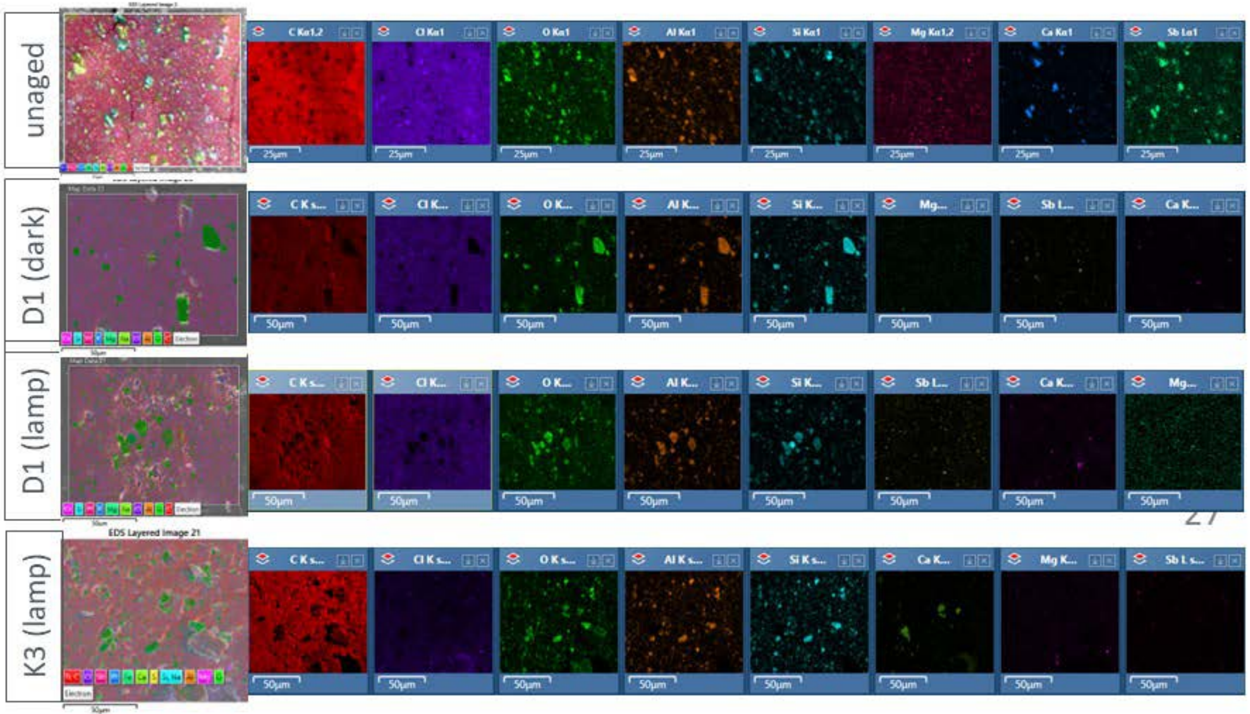
M2212-8003 (XLPO/XLPO): Quantitative Composition



Composition (EDS) of D1 and K3 C-AST Specimens

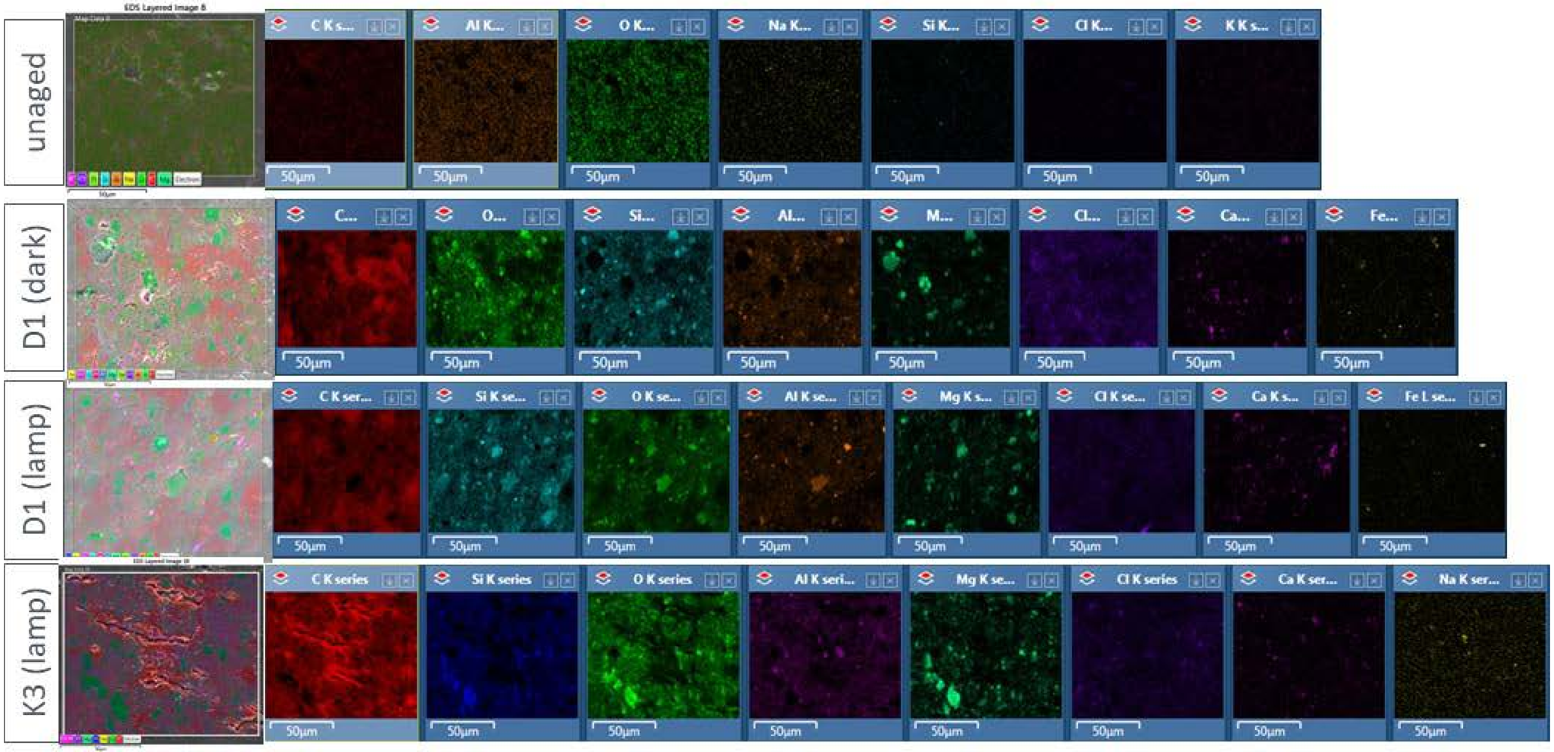
M2212-8004 (building, PA/PVC): Quantitative Composition

- Cl, Al, Si, observed (including composition clusters) in addition to C, O. Cl is part of PVC.
- Trace elements: K, Mg, Ca, Sb

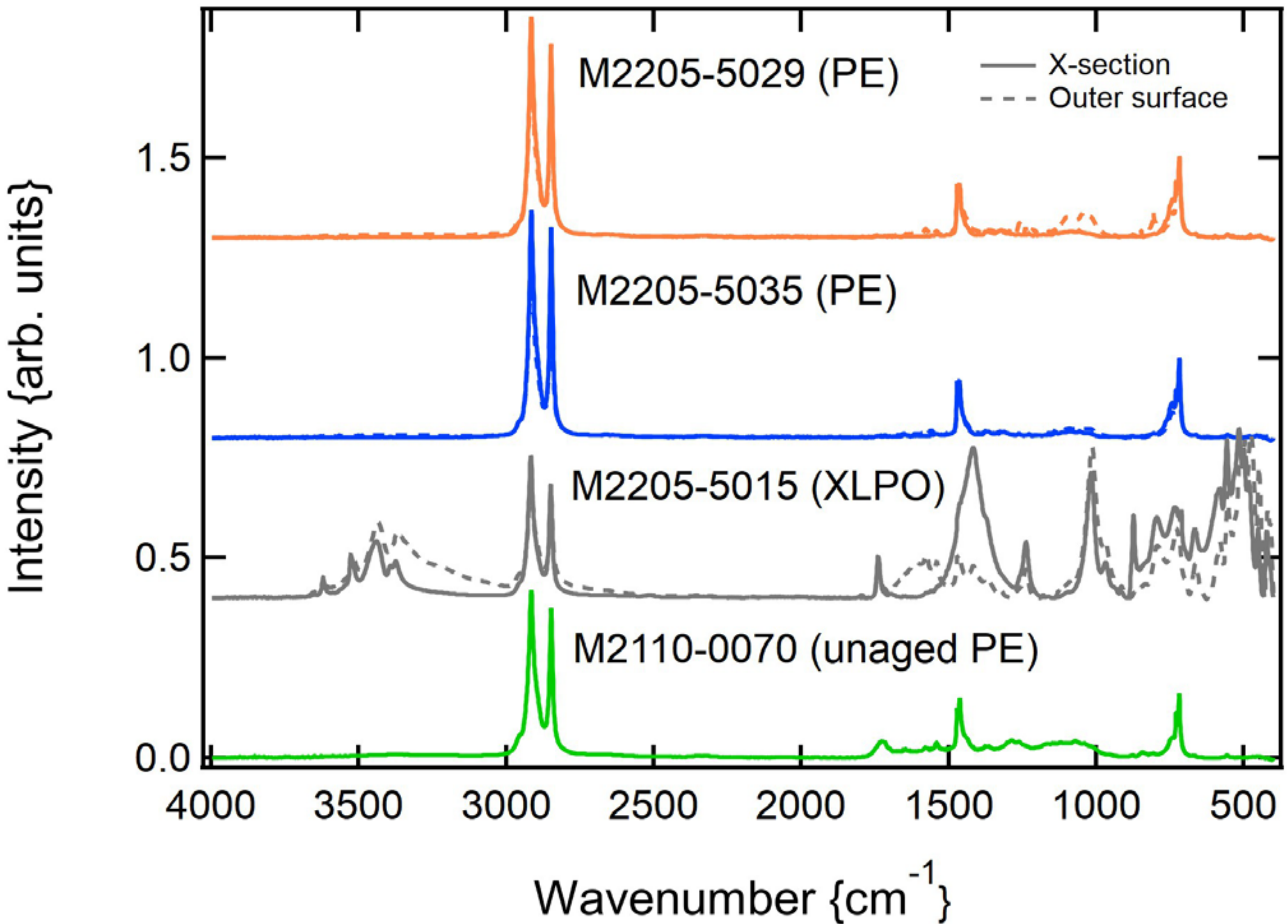


Composition (EDS) of D1 and K3 C-AST Specimens

M2212-8006 (CPE Outer): Quantitative Composition

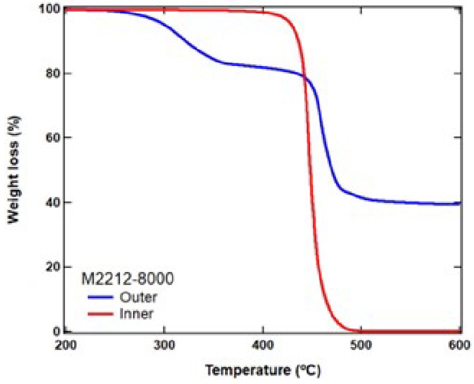


FTIR (Polymer Structure) of Oceanside and Reference Cables



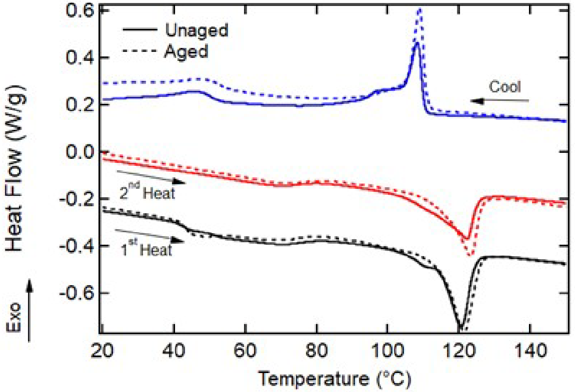
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

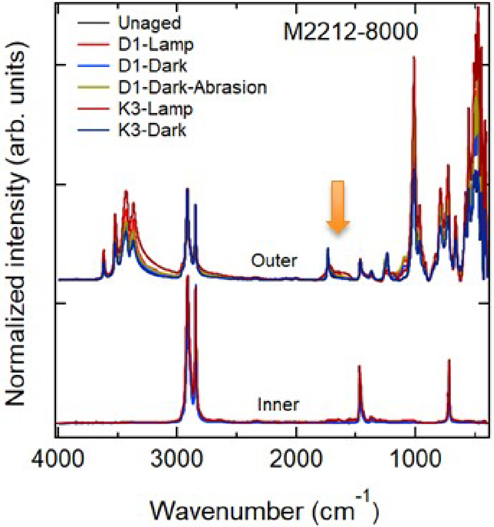
M2212-8000 (IEC, Black, XLPO/XLPO): Polymer Characterizations



TGA of unaged, inner and outer cable jacket: outer layer contains 40% of additives and fillers that don't decompose below 700°C.

