BLACK DIAMOND STRUCTURES™

MOLECULAR REBAR®: Discrete carbon nanotube additives for Enhanced Flooded Batteries

Customer Study & Material Science behind Enhanced DCA & Cycle Life

Dr. Tao Gu

Black Diamond Structures - China

BLACK DIAMOND STRUCTURES™

Who We Are

Black Diamond Structures™ is a global leader in nanotechnology with the mission to help manufacturers create the next generation of world-class batteries.

Our unique products, based on the proprietary **MOLECULAR REBAR®** technology, together with our team of world-class nanotechnology experts alter your battery's "DNA", unlocking its full potential… fast.

Our teams work directly with our customers to find solutions that enhance the battery's mechanical and electrochemical properties to meet market challenges for decades to come.

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YOUR NANO CONNECTION

Our Joint-Venture Partners

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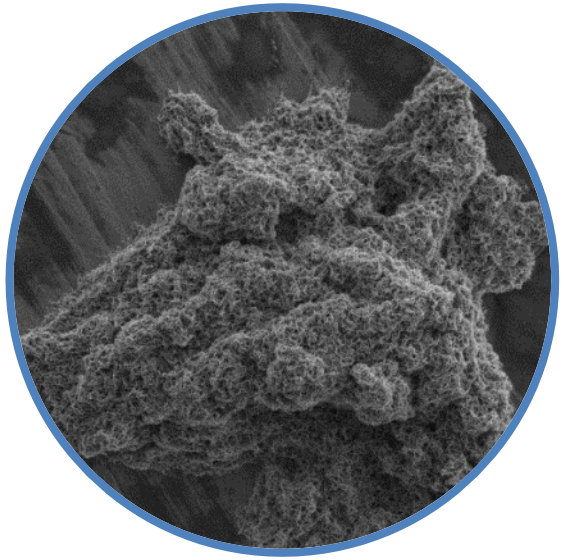
MOLECULAR REBAR® DESIGN

MOLECULAR REBAR® Technology Platform

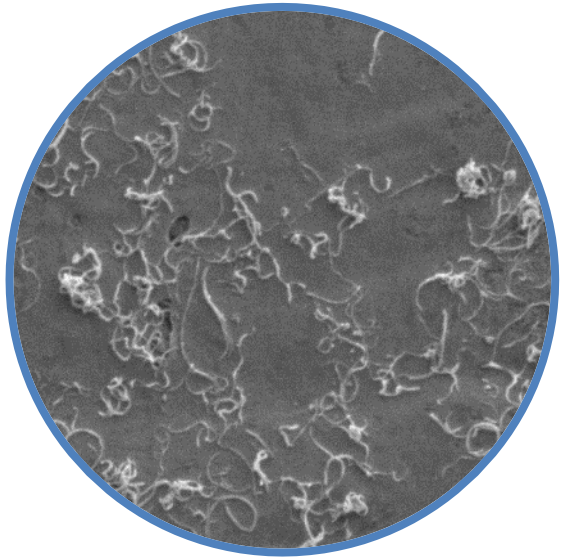
Key Competitive Advantage

Raw Carbon Nanotubes → Detangling + Purification → Formulation + Dispersion → Manufacturer Integration



