# Epoxy Based Nanodielectrics for High Voltage Insulation

Student: Ganpathy Iyer (ASU) and Zhen Chen (WSU)
Faculty: Ravi Gorur (ASU) and Bob Olsen (WSU)
Industry Advisors: SRP, AEP, EPRI, and ABB

PSERC Public Webinar Based on PSERC Project T-42
September 18, 2012

PSERC

# Introduction

- Epoxies offer several advantages over conventional porcelain
  - Lighter
  - Non-brittle (does not chip or break)
  - Can be easily molded into complicated shapes
  - Easy to manufacture
- Epoxy insulated devices are used extensively in low and medium voltage utility applications:
  - Bus support insulators
  - Vacuum reclosers, sectionalizers
  - Fuse cutouts
  - Instrument transformers (current and voltage transformers )
  - Pin and post type insulators
  - Bushings

Current Transformer

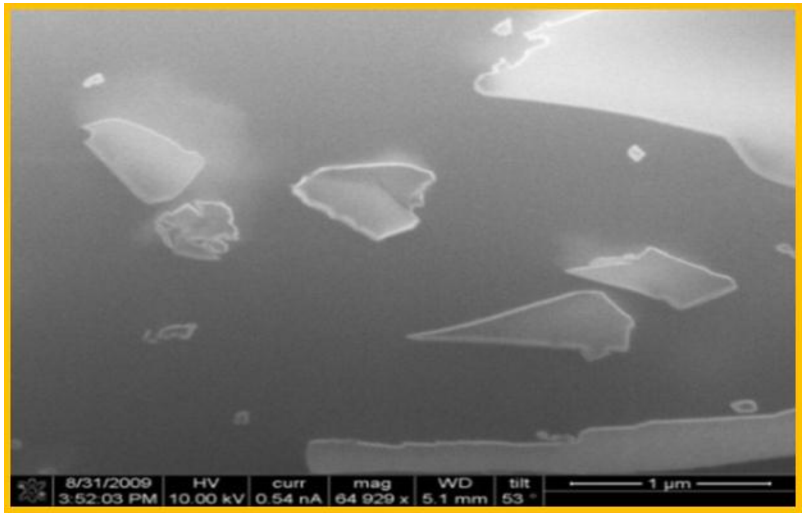
Potential Transformer

Post Insulator

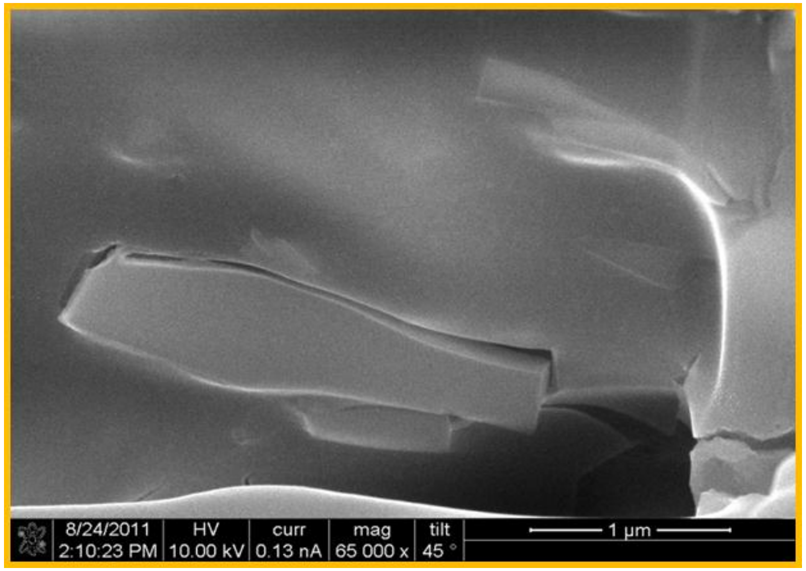
# Micro-Fillers

- Inorganic micro-sized fillers are added to materials for
  - Improving tracking and erosion resistance
  - Increasing resistance to partial discharges
  - Reducing cost
  - Improve mechanical properties

- **Pointed edges, irregular shapes and bad interfaces causes high localized electrical stresses**