DSC of unaged and D1-aged, outer cable jacket: Differences in crystallinity and melting behavior observed upon aging.

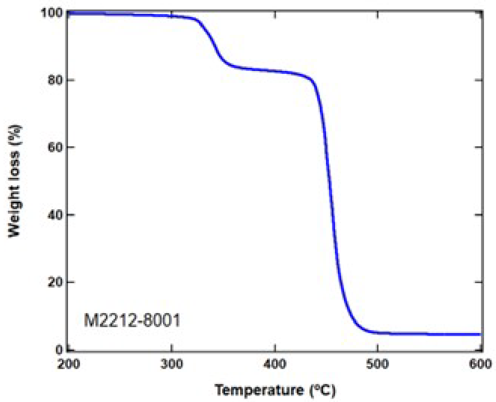




FTIR spectra of unaged and aged (D1 and K3) cable jackets: K3 has 2x greater UV dose –> greater UV photo-oxidation damage on lamp side; minor effect on inner jacket.

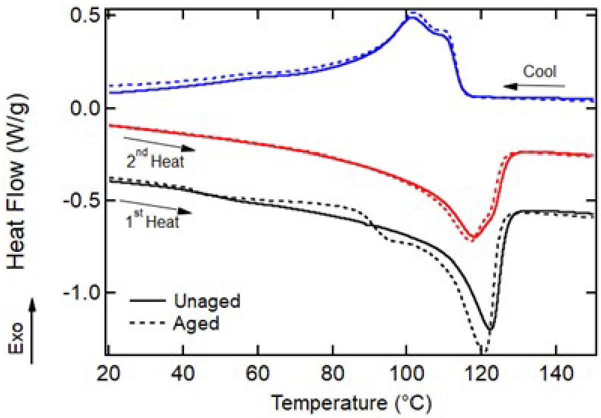
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

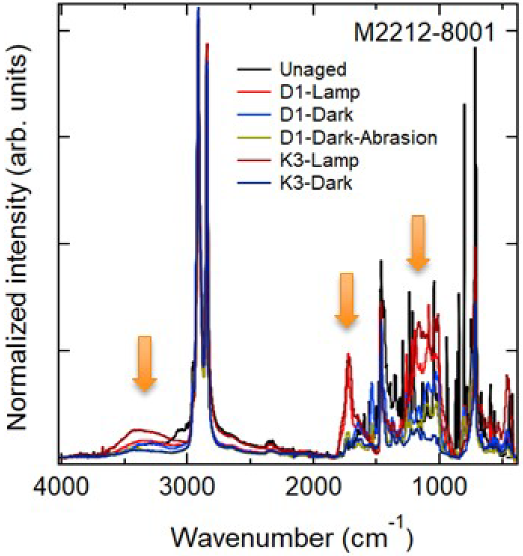
M2212-8001 (NEC, Gray, XLPE): Polymer Characterizations



TGA of unaged cable jacket:
Single type of cable jacket throughout its thickness, 95% of jacket formed of a copolymer.

DSC of unaged and D1-aged cable jacket:
Based on transition temperatures, 75% is formed of semi-crystalline HDPE; minor crystallinity changes upon aging.

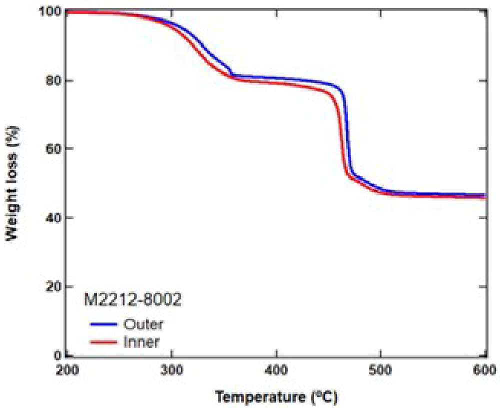




FTIR spectra of unaged and aged (D1 and K3) cable jackets:
1800 cm^{-1} – 400 cm^{-1} region mainly attributed to additives; UV photo-oxidation on the lamp side.

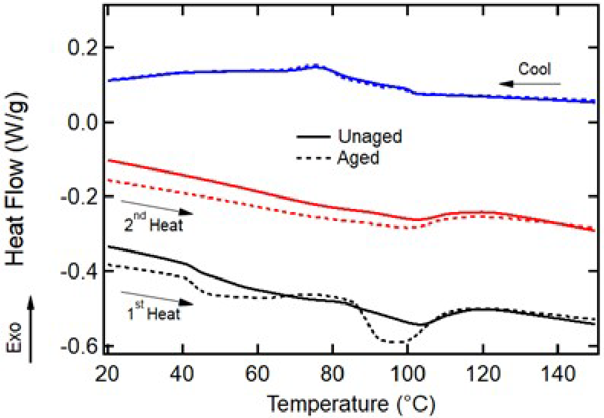
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

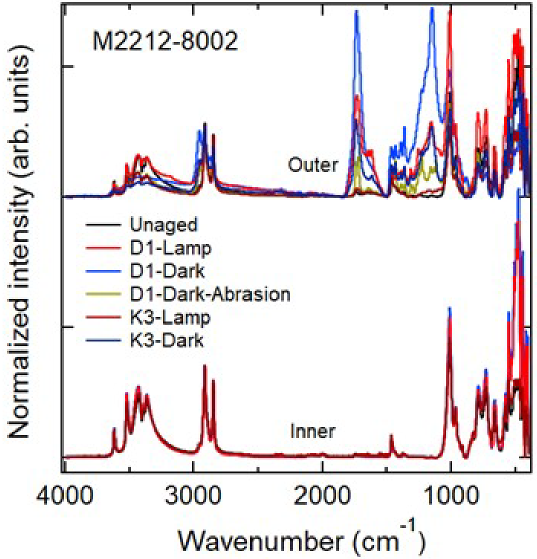
M2212-8002 (IEC, Black, XLPO/LDPE): Polymer Characterizations



TGA of unaged cable jacket: Inner and outer cable jackets have different colors, but contain same copolymers with likely different additive formulation.

DSC of unaged and D1-aged cable jacket: ~30% of jacket formed of LDPE – small crystallization peak at ~100°C.

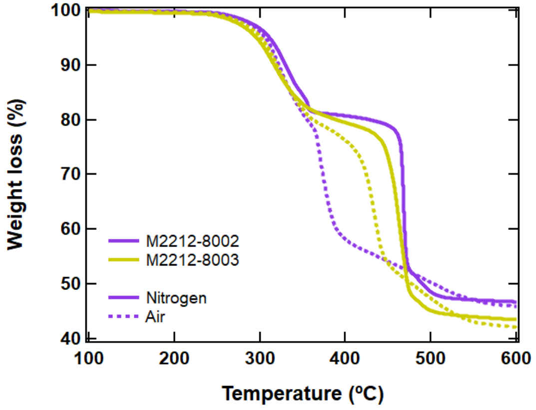


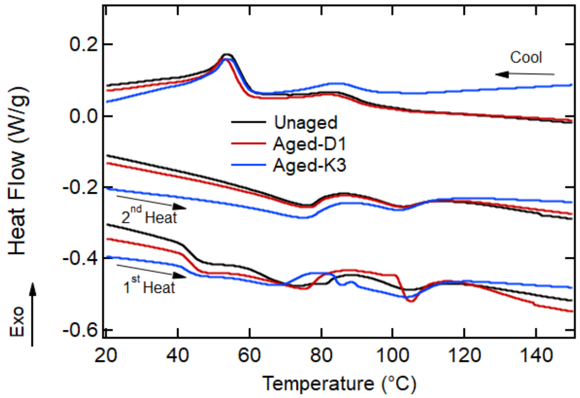


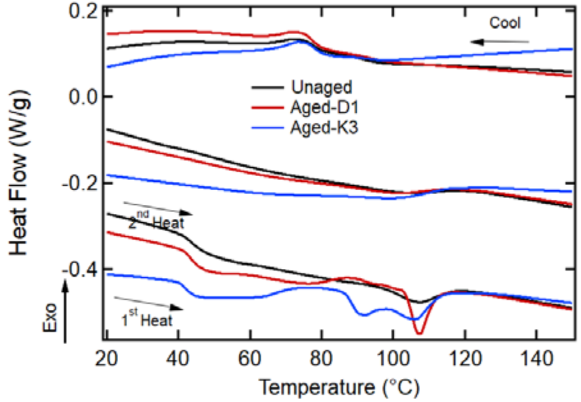
FTIR spectra of unaged and aged (D1 and K3) cable jackets: surface degradation of the outer jacket on both lamp and dark side – to be further understood.

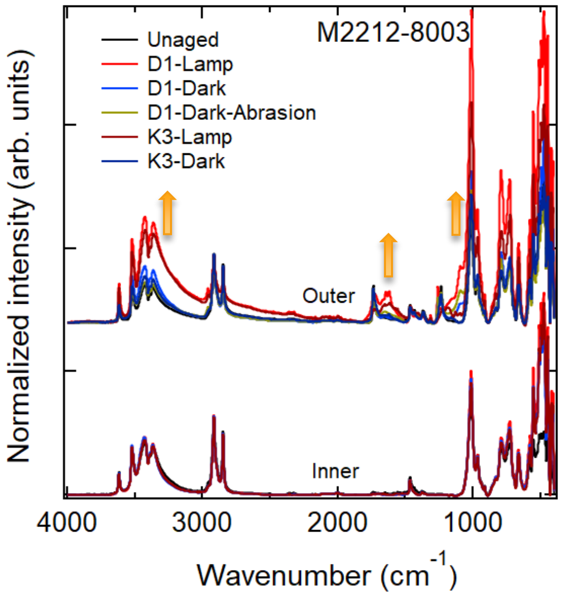
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

M2212-8003 (IEC, Black, XLPO/XLPO): Polymer Characterizations





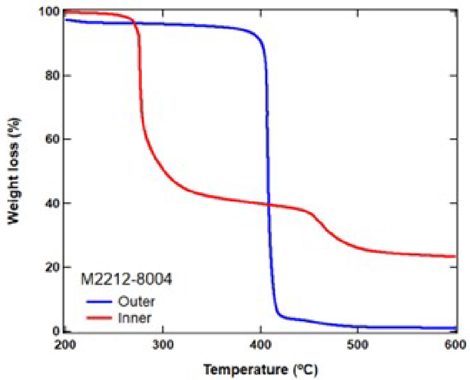




TGA comparing outer jackets of -8002 and -8003 having same copolymers, but different flame inhibitors

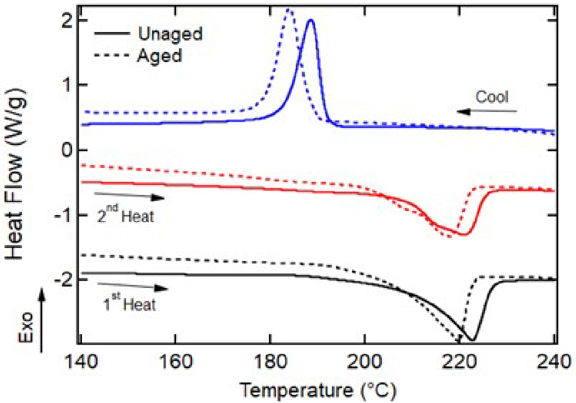
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

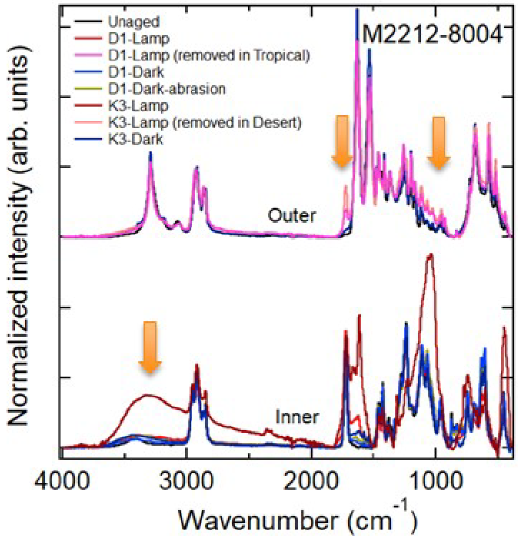
M2212-8004 (Building, Red, PA/PVC): Polymer Characterizations



TGA of unaged cable jacket:
PVC inner and polyamide (PA) outer materials identified; PVC contains >20% of additives and plasticizers.

DSC of unaged and D1-aged outer cable jacket:
PA outer layer irreversibly increases in crystallinity and brittleness, crack and peels off in bent areas exposing PVC to the lamp and chamber stresses. Presently assessing uniformity.