Aggregates of Dirty, Entangled CNT's

Hard to Implement, Poor Transfer of Properties

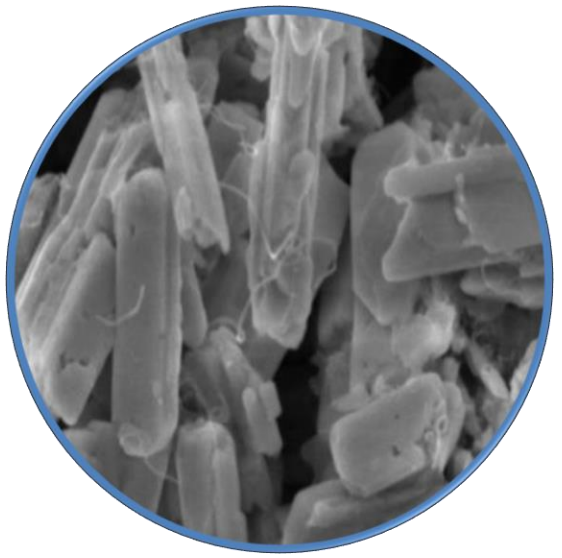


Clean, Detangled MOLECULAR REBAR

Discrete, individual tubes

Formulated MOLECULAR REBAR

Optimized for System Compatibility, Ease of Use



MOLECULAR REBAR in Lead Paste

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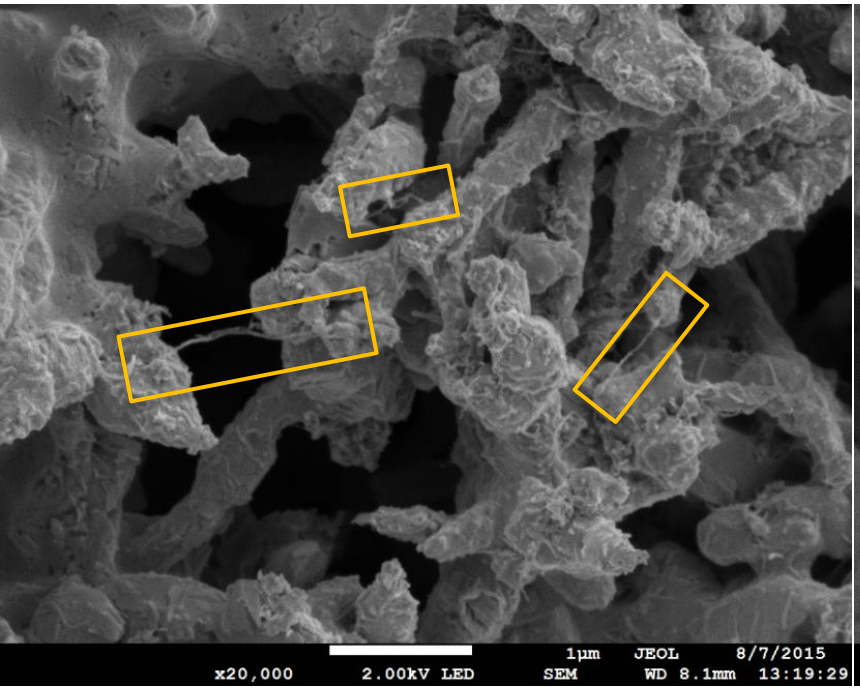
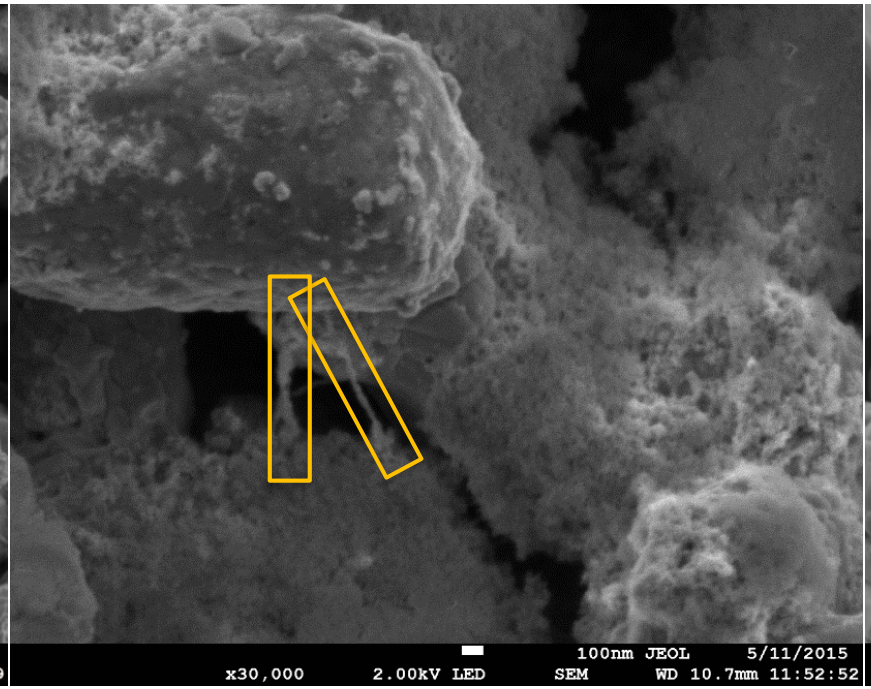
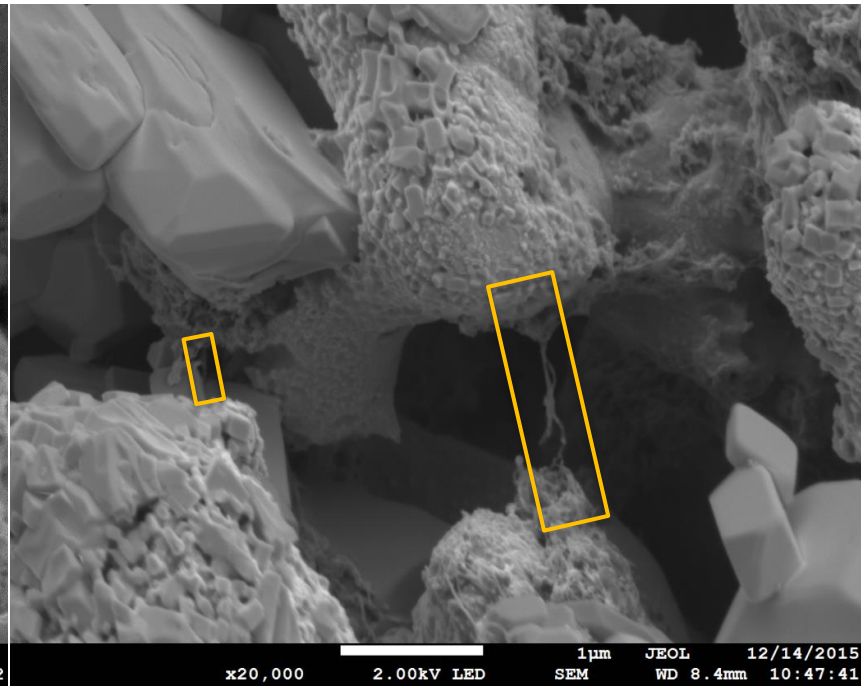
MOLECULAR REBAR®: The Nano-Connector

- **Molecular Rebar products provide nanoscale reinforcements which:**
  - Act to bring the active material together, reinforcing plate structure → **Enhanced robustness**
  - Alter crystal packing to enhance surface area and modify pore structure → **Improved electrical performance**
  - Restrict the growth of large, insulating lead sulfate crystals → **Consistency of performance**