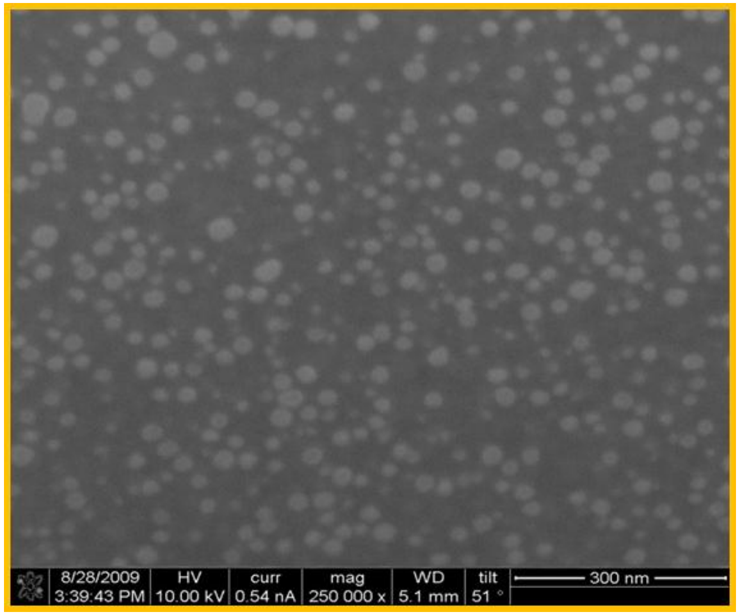

**Sharp, pointed edges of micro-fillers**



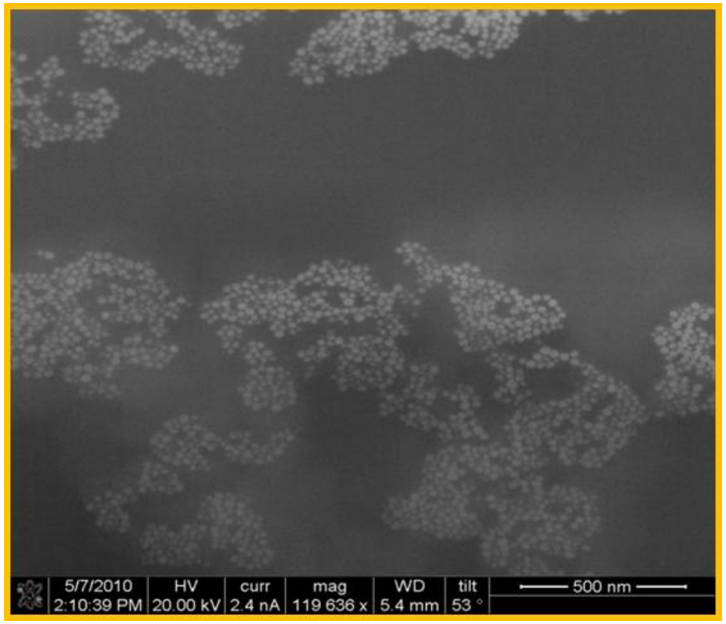

**Bad interfaces with the base matrix**

# Nanocomposites

- Addition of nano-sized particles can result in improving properties such as:
  - Mechanical strength
  - Corona resistance
  - Dielectric strength
  - Surface hydrophobicity
- Nanofiller advantages
  - Lesser filler concentration
  - Uniform shape
  - Large specific surface area
- Possible advantages
  - Compaction
  - Better stress distribution
  - Longer life




**Dispersed nanofillers**




**Agglomerated nanofillers**

# Samples Evaluated

| Sample Number | Filler concentration (wt %) |
|---|---|
| 1 | 65% M* |
| 2 | 62.5% M+ 2.5% N |
| 3 | 60% M + 5% N |
| 4 | 65% M + 5% N |
| 5 | 5% N** |
| 6 | 0% (Unfilled) |
| 7 | 2.5% N |