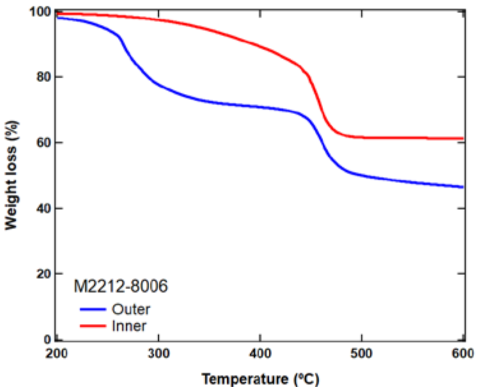


FTIR spectra of unaged and aged (D1 and K3) cable jackets:
Outer PA cracked, peeled off and was collected throughout the test (Tropical, Desert steps); exposed PVC degraded under UV.

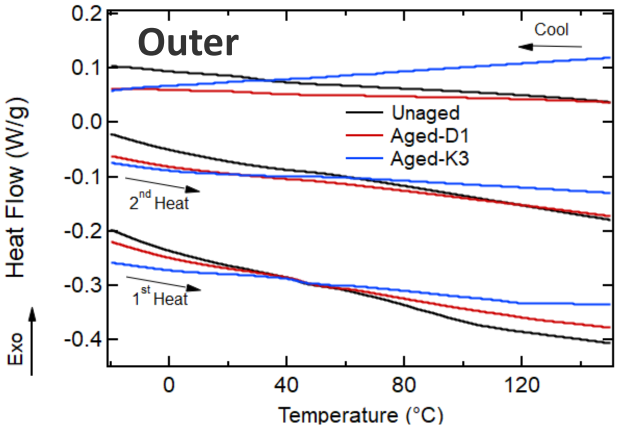
Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

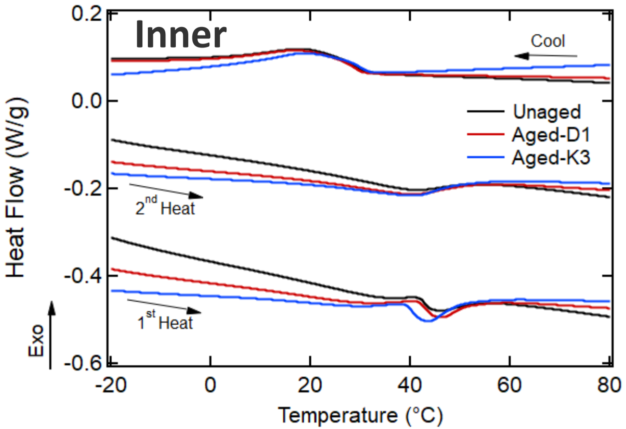
M2212-8006 (Multi-conductor, Black, CPE/EPDM): Polymer Characterizations

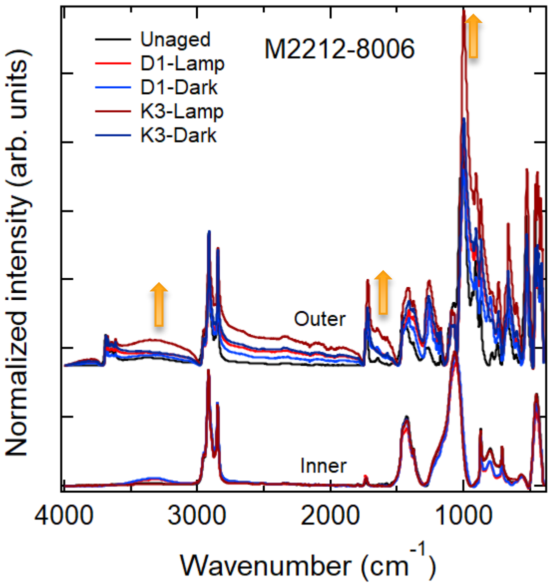
TGA of unaged cable jacket: up to ~60% of inorganic additives and fillers



DSC: mostly amorphous polymers



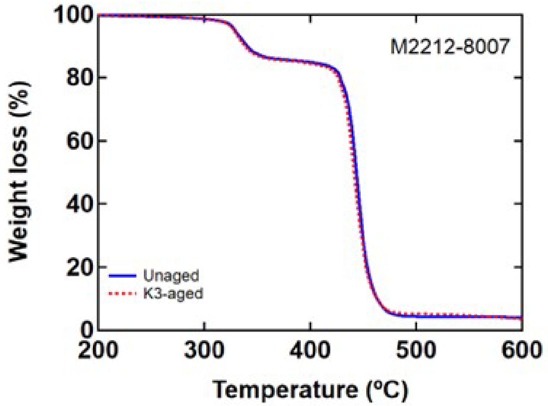




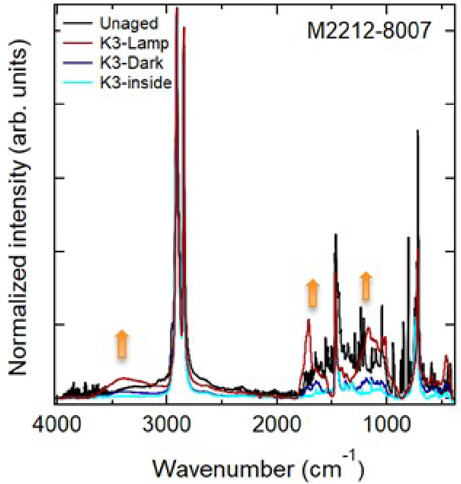
FTIR: Greatest changes with K3 on lamp side exposing more Si; inner cables unaffected

Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

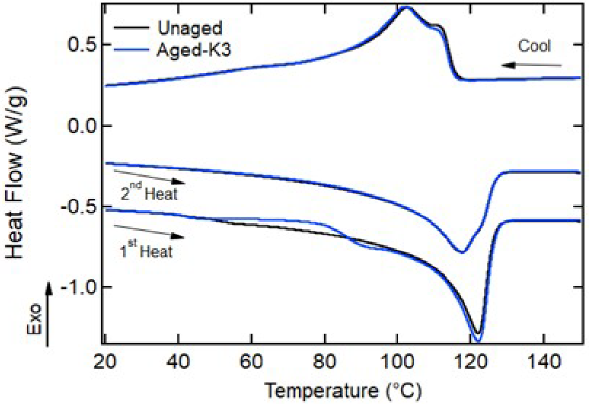
M2212-8007 (NEC, Red, XLPE): Polymer Characterizations



- Single-layer red PV cable jacket from *chemically* cross-linked polyethylene (XLPE) with melting temperature range between 60-130°C (DSC).



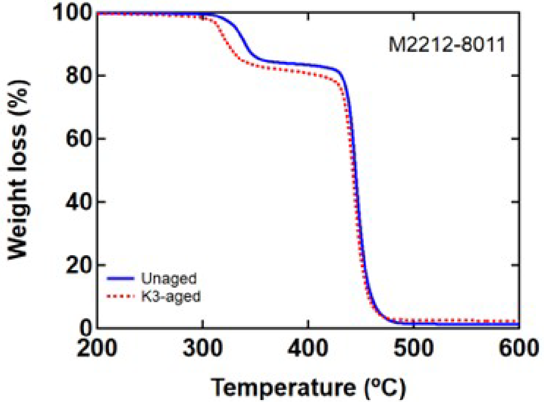
- The jacket is formed of ~80% of polyethylene, but contains copolymers starting to decompose at ~320°C (TGA).



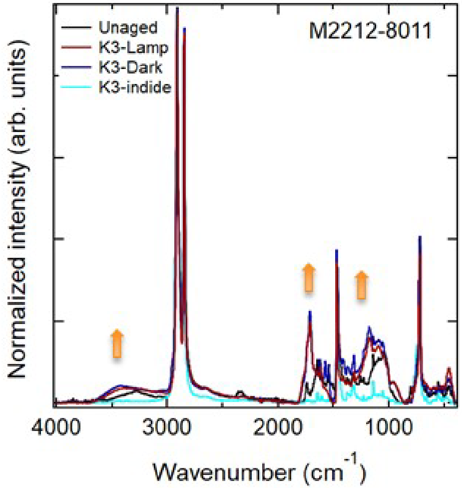
- Numerous sharp FTIR peaks in the unaged spectra are from the chalky treatment of the surface.
- Aging removes the chalky layer and on the lamp side, peaks corresponding to UV photo-oxidation increase.

Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

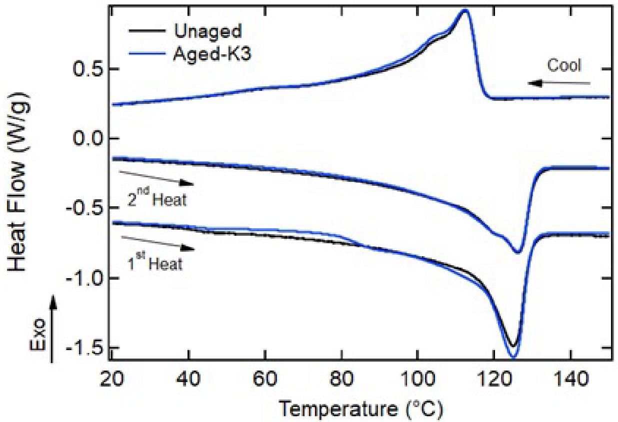
M2212-8011 (NEC, Red, XLPE): Polymer Characterizations



- Single-layer red PV cable jacket from chemically cross-linked polyethylene (XLPE), similar to -8007 without the chalky surface appearance (FTIR).



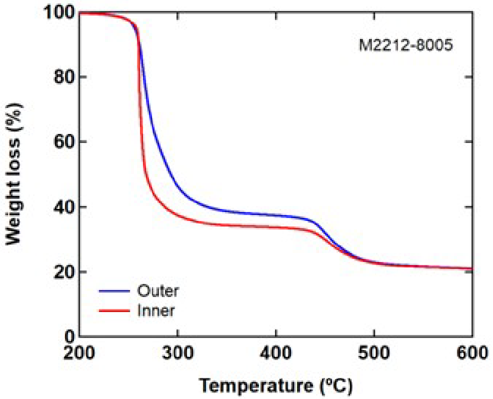
- Changes upon aging observed in the thermal decomposition profiles (TGA) and minor changes in crystallinity (DSC).

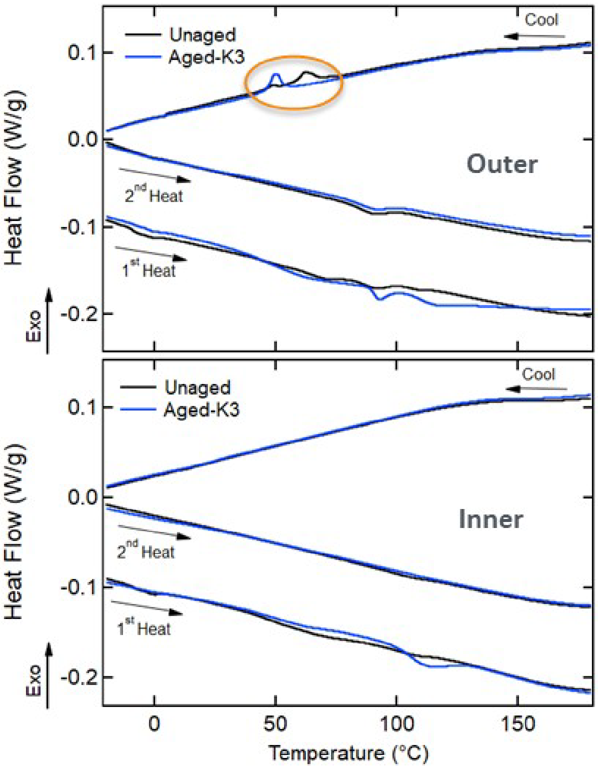


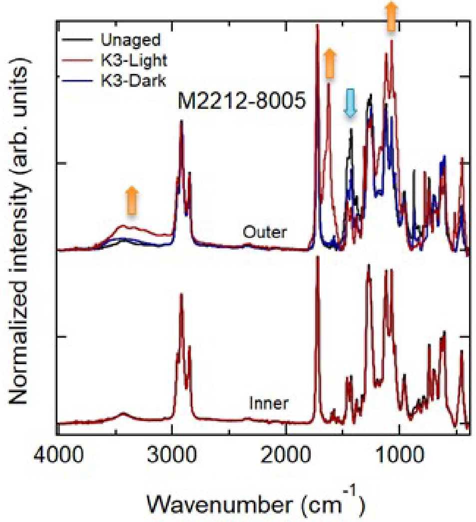
- Increase in oxygen-containing spectral bands suggest surface damage (FTIR) -> to be verified if damage is equal on lamp and dark side.