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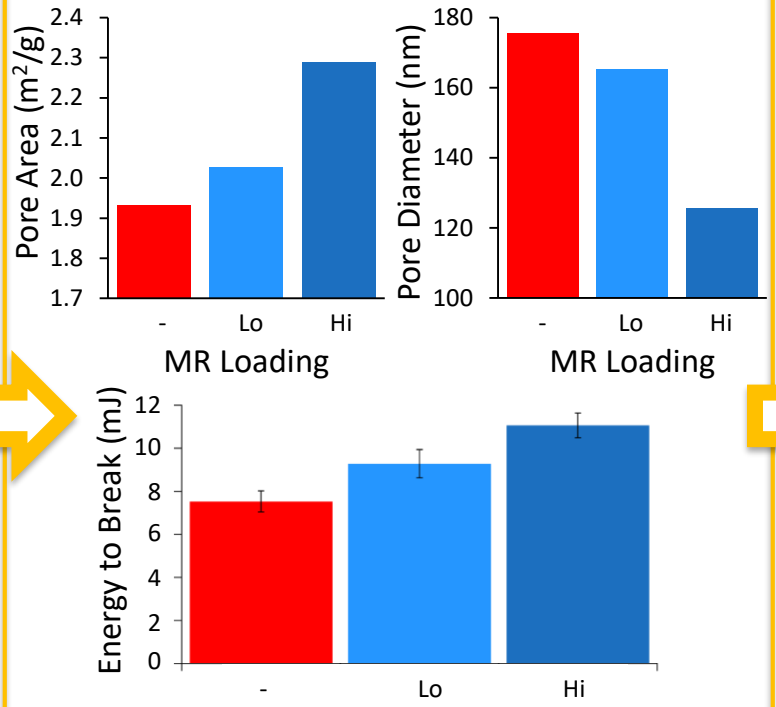
Changing the DNA of Your Battery

Production Line

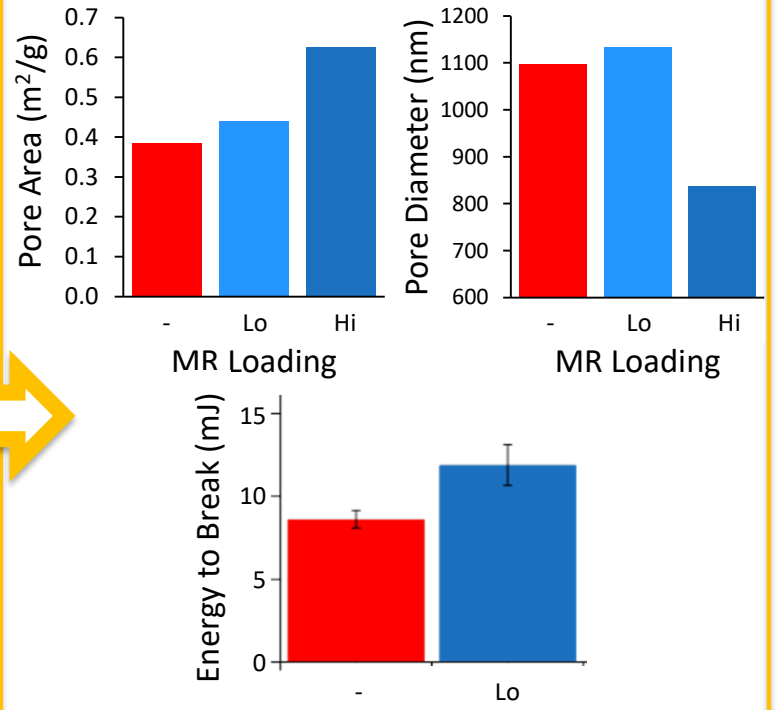
- MR presence is ***immediately*** felt
- Altered plasticity, still workable
- Increased grid-material adhesion
- Fewer rejected plates

Cured Plate



- Increased surface area
- Decreased pore diameter
- Increased material strength

Formed/In-Use Plate



- Persistent surface area increases
- Persistent pore structure
- Persistent plate strength
- Consistent performance

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Enhanced Flooded Battery: Pb1200 Series

- **Key Features:**
  - Use in Negative and/or Positive Electrode
  - Compete with VRLA products
  - Meet challenging OEM specifications
  - Enhance or Enable NAM Advanced Carbon solutions

- **Pb1200 Series provides performance increases across the following tests:**
  - Dynamic Charge Acceptance
  - Durability Life Cycle Tests
  - Micro-Hybrid Life Cycle Tests

Our Approach to EFB Development

The BDS approach requires open discussion with MFRs, particularly around expander/carbon additions

- **BDS wants to work with you to find success… fast:**
  - Trying MR without collaboration could repeat missteps BDS has already experienced
  - EFB in particular is more complex than most applications
  - Customers have likely already optimized their expander composition around a specific carbon or design
  - Clarity on existing designs may change:
    - Molecular Rebar product selection
    - Molecular Rebar loading level recommendation
    - Suggested expander/carbon adjustments

- **BDS will leverage experiences that align with MFR's stated goals to help steer our collaboration:**
  - Approach and necessary support from BDS will shift depending on customer product development status
  - Our recommendations will be tailored toward each MFR's needs
  - Example: Customer Testimonial (following slides) starts at "Day 0" with no baseline EFB design

EFB Customer Development – Shared Testimonial

Pb1200 Series NAM products added to a simple SLI recipe provides a step change in Performance