*M- Micro **N- Nano

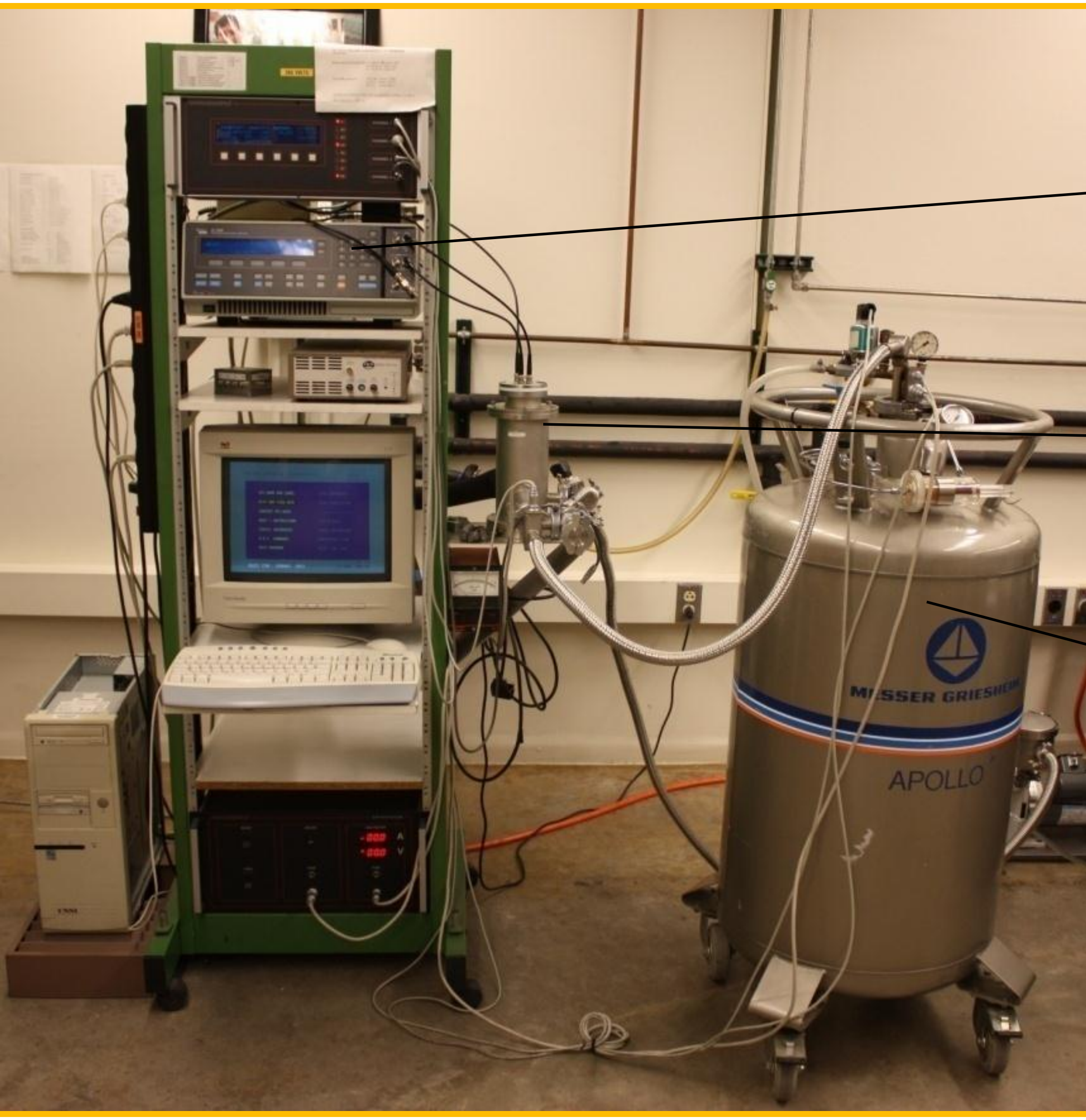
# Dielectric Spectroscopy

- Commonly used technique to record the behavior of complex permittivity as a function of temperature at different frequencies

- Inferences of interfacial polarization, conduction processes, dipole polarization effects can be made from real and imaginary permittivity values