Characteristics (FTIR, DSC, TGA) of D1 and K3 C-AST Specimens

M2212-8005 (Controller, Black, TPE): Polymer Characterizations







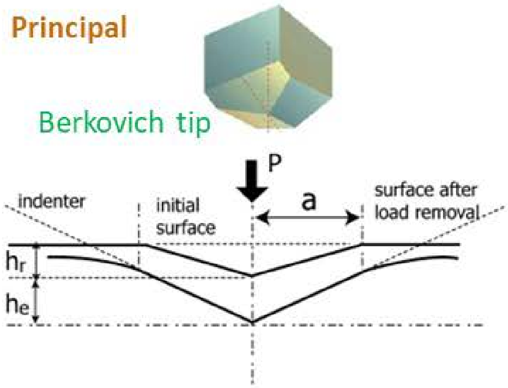
- Inner and outer jackets are formed of thermoplastic elastomer (TPE) forming 80% of the jacket and starting decomposing at ~250°C
- Outer jacket contains a small crystalline fraction, whereas inner one is mostly amorphous

- <u>FTIR spectra before and after K3 aging:</u> an increase in carbonyl (C=O), hydroxyl (-OH) and C-O bands observed on the lamp side from UV photo-oxidation; a reduction at 1500 cm^{-1} may result from degradation of surface additives

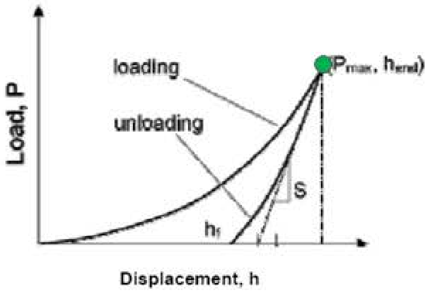
Mechanical Behavior (Instrumented Indentation) Methodology

Instrumented Indentation Measurement Methodology

Principal



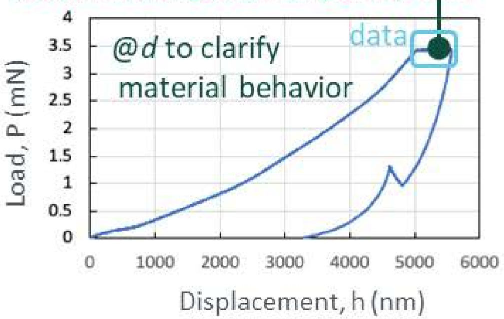
Traditional Indentation



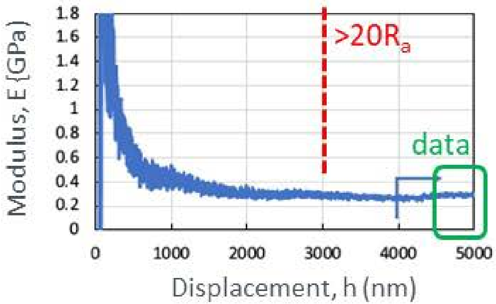
one data point (at unloading)

Typical Load-Depth

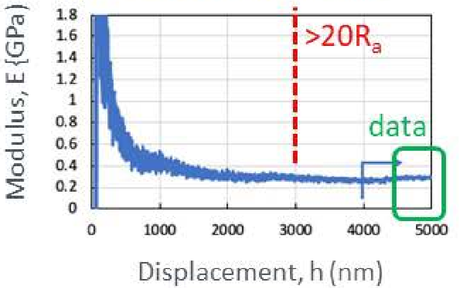
polymers: long stabilizing creep hold



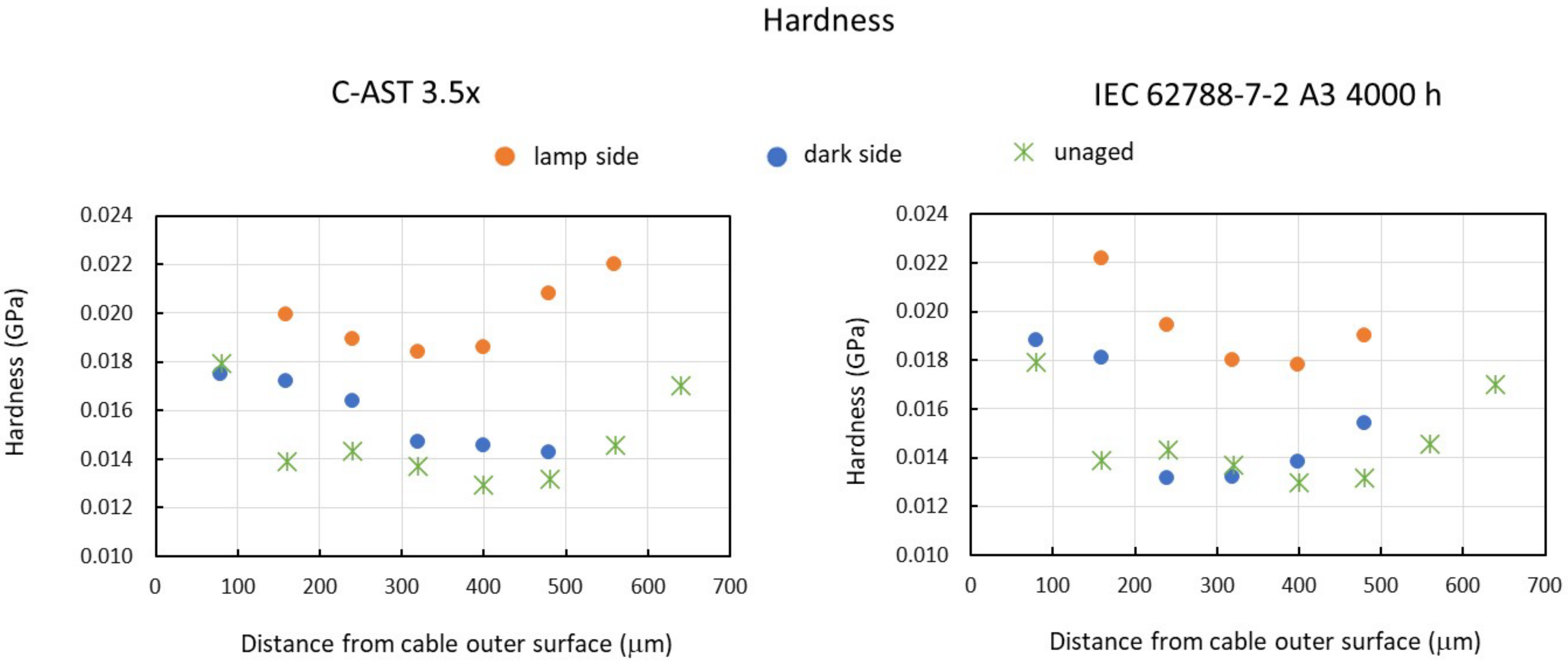
Modulus Measurement



Hardness Measurement

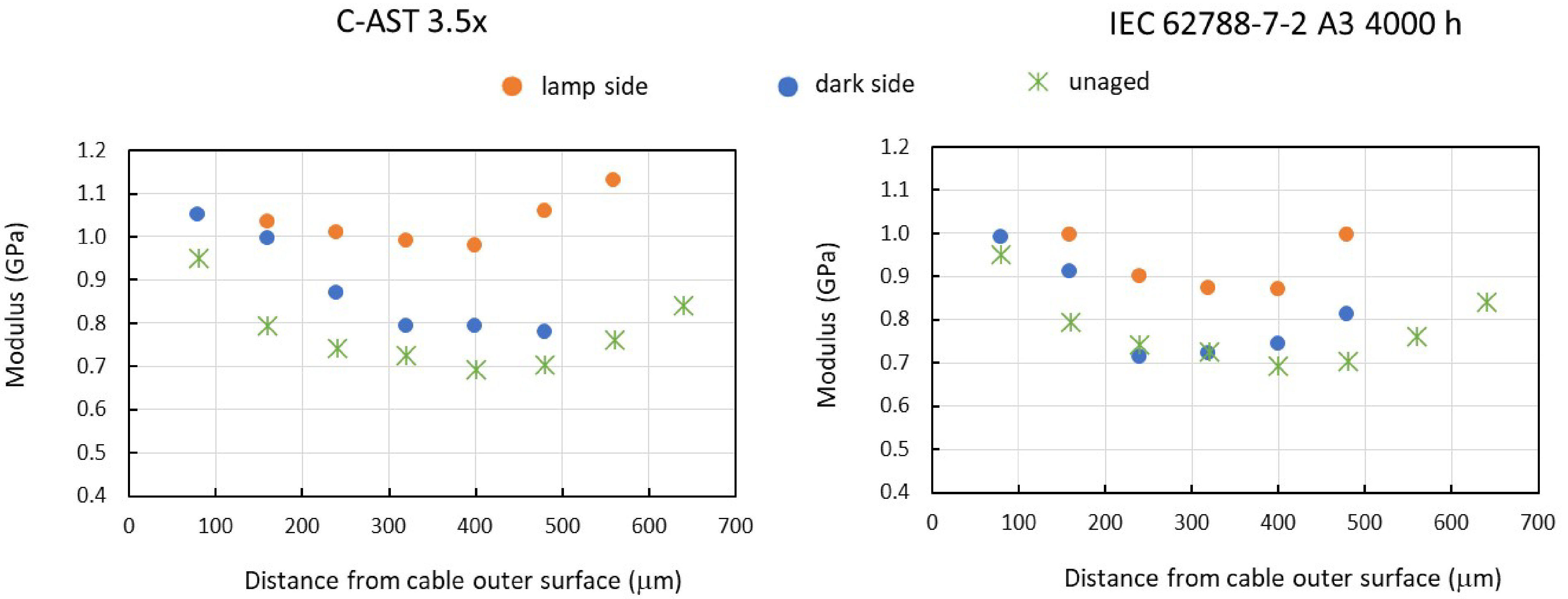


Mechanical Behavior (Indentation) of M2110-0058 (red, for PVC inner)

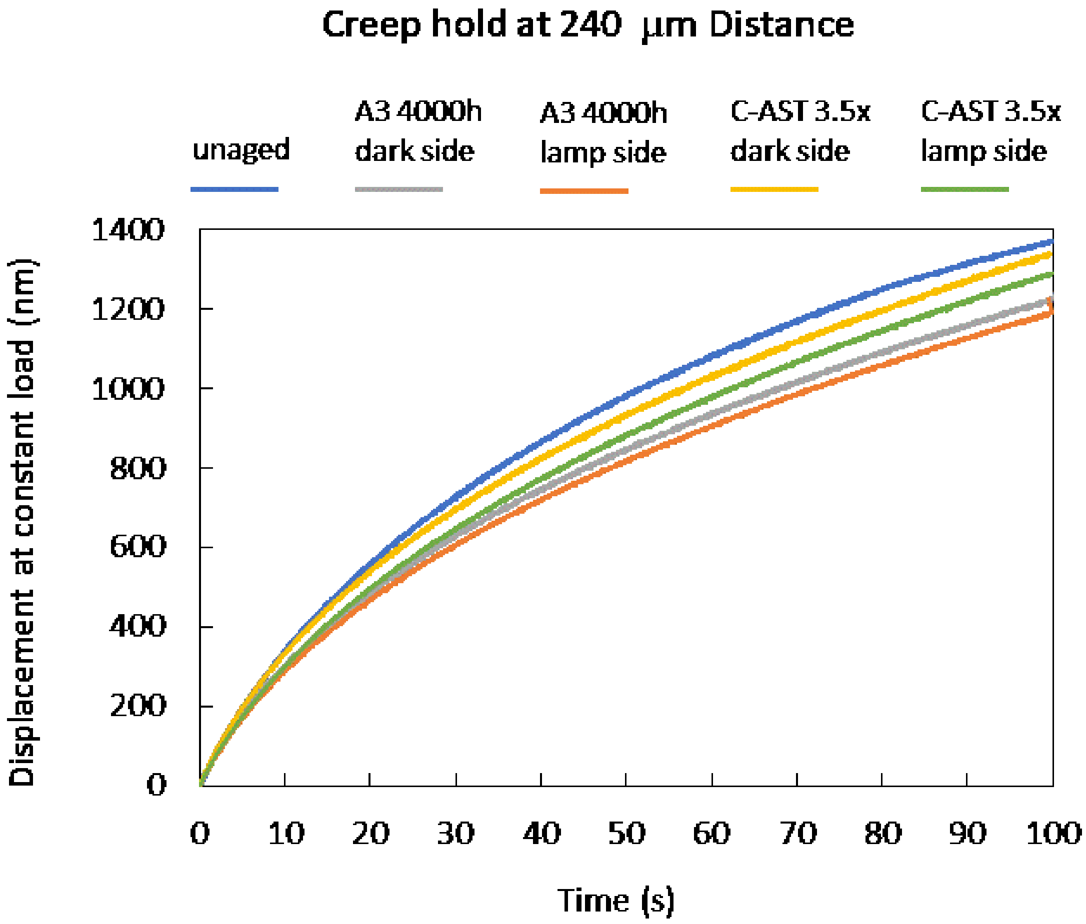


Mechanical Behavior (Indentation) of M2110-0058 (red, for PVC inner)