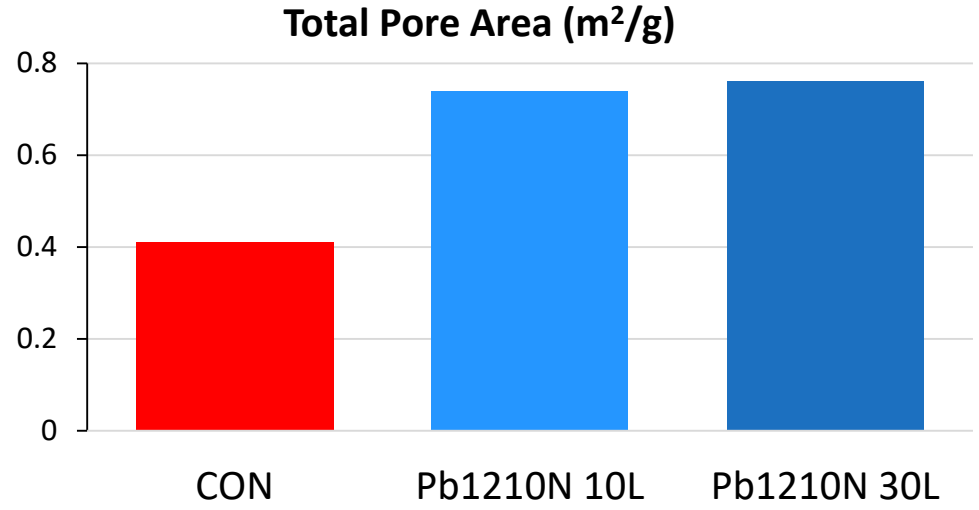
Pb1210N in 60Ah 12V SLI Batteries			
Description	**Control**	**10L Pb1210N**	**30L Pb1210N**
C_{20}	59 Ah	61 Ah	60Ah
CCA – 10 s Voltage	7.25 V	7.75 V	7.60V
CCA – time until 6V	120 s	150 s	142s
EN 50342-6 DCA	0.26 A/Ah	0.38 A/Ah	0.42A/Ah
Toyota Regen (CA)	400 As	500 As	540As
SAE J2801	13	12	12
EN 50342-6 17.5% DOD	4 Units	7 Units	7 Units

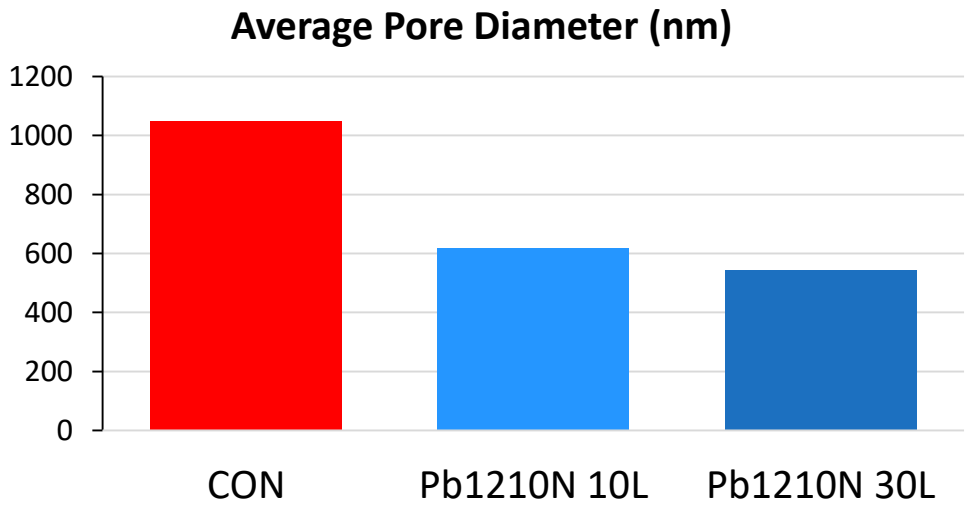
Hammond HE-631: 0.075% Carbon
0.225% Lignin
0.450% $BaSO_4$

- **Both Control & MR variants use same amount HE-631**
  - Only difference is the addition of Pb1210N
- **Black Diamond Structures' process followed:**
  - Initial joint assessment of recipe and design
  - Discussion of targeted goals and limitations
  - Current MFR product evaluated
    - Here, customer had no current EFB prototype; commercial SLI product used as baseline
  - Initial data dissection and analysis provided by BDS
  - Data drove next build with design/recipe modifications and MR product selection

Plate Analysis Support Balancing Exp./Pb1210N

- **Porosimetry Analysis from formed plates:**





- **Pb1210N will increase the total pore surface area and reduce the average pore diameter (Cured and Formed)**
  - Increased number of smaller pores
  - Higher surface area for lead reactions
  - More crystal and pore uniformity
- **This shift must be balanced with the expander, similar to the "carbon-lignin uptake" phenomena**
- **BDS provided plate analytics can help find the right targets and confirm implementation**