- Can be used to compare electrical performance

# Dielectric Spectroscopy




Experimental setup

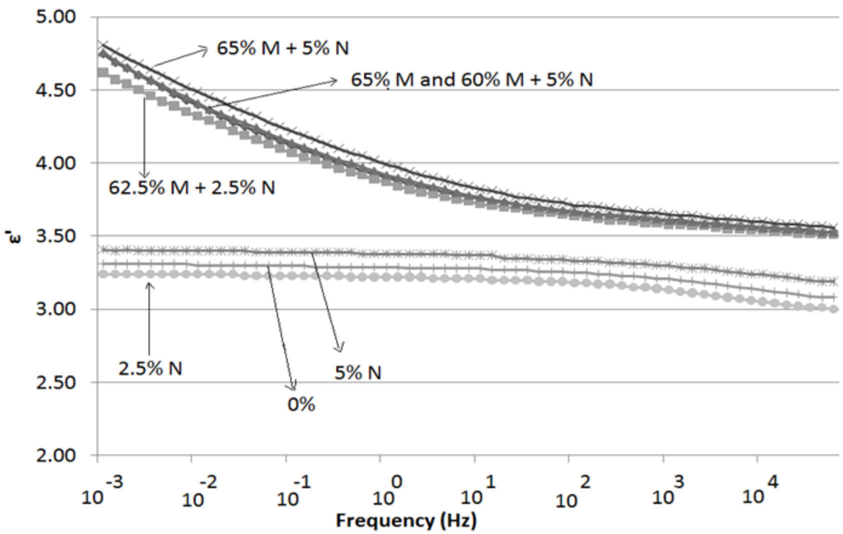
Solartron 1260 (Impedance Analyzer)

Sample holder

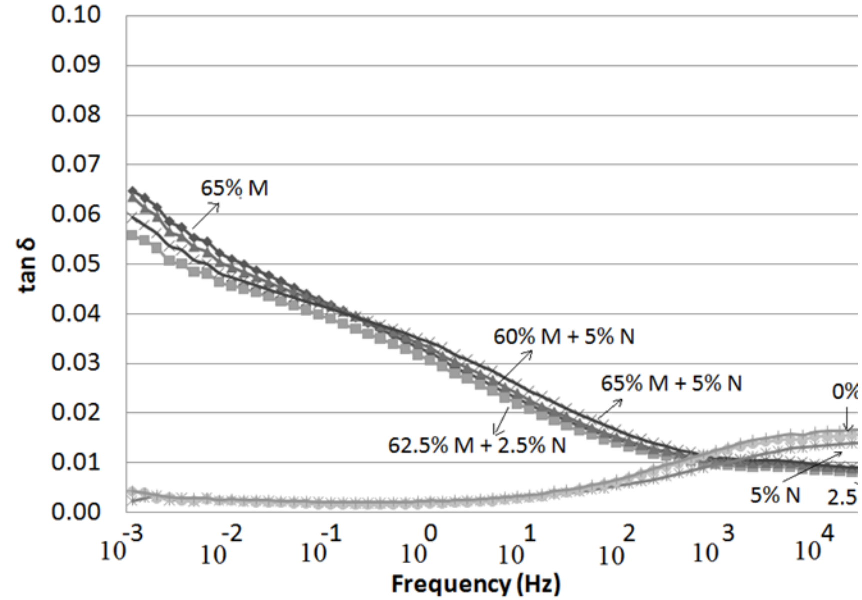
Cylinder containing LN2 for Temperature Control

| |
|---|
| **Voltage Applied: 50 V** |
| Frequency Range: 1 mHz – 56 kHz |
| Temperatures: RT, 233 K, 333 K, 393 K |