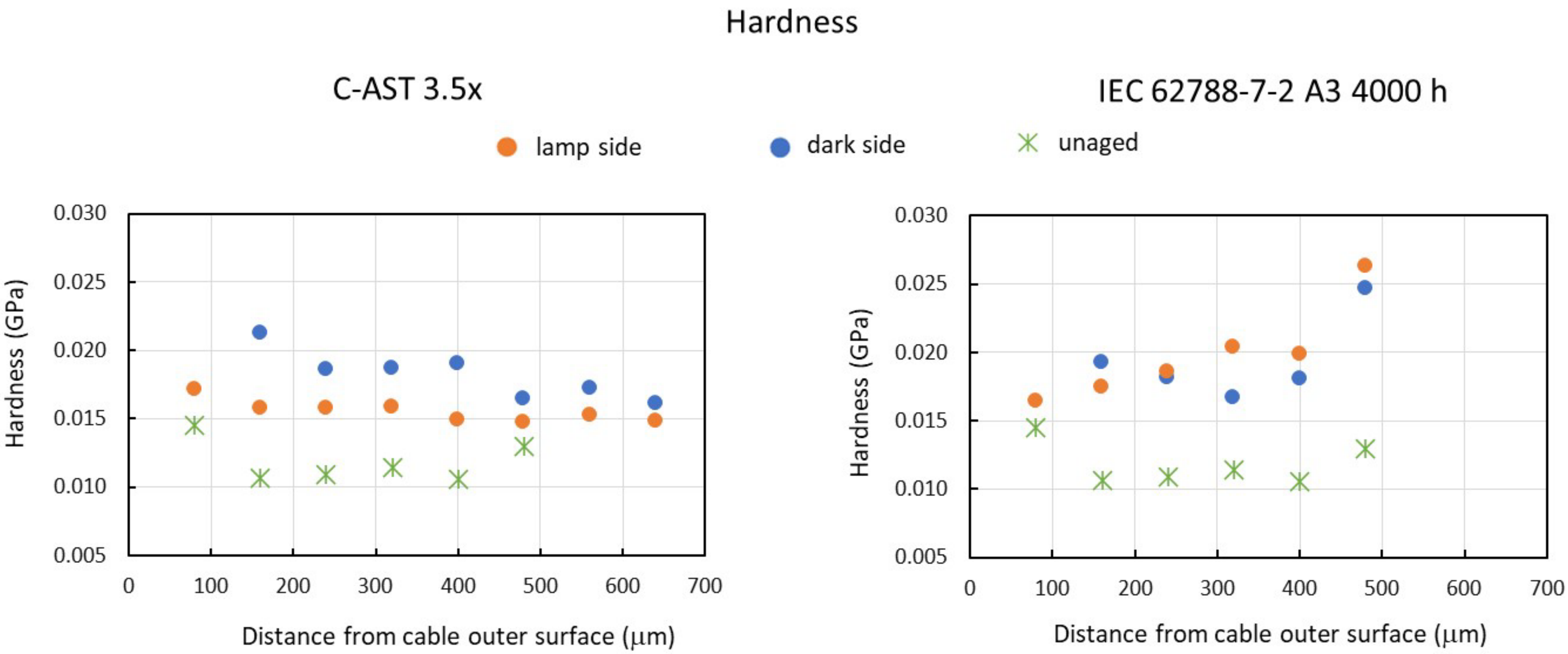
Modulus



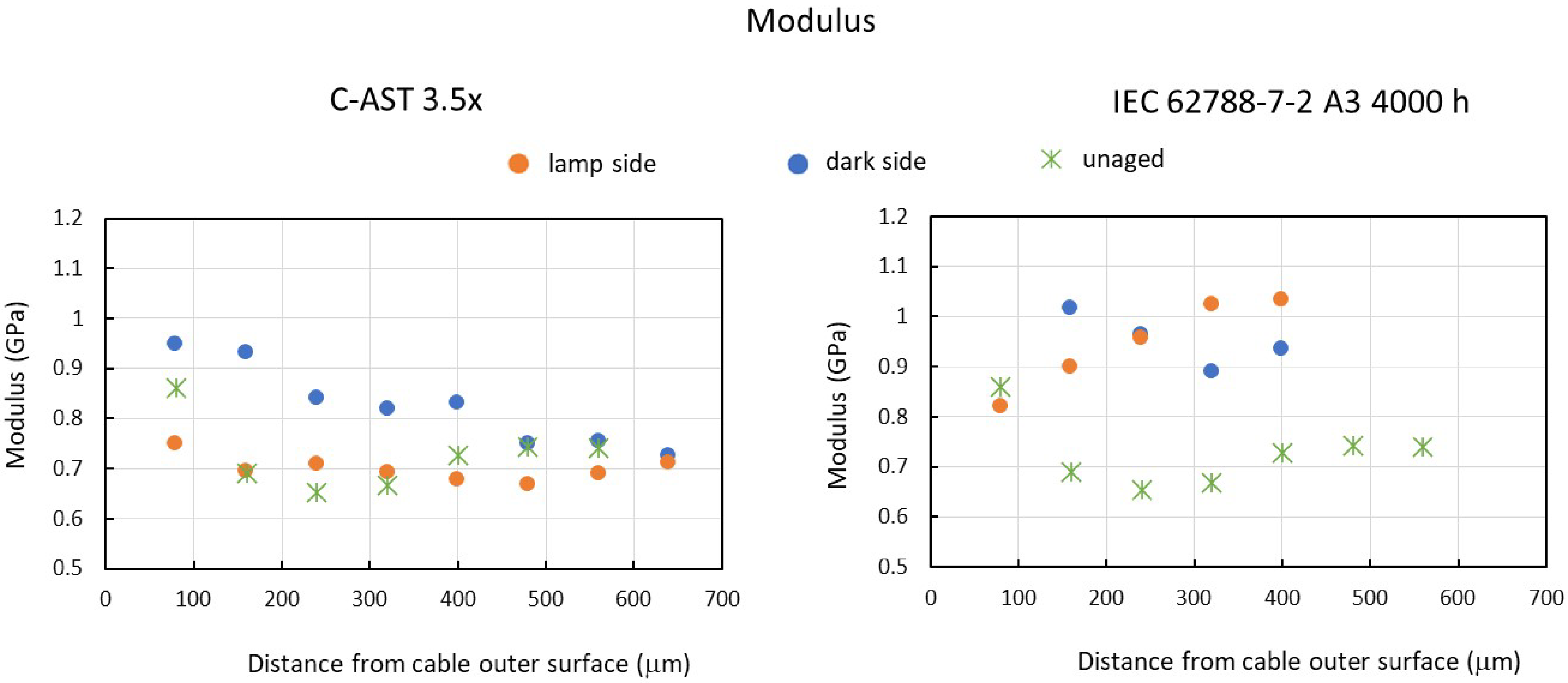
Mechanical Behavior (Indentation) of M2110-0058 (red, for PVC inner)



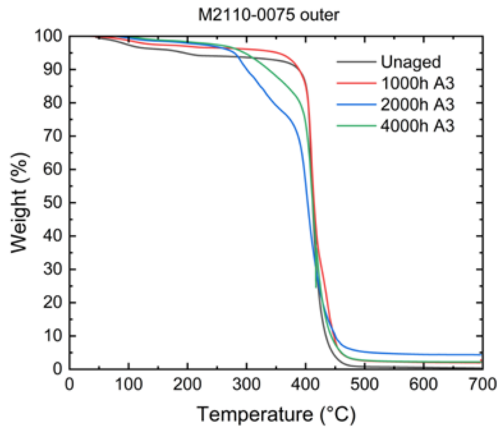
Mechanical Behavior (Indentation) of M2110-0075 (red, for PVC inner)

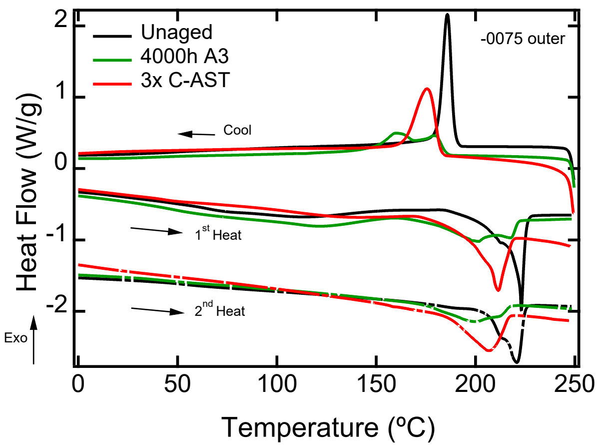


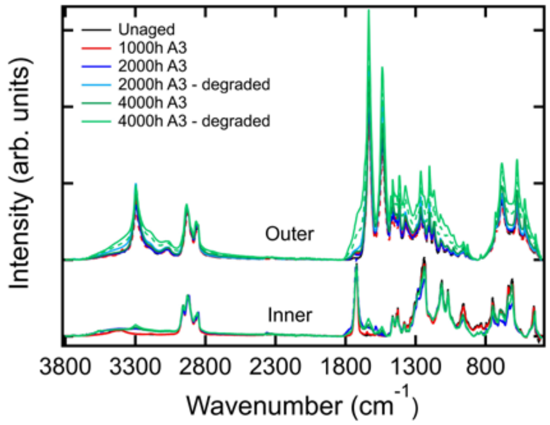
Mechanical Behavior (Indentation) of M2110-0075 (red, for PVC inner)

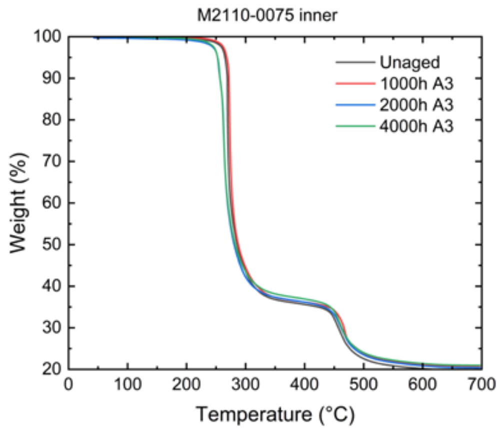


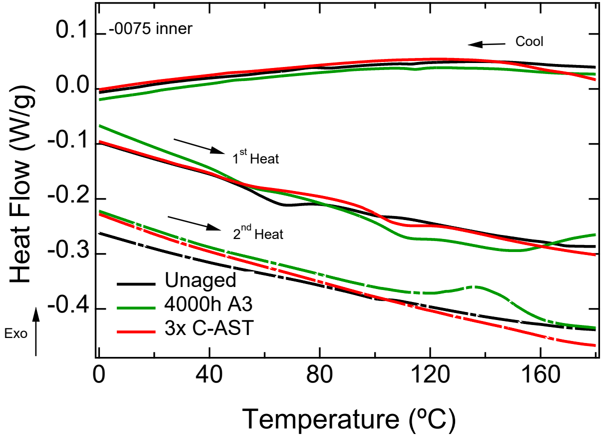
Characteristics (FTIR, DSC, TGA) of M2110-0075 (red, PA/PVC)