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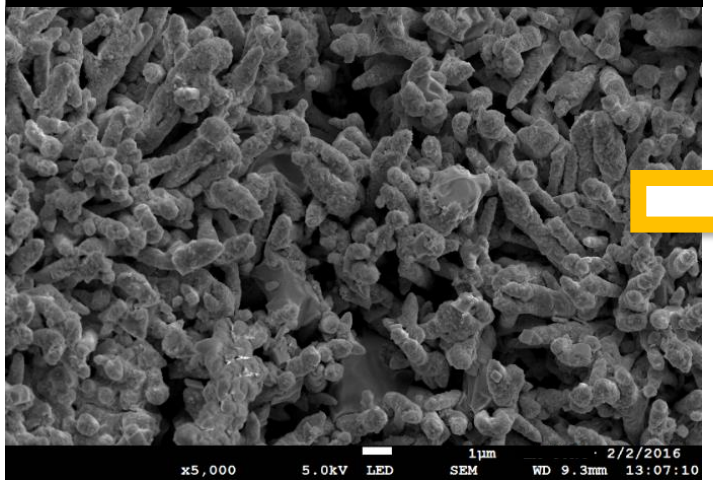
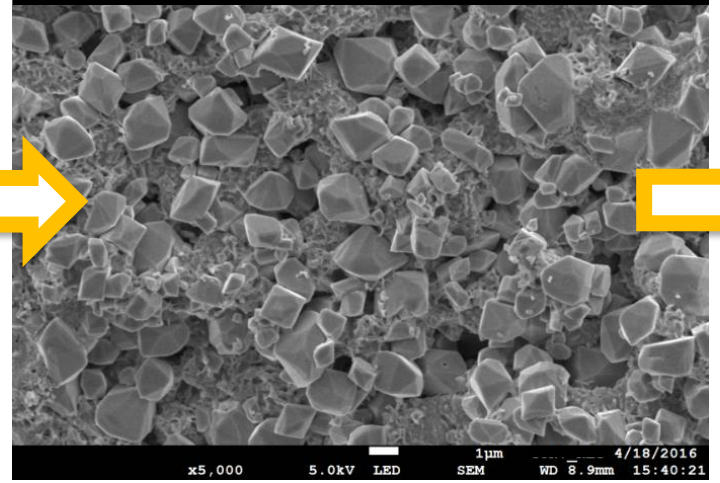
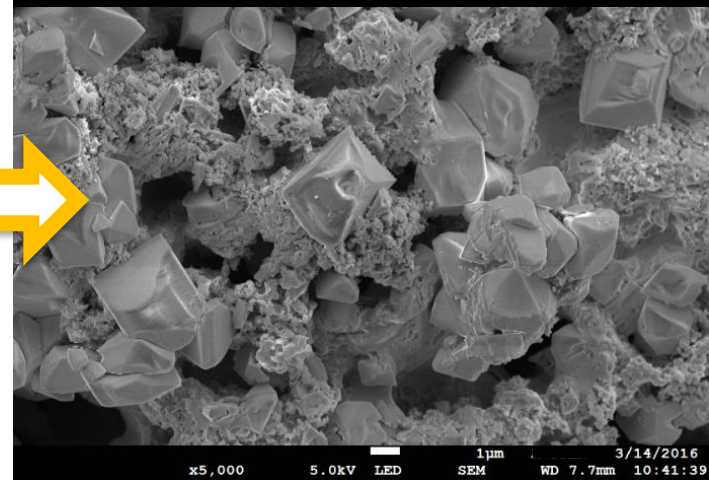
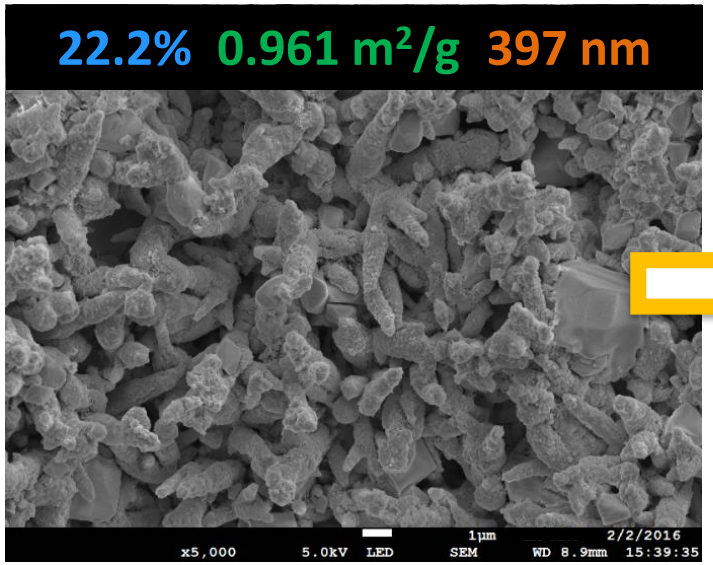
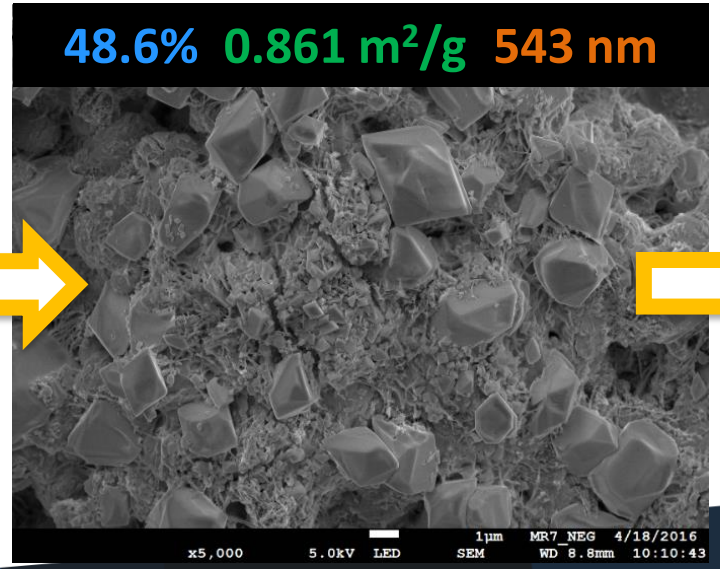
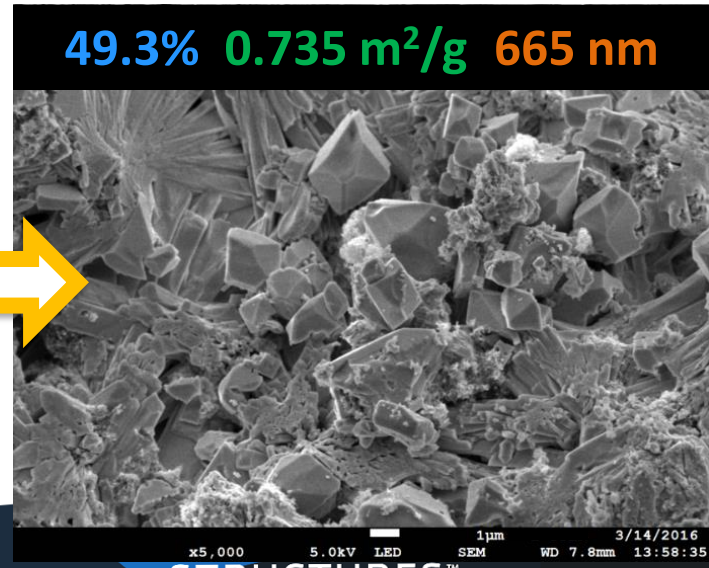
MR Influences Crystal Structure Thru Life