# Dielectric Spectroscopy - Room Temperature (RT)



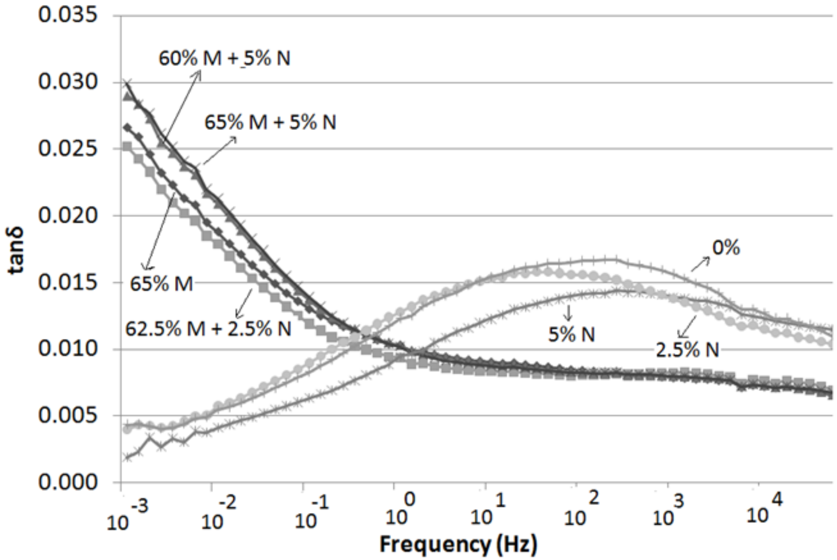

**Real Permittivity**




**tanδ**

- Low real permittivity and tan delta of nano-samples could be due to the large interfacial areas of the nanocomposites
- Maxwell Wagner Sillars (MWS) polarization in micro, micro+ nanofilled samples due to space charge build-up between the micro-fillers and the base matrix

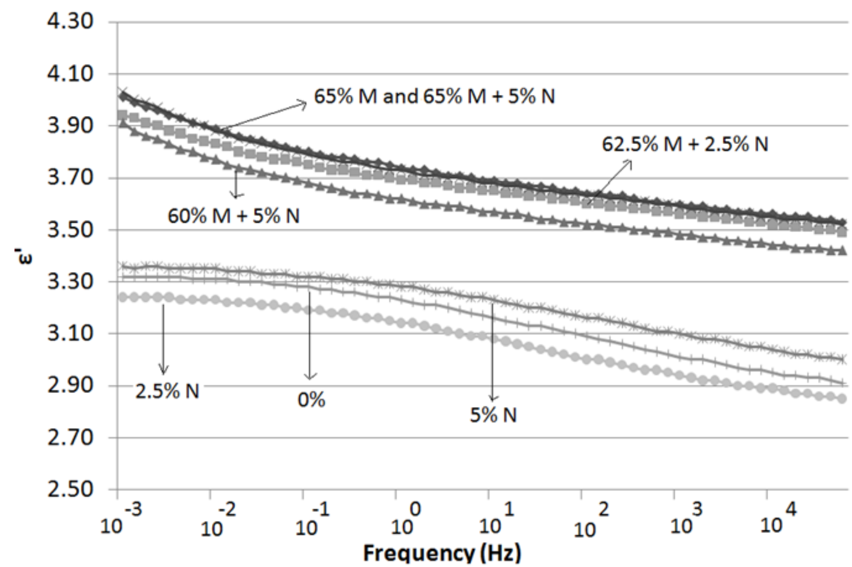
# Dielectric Spectroscopy - 233K (-40°C)