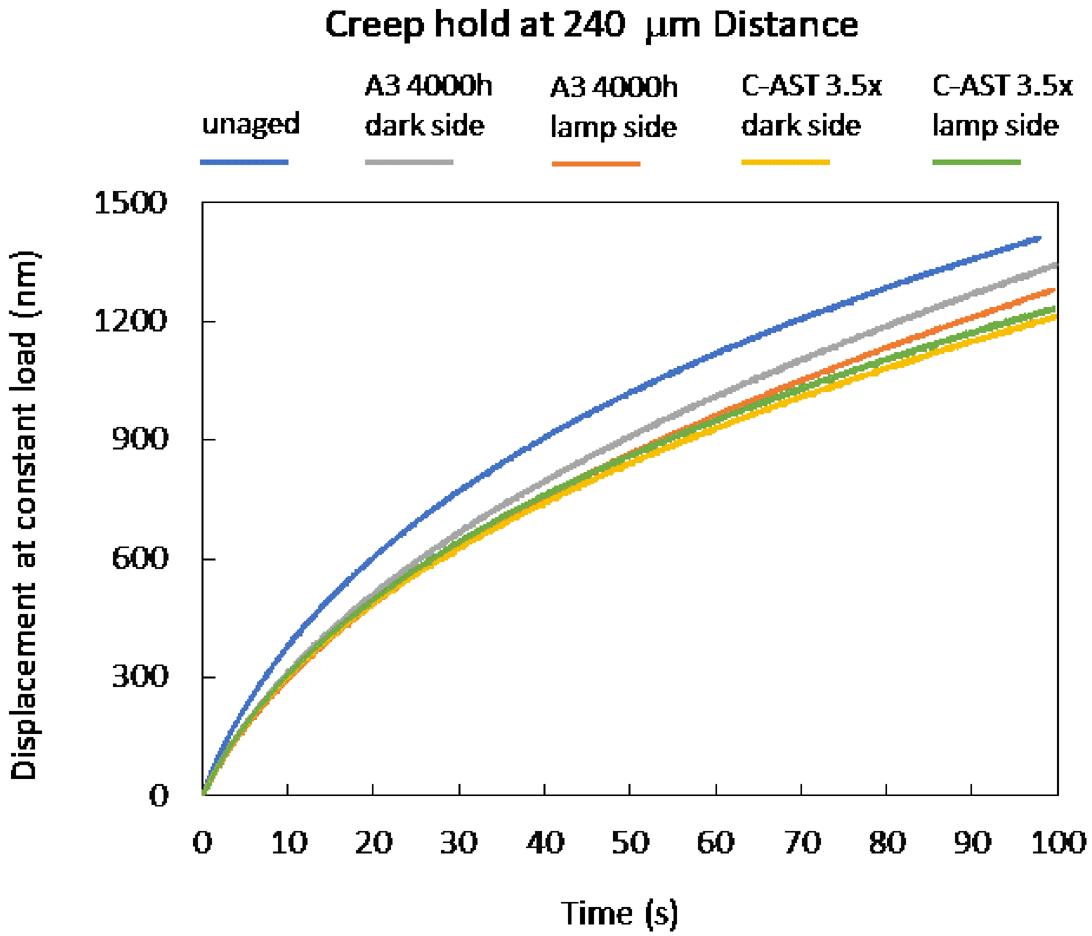




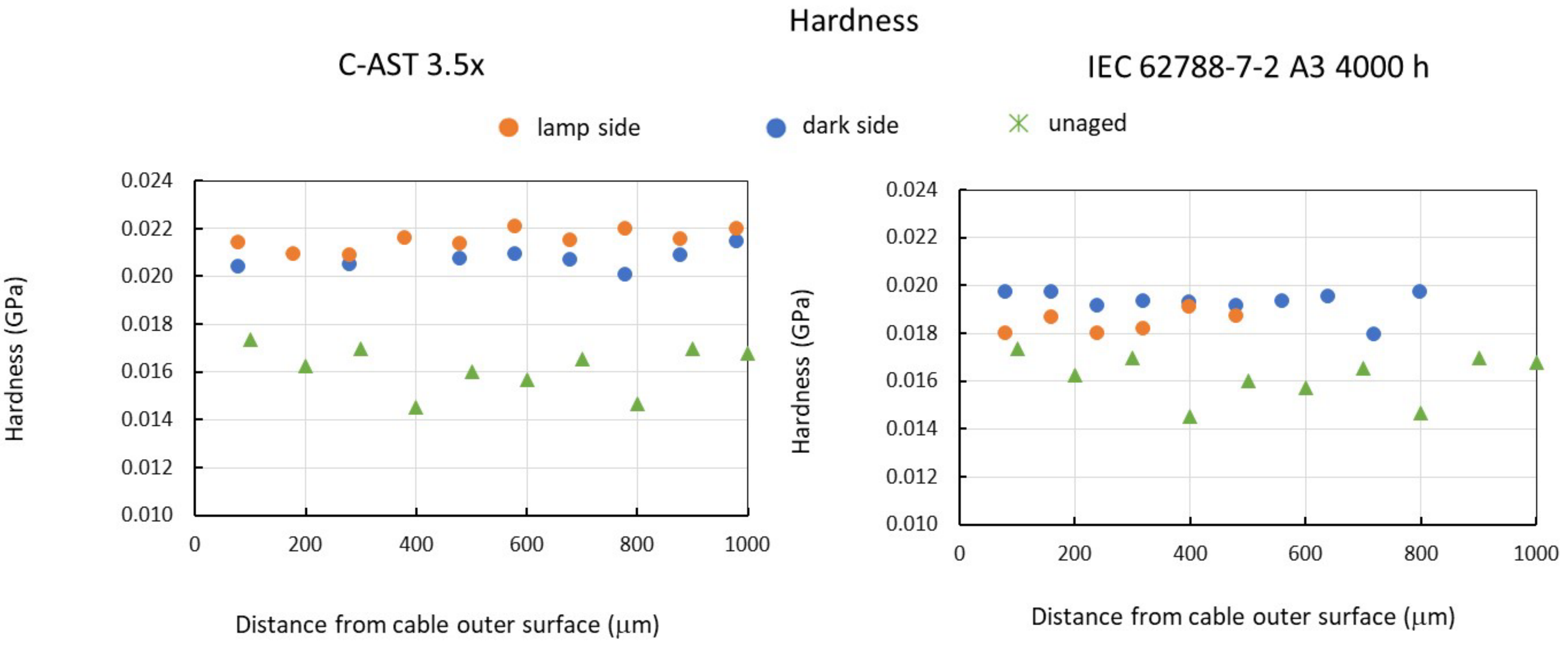




Mechanical Behavior (Indentation) of M2110-0075 (red, for PVC inner)

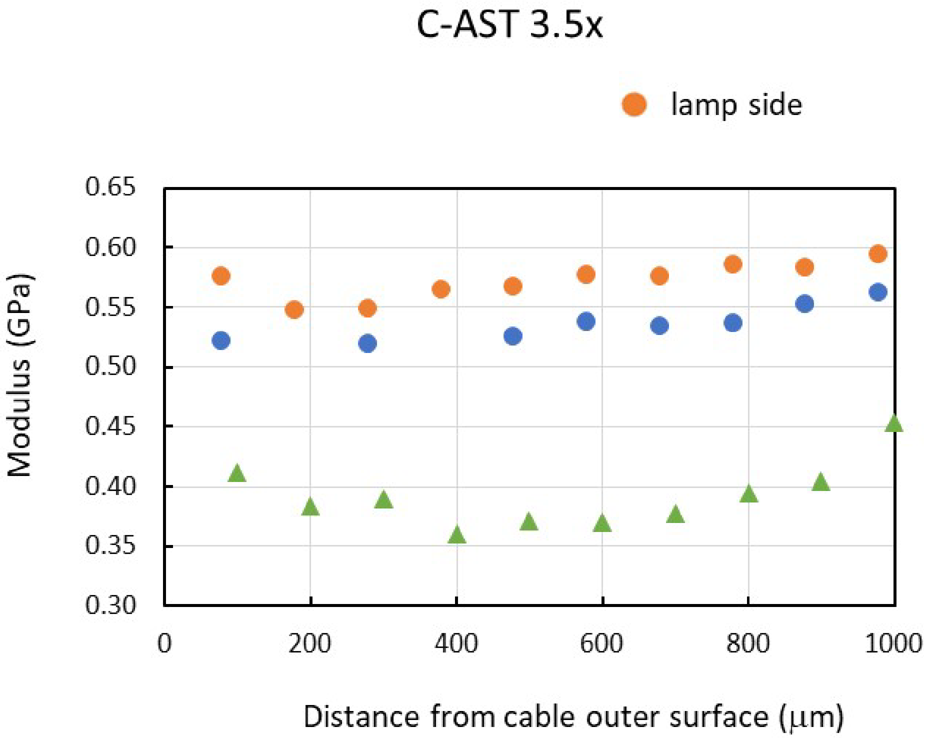


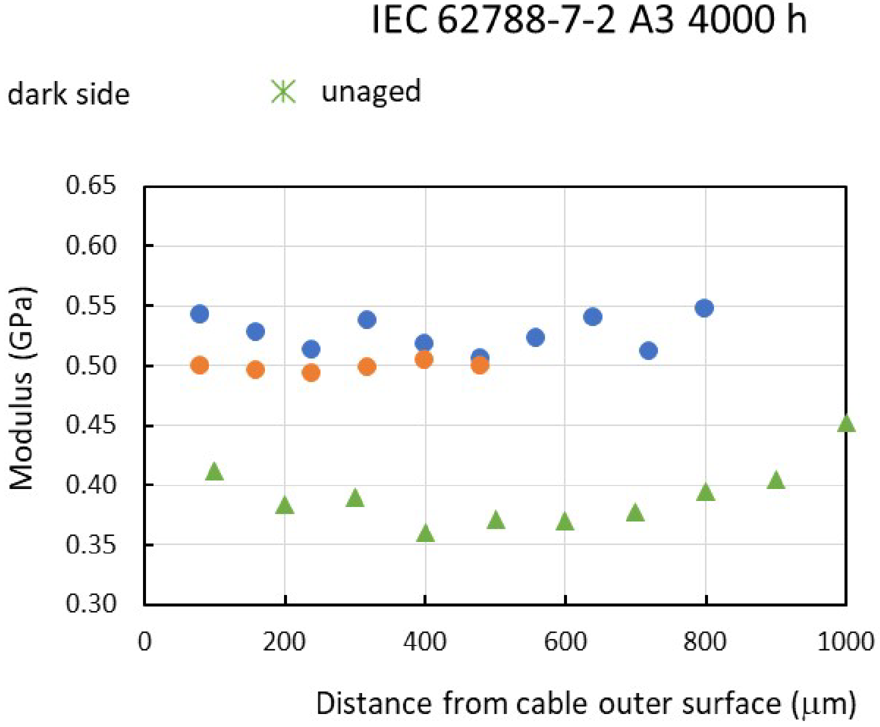
Mechanical Behavior (Indentation) of M2110-0070 (red, PE)



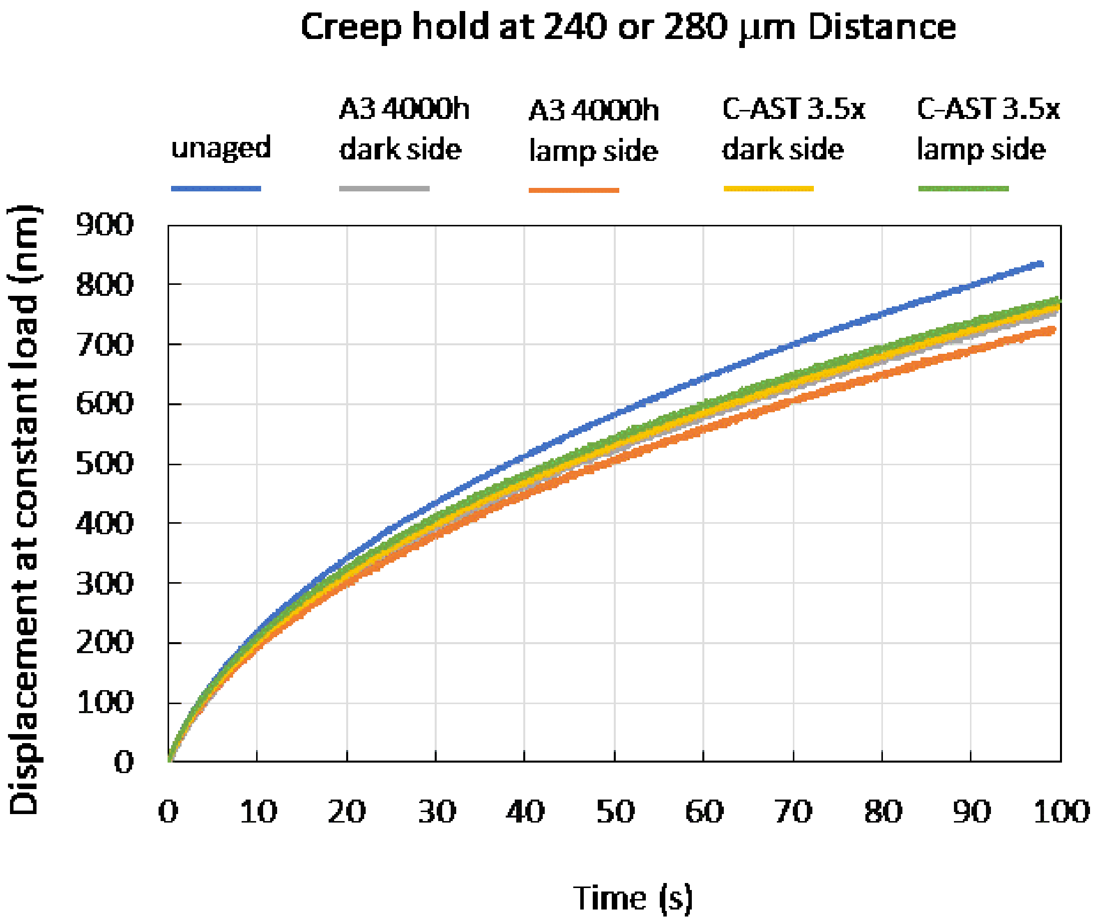
Mechanical Behavior (Indentation) of M2110-0070 (red, PE)