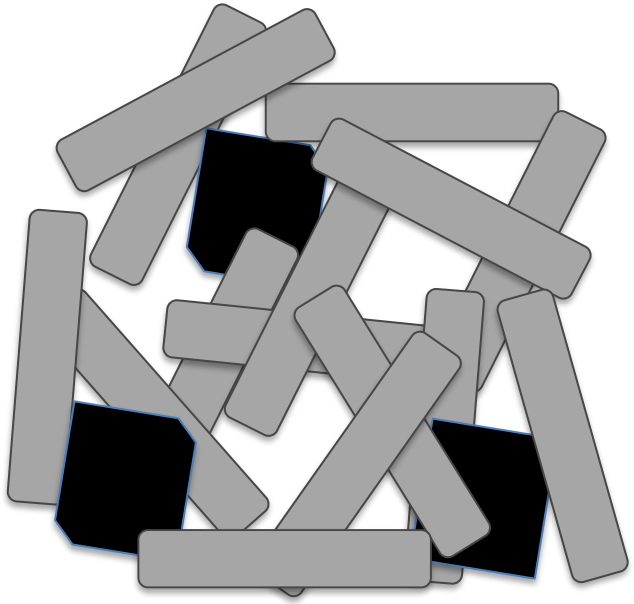
Total Sulfate % (XRD)
Surface Area (MIP)
Av. Pore Diameter (MIP)

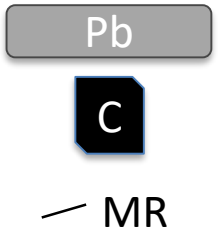
- **CON Progress**
  - Loosely packed Pb w/ large cavities
  - $PbSO_4$ covers surface
  - Large $PbSO_4$ and bundled materials
- **MR Progress**
  - Closely packed Pb w/ small cavities
  - Fewer $PbSO_4$ crystals
  - **Sulfate %**, **high surface area**, **low pore size** maintained

Beginning of Life	Mid-Life	End-of-Life
15.3% 0.672 m^2/g 466 nm	53.8% 0.594 m^2/g 779 nm	73.7% 0.547 m^2/g 1026 nm
		
22.2% 0.961 m^2/g 397 nm	48.6% 0.861 m^2/g 543 nm	49.3% 0.735 m^2/g 665 nm
		

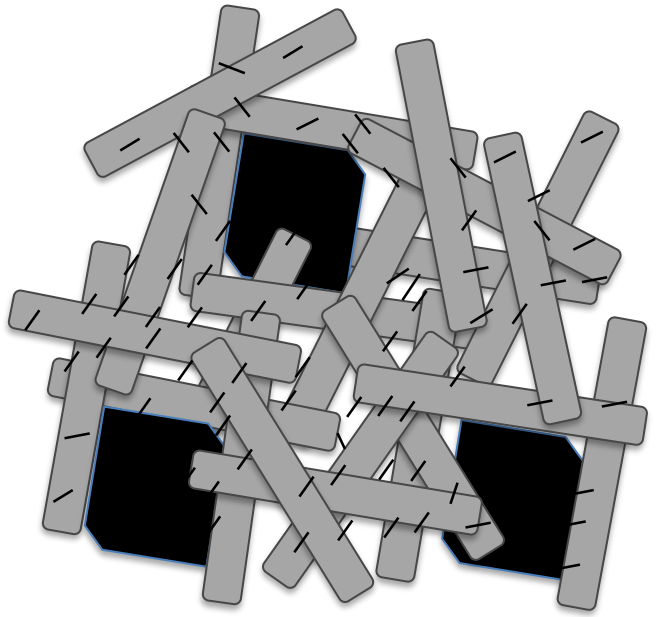
Working Theory Representations

Exaggerated Control NAM





Exaggerated Molecular Rebar NAM



- Comparatively low surface area, large pore diameter
- Lighter crystal packing
- Poorer interaction with carbon
- Expander balance well known from prior designs