tanδ

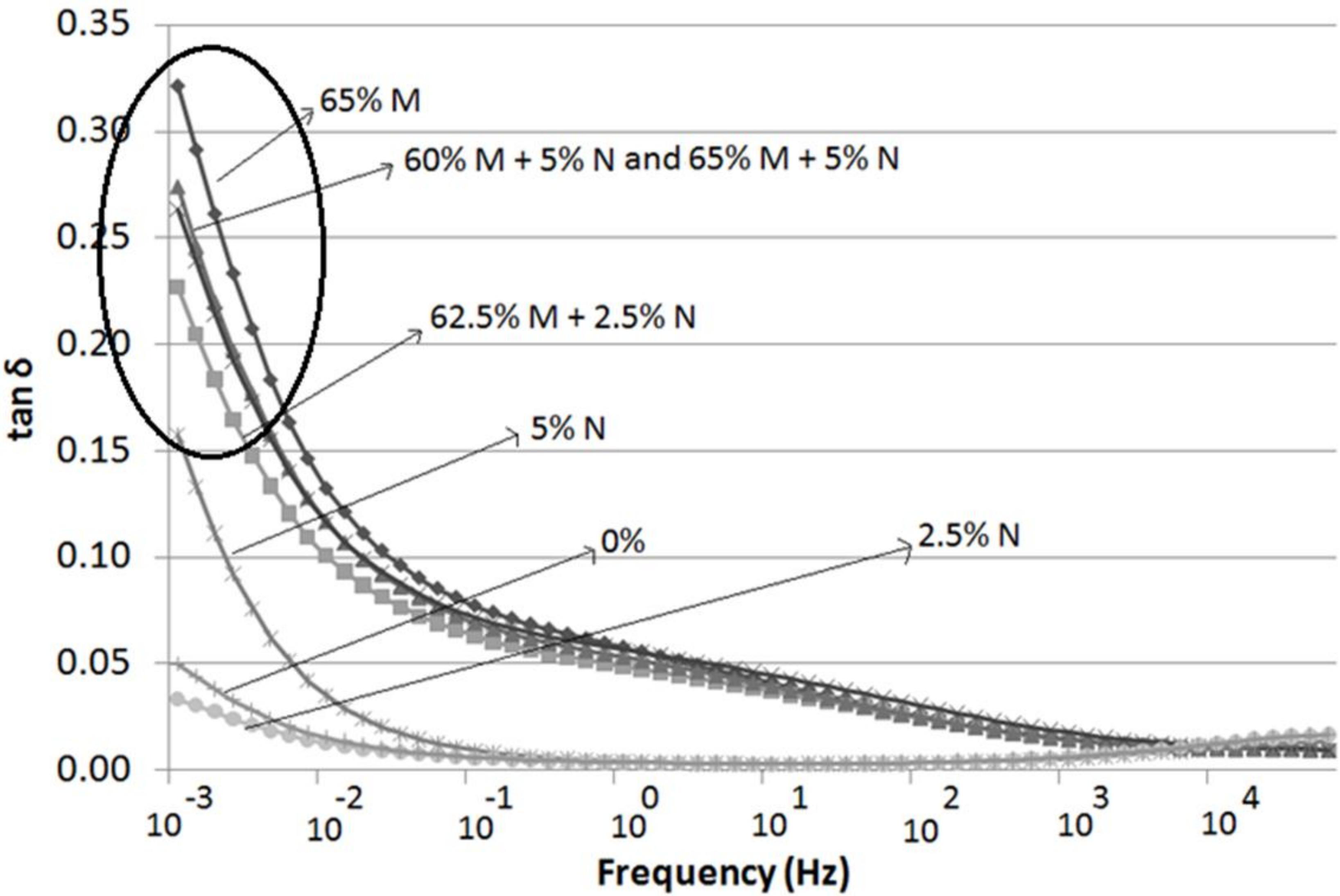
- ❑ Secondary relaxations in nanofilled and unfilled sample.
- ❑ Also present in the micro-filled samples but overlapped by MWS polarization

- ❑ 5% N has higher real permittivity as compared to the 0% filled sample while the 2.5% N sample has lower real permittivity