Modulus



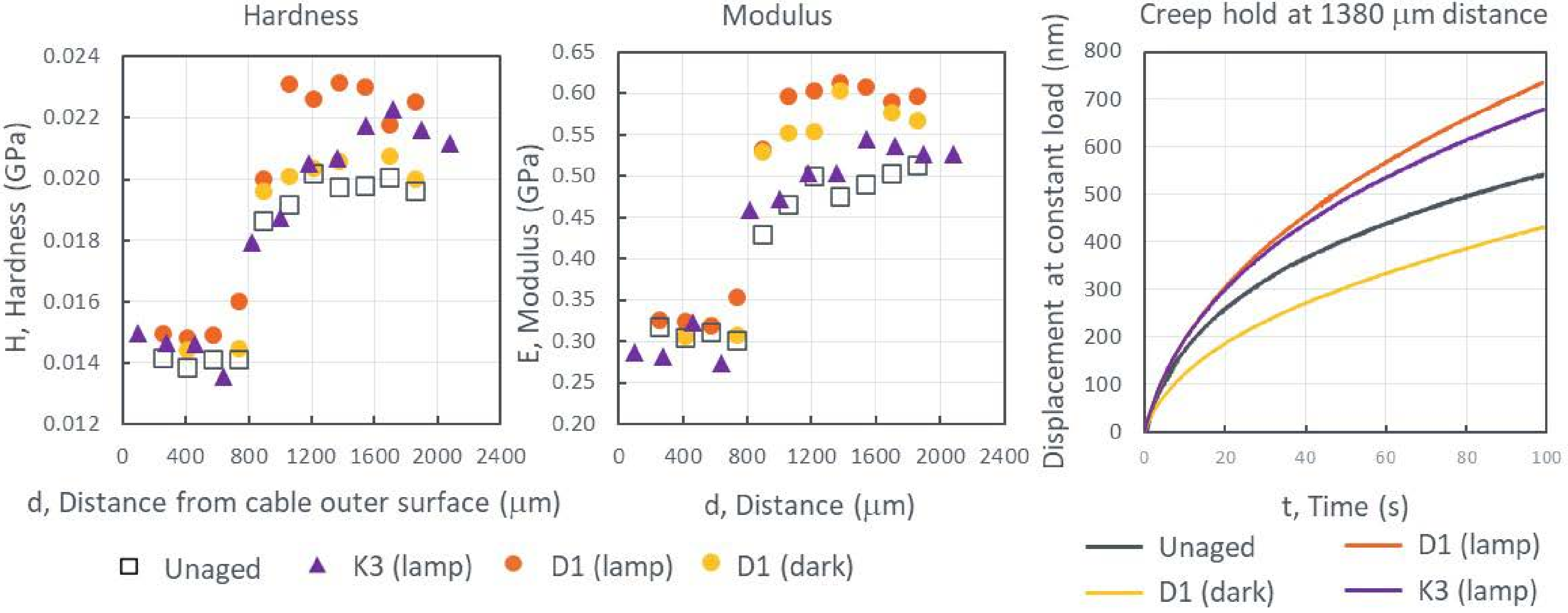


Mechanical Behavior (Indentation) of M2110-0070 (red, PE)



Mechanical Behavior (Indentation) of M2212-8000 Specimens

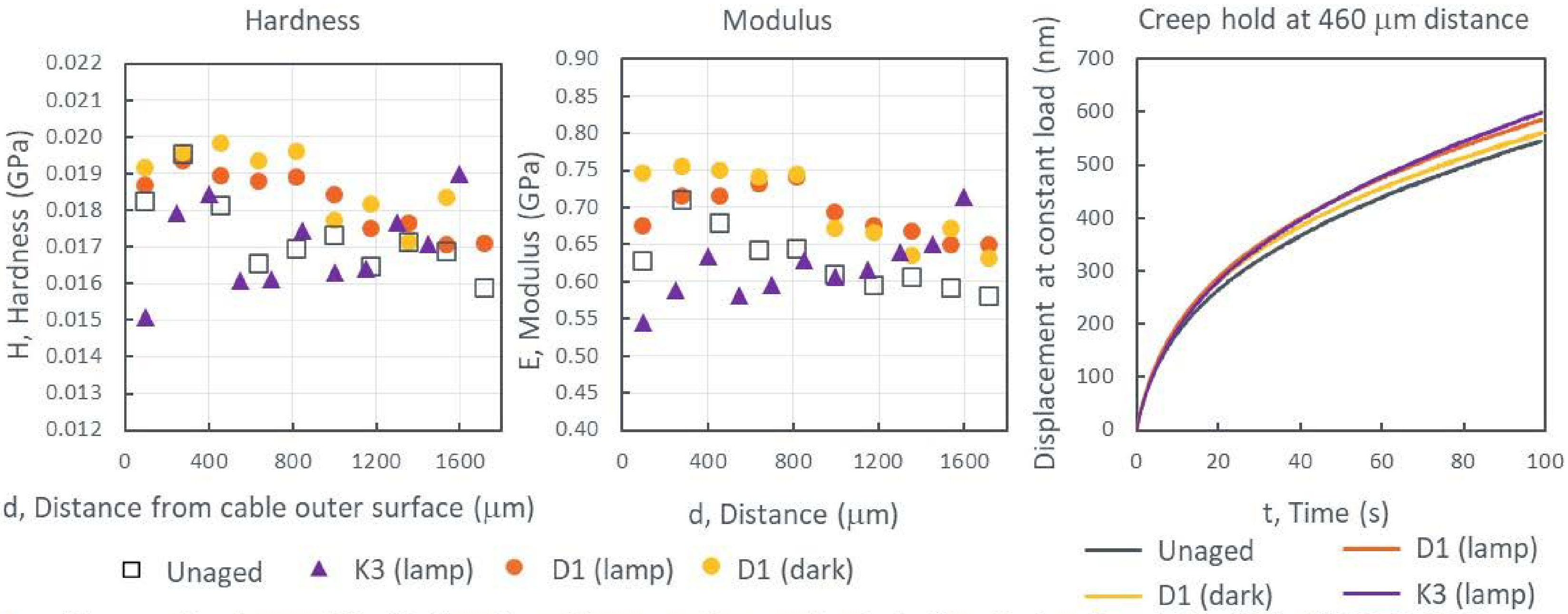
Instrumented Indentation of M2212-8000 (IEC, Black, XLPO outer/LDPE inner)



- Different jacket materials (outer, inner) identified for M2212-8000.
- Subtle distinction at best for PO's, PE's. Most distinguished for ocean side PEI location (chemical degradation).
- Macro cracks can transmit light; thermal degradation suspect for red M2110-0070 despite micro cracks.

Mechanical Behavior (Indentation) of M2212-8002 Specimens

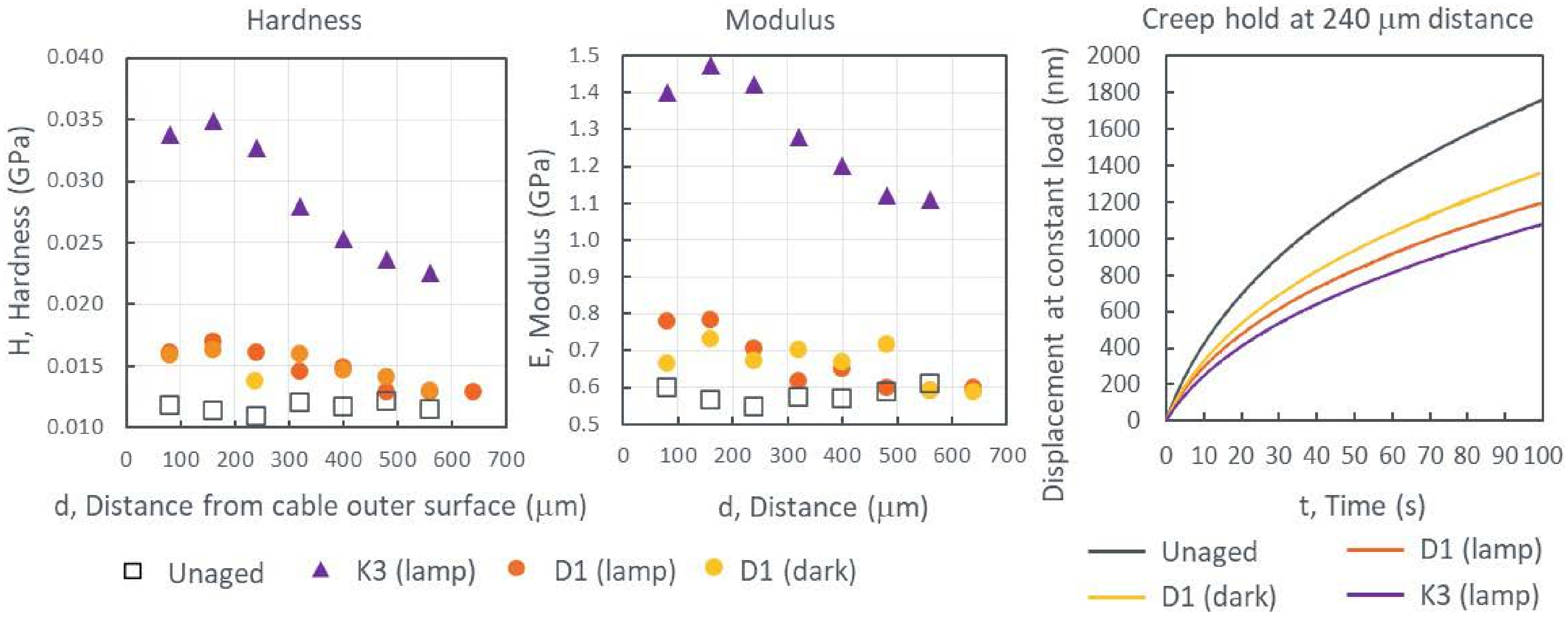
Instrumented Indentation of M2212-8002 (IEC, Black, XLPO outer/ XLPO inner)



- Microcracks observed for K3 (lamp) specimen; modest mechanical effect for irradiated side (UV) of M2212-8002.
- H (elastic & inelastic), E (elastic) shown to aid tribological analysis.
- Creep (inelastic) often best revealed aging in a logical rank order.
- Microcracks: limited UV transmittance at 460 μm. Possible warmer irradiated side.

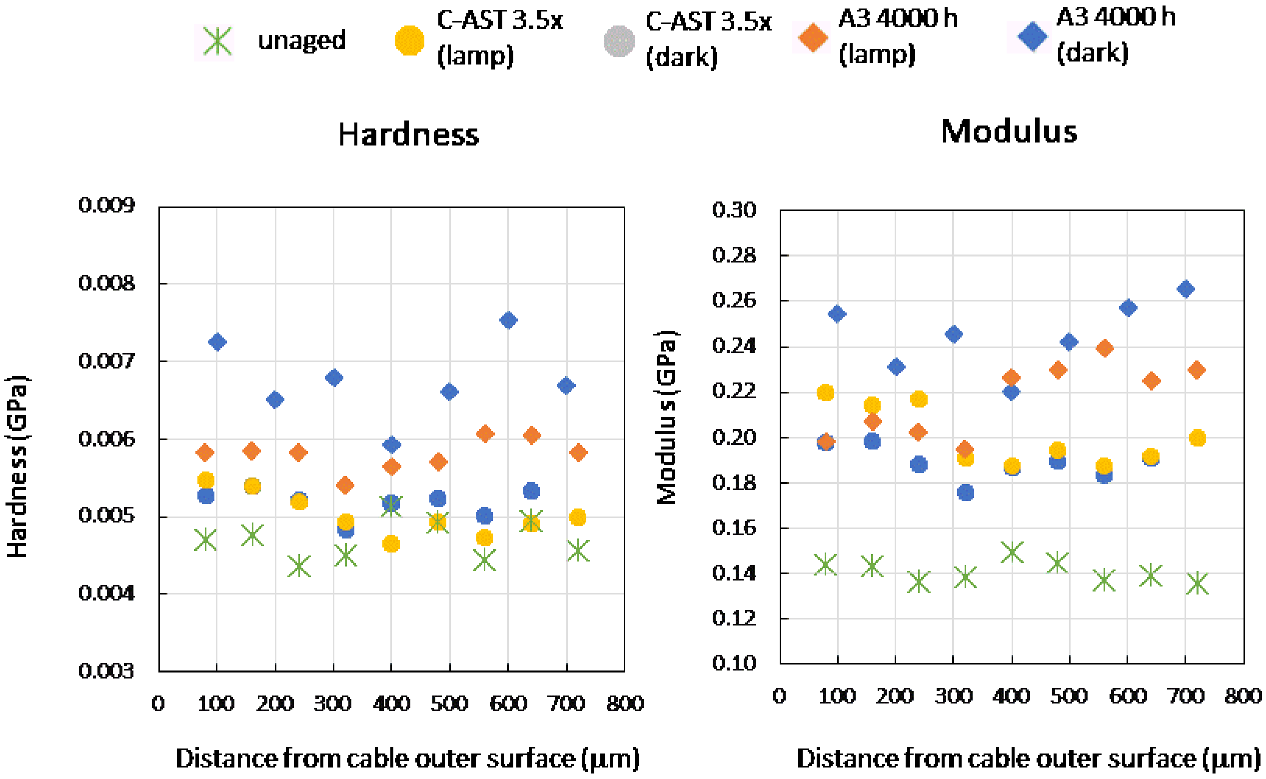
Mechanical Behavior (Indentation) of M2212-8004 Specimens

Instrumented Indentation of M2212-8004 (Building, Red, PVC inner)

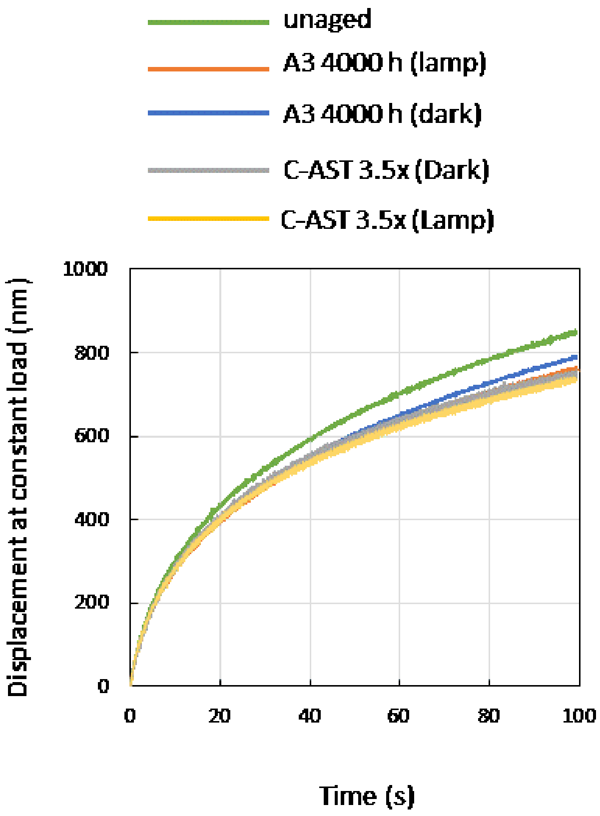


- Indentation previously readily distinguished PVC, including C-AST and IEC 62788-7-2 UV weathering.
- Photo degradation for M2212-8004, M2110-0058. Thermal degradation only for M2110-0075.
- Red jackets. Possible mechanism(s): additive degradation, loss of plasticizer. TBD.