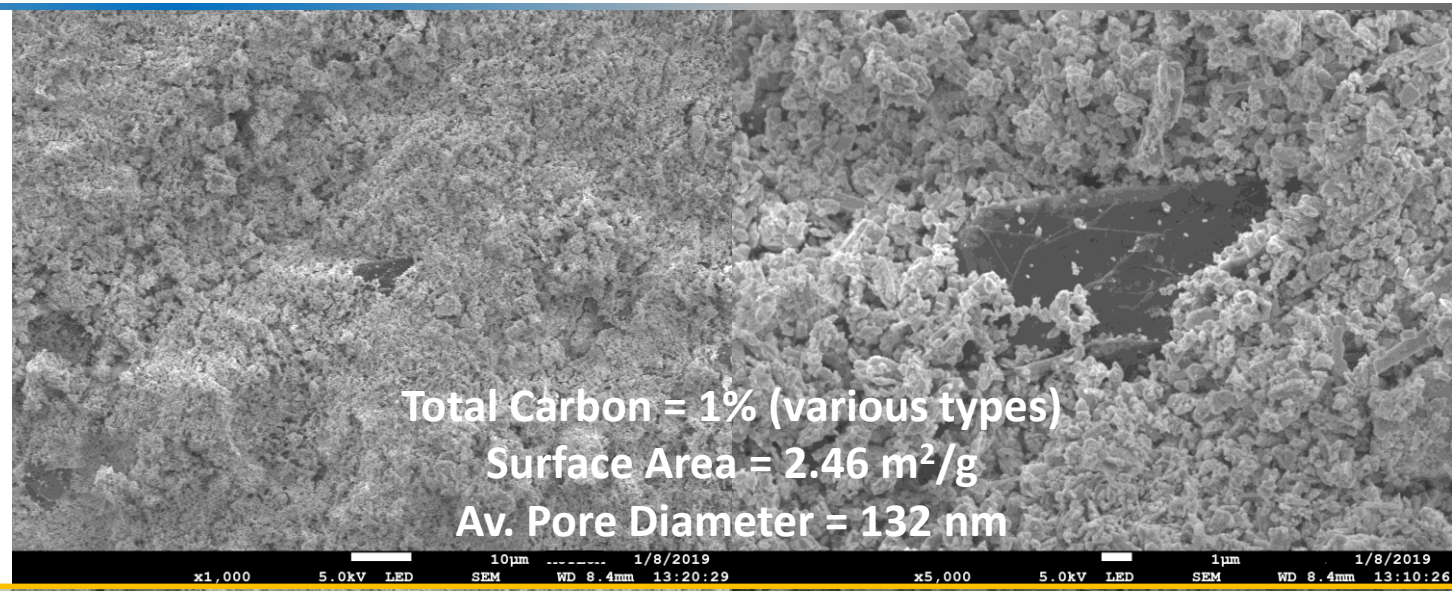
- Comparatively high surface area, small pore diameter
- Denser crystal packing
- Heightened interaction with carbon
- Nano-restructured Pb-C alloy may benefit from expander optimization

Formulation Simplicity and the Role of Carbon

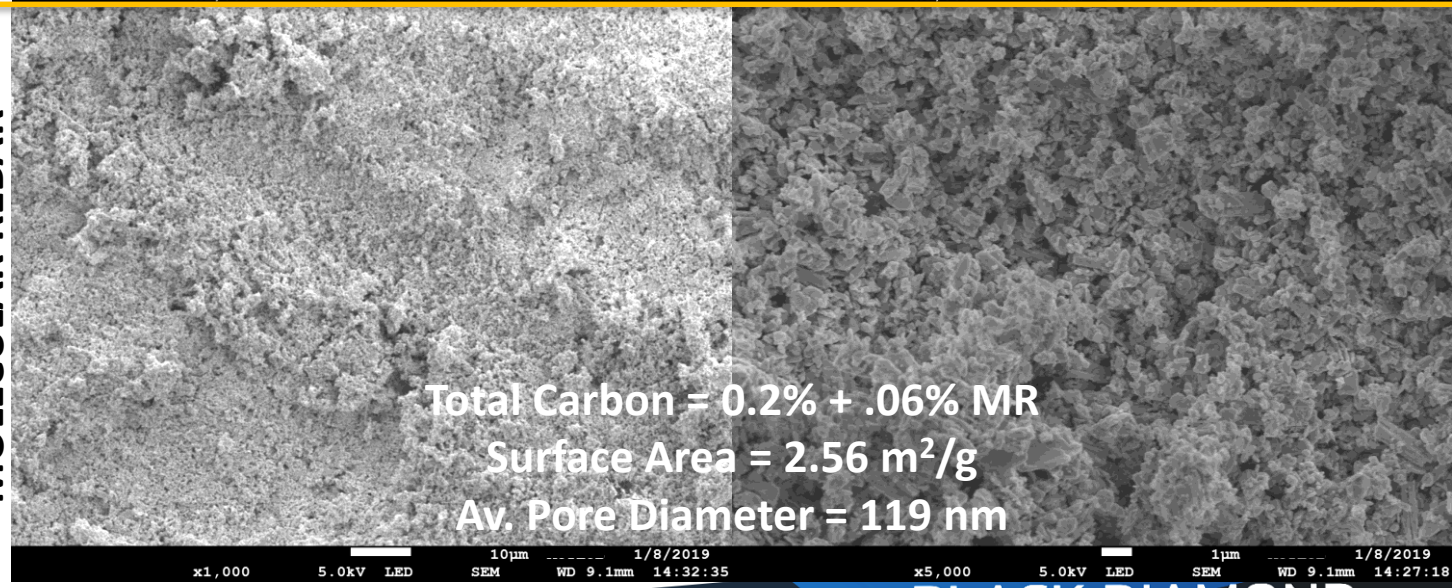
- **The concept of a lead-carbon electrode is not new, just difficult to execute and scale**
  - Not easy to create desired “carbon-lead alloy”
- **High-carbon containing plates suffer from unintended imbalances**
  - % carbon needed for performance often leads to significant production/recipe adjustments
  - Carbon/Lignin ratios become unbalanced; many paste recipes are optimized to balance around the Carbon
- **A simplified design approach with Molecular Rebar at its core, with optimized Carbon %, can yield a “Pb-C electrode” with excellent properties**
  - Use the Carbon you want, with higher effectiveness