Real Permittivity

# Dielectric Spectroscopy - 333K (60°C)

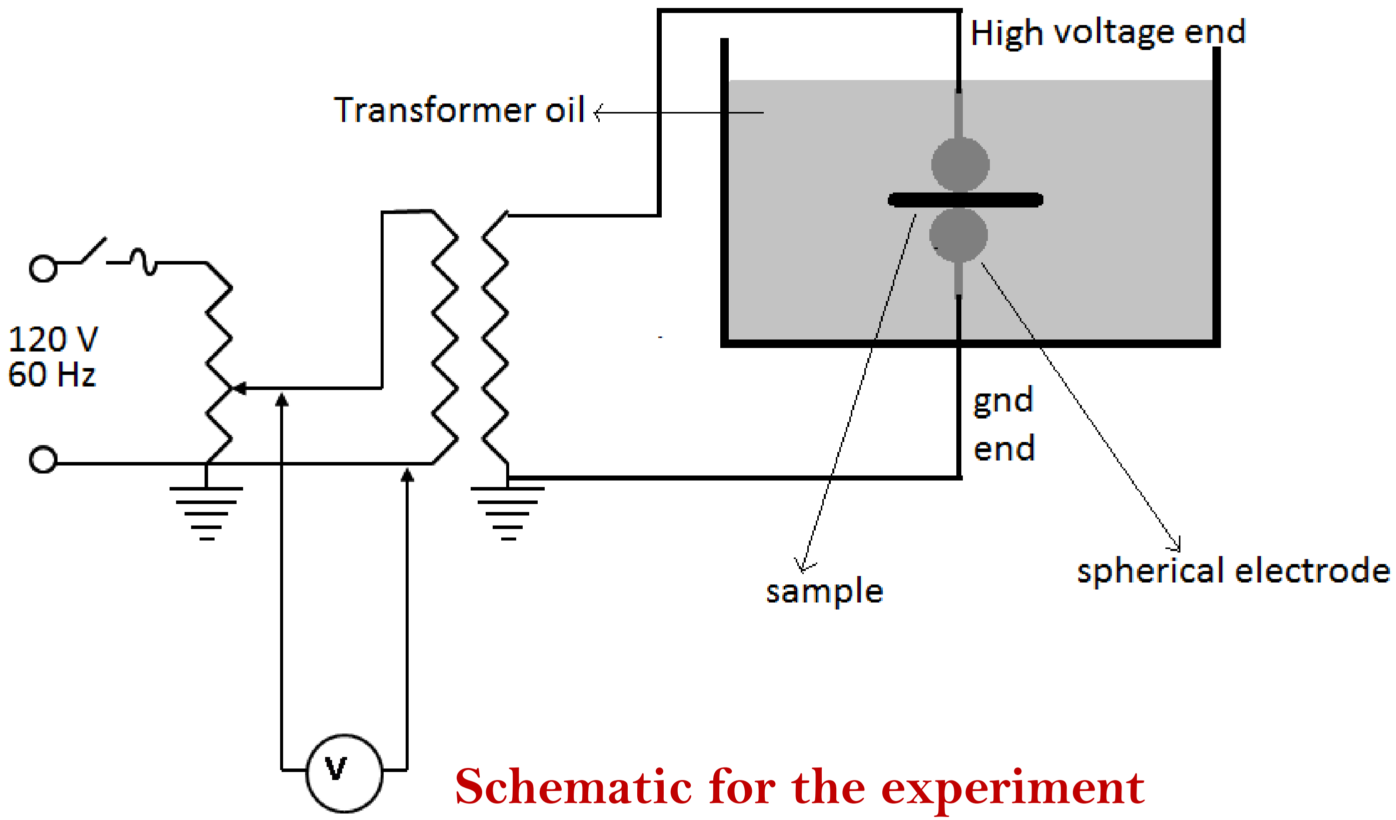



tanδ

# Dielectric Spectroscopy - Summary

- Showed differences in the data for micro, micro+nanofilled samples, nanofilled and unfilled, samples
- Showed significant reductions in dielectric losses ($\tan\delta$) for micro+nanofilled samples as compared to microfilled samples
- Showed that 5% by weight of nanofiller is required to get improved electrical properties

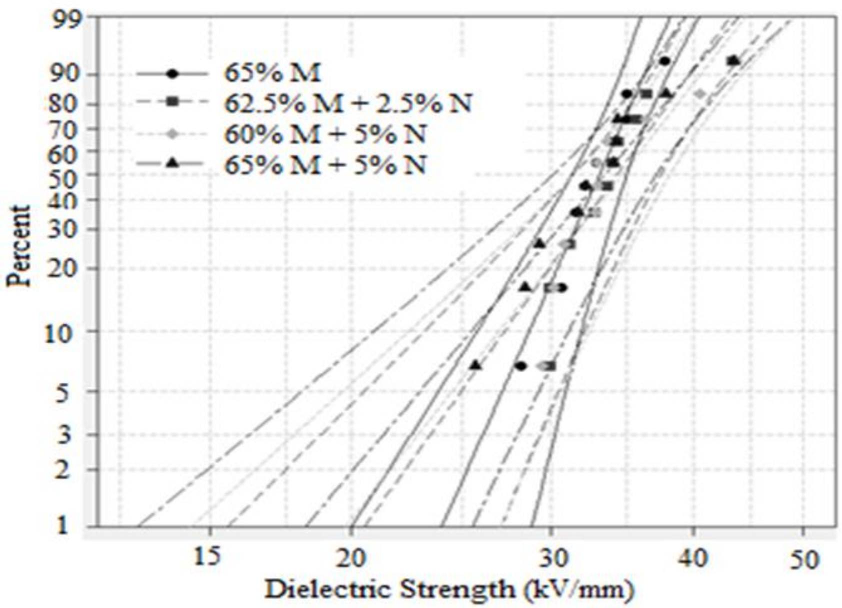
# Dielectric Strength Experiments