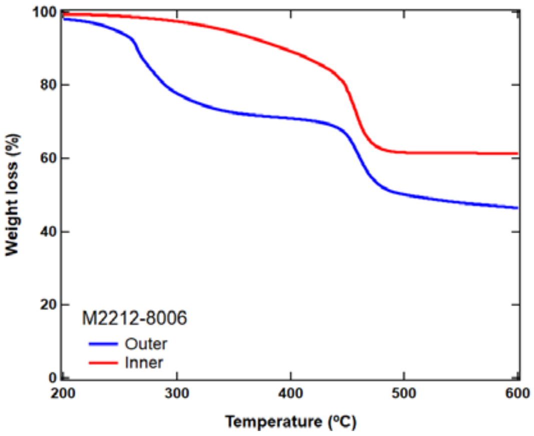
Mechanical Behavior (Indentation) of M2110-0063 (black, rubber)

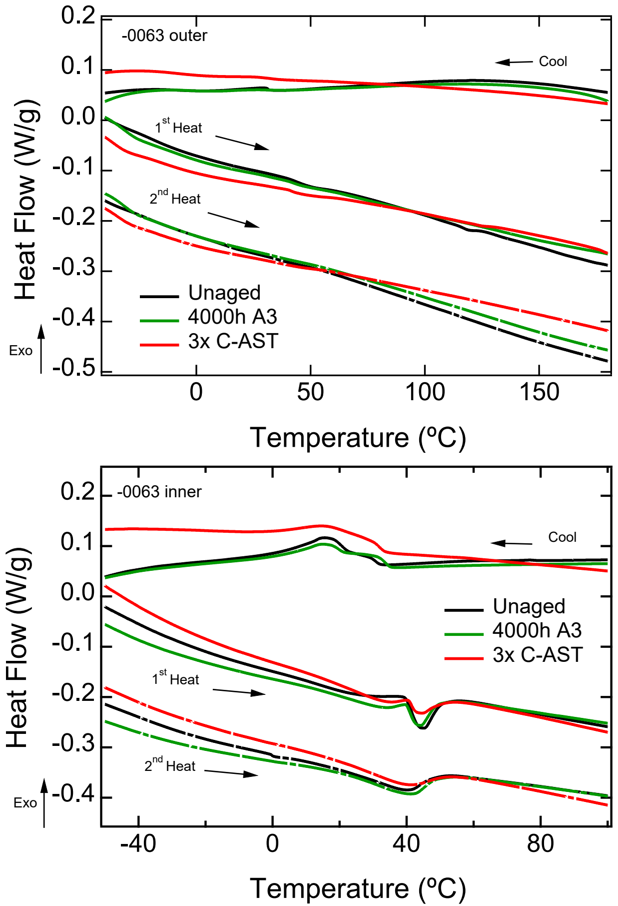


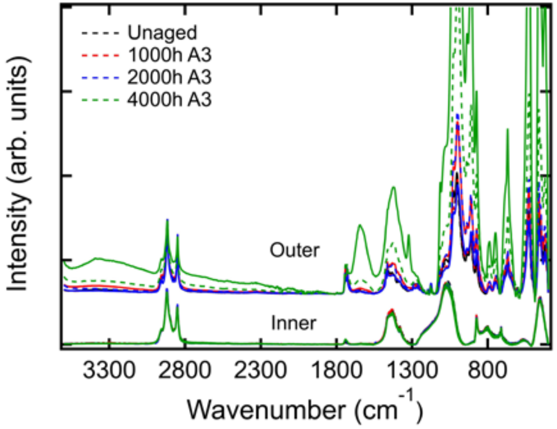
Creep hold at 240 µm Distance



Characteristics (FTIR, DSC, TGA) of M2110-0063 (black, rubber)

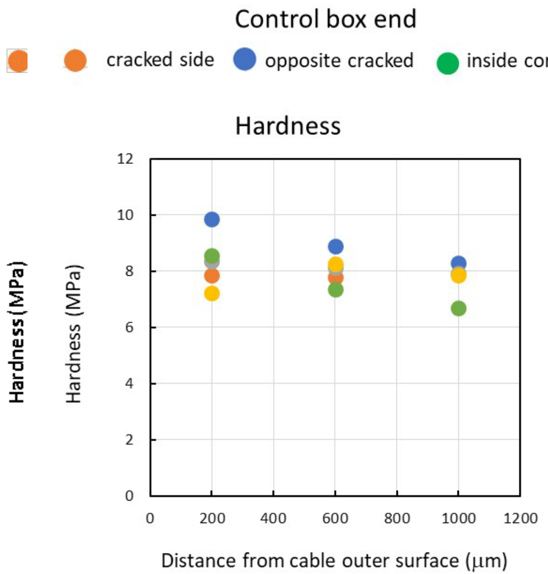


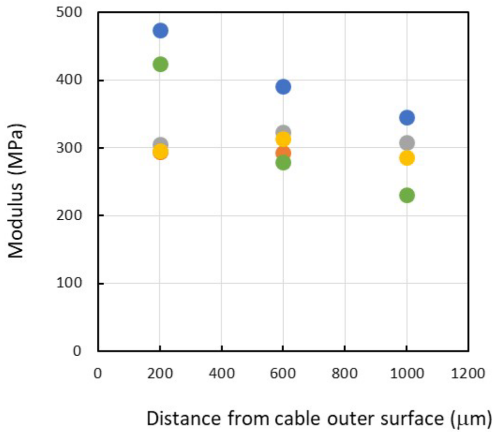


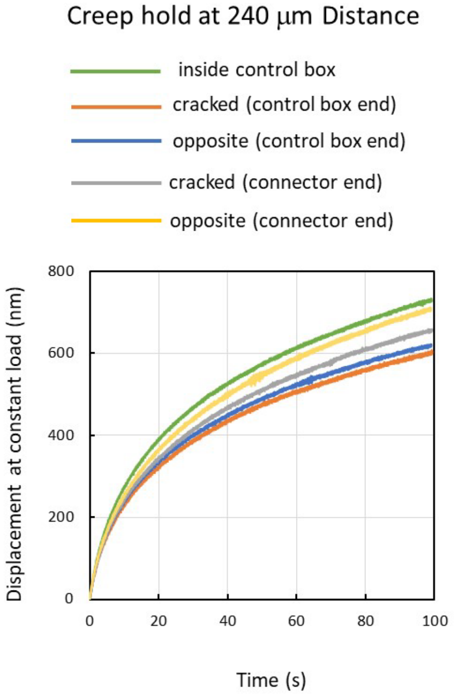


Mechanical Behavior (Indentation) of M2202-0103 (black, rubber)

Sample: 2202-0103, Tracker cable (rubber, multi-conductor)

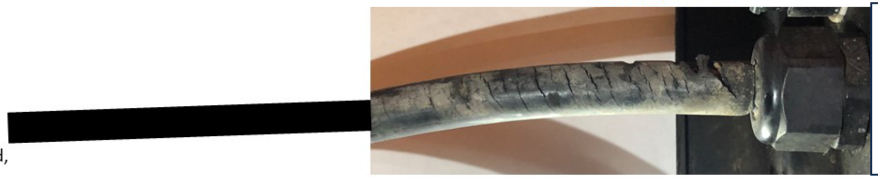






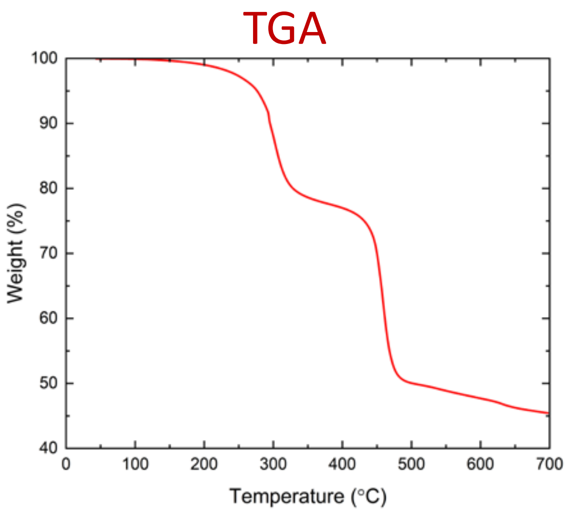
controller end (most macro-cracked)

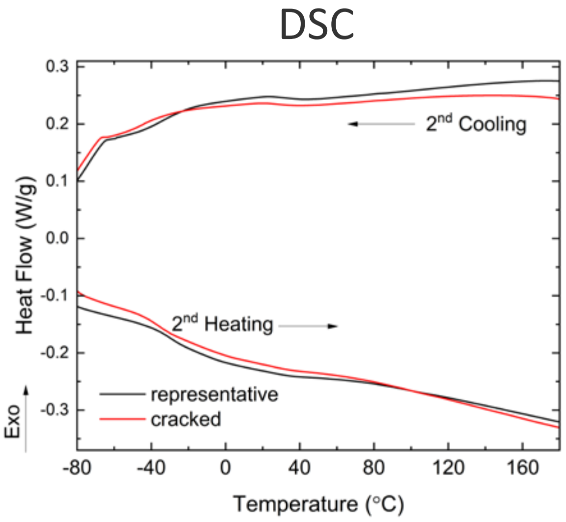
connector end
(may be macro-cracked, not as severe)

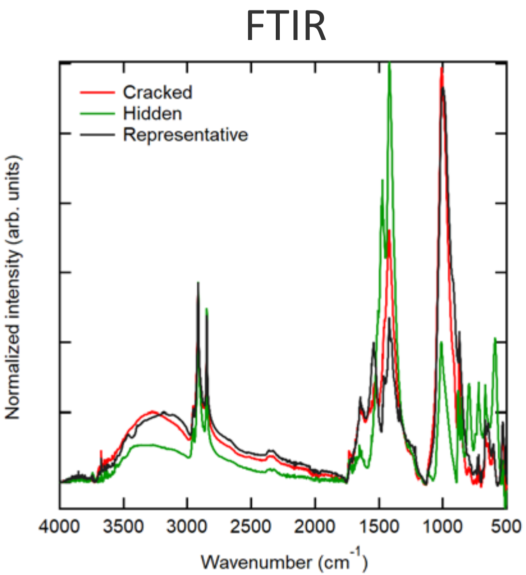


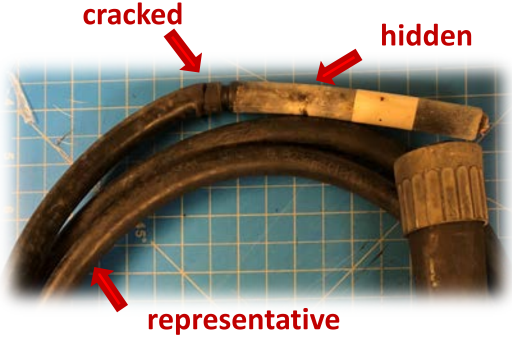
Inside
(not in direct environment, most like unaged)

Characteristics (FTIR, DSC, TGA) of M2202-0101/-0107 (black, rubber)









Acknowledgements

☞Thanks to:

-Dr. Michael Kempe and Bill Sekulic of NREL.

-Marianne Rodgers and Jessica Ma of the Wind Energy Institute of Canada (WEICan) for help with field specimens

-Numerous additional collaborators for field specimens (confidential).

-PVQAT TG10 (~200 recent followers).

CPS / Agreements 38524, 52802:

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office (SETO). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL STM campus, Dennis Schroeder

NREL/PR-5K00-91535

Additional comments & questions: David.Miller@nrel.gov