Achieve the performance you need in DCA, further enhance cycle life, and mitigate water-loss

CONTROL



MOLECULAR REBAR®



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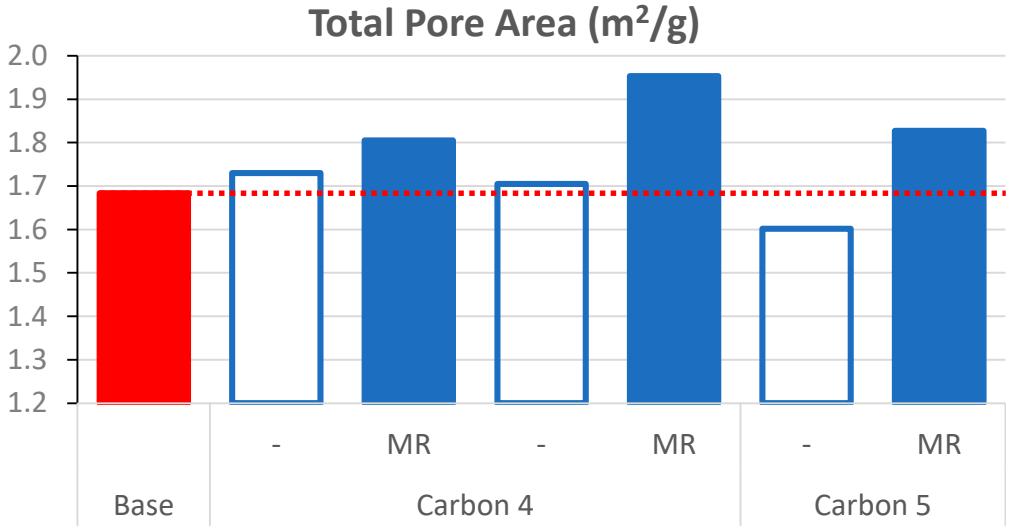
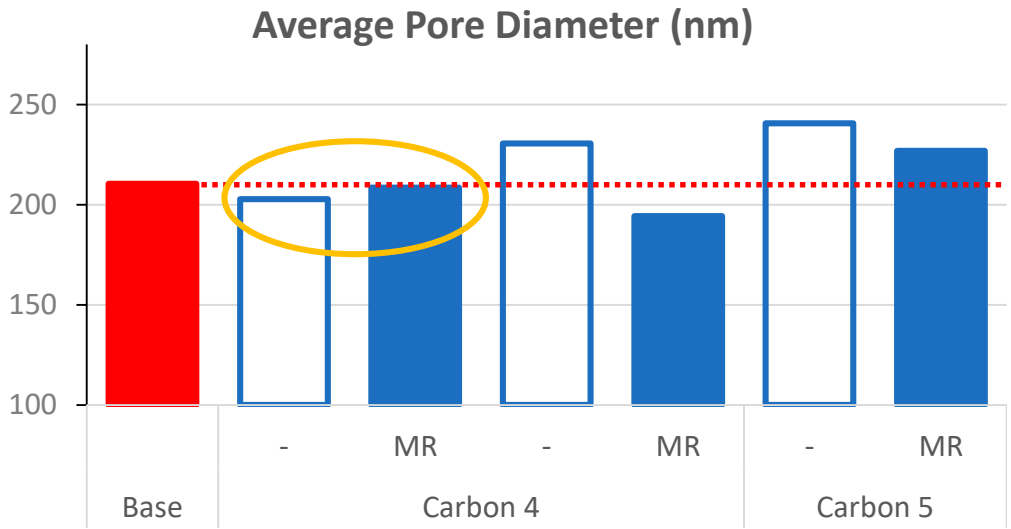
Implementing Molecular Rebar For Your Battery

Maximized Battery Performance with Molecular Rebar® Still Requires Expander and Carbon





Protocol: 1kg Leady Oxide, 0.20-1.0% C/0.2-0.5% Lignin/0.25-0.80 $BaSO_4$ per C-MFR instruction, 4.25 g/mL density, 3BS cure

But Which Expander/Carbons???

- The expander/carbon recipe should be discussed with your BDS Application Development Engineer
- Molecular Rebar-based products increase surface area, decrease pore diameter with ***most*** carbons (DUF/FOR)
- This is in addition to the mechanical, maintained structure, other benefits, etc.
- Simplifying complex formulations and designing around Molecular Rebar optimizes structure and performance, eases production implementation

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Summary

- **Black Diamond Structures™ develops advanced applications like EFB as a collaborative partnership**
  - Can provide expertise, testing circuits, plate and analysis

- **MOLECULAR REBAR® Effects**
  - Modified, more uniform, more efficient, active mass morphology
  - Improved consistency of structure of active mass throughout cycling/life
  - Other unknown mechanistic contributors

- **Performance Translation**
  - Better Consistency of all Performance Metrics over life
  - Improved Charge Efficiency & DCA
  - Enhanced Cycle Life, particularly PSOC and other high sulfation conditions

Meet the OEM Specifications, Exceed their in-field Expectations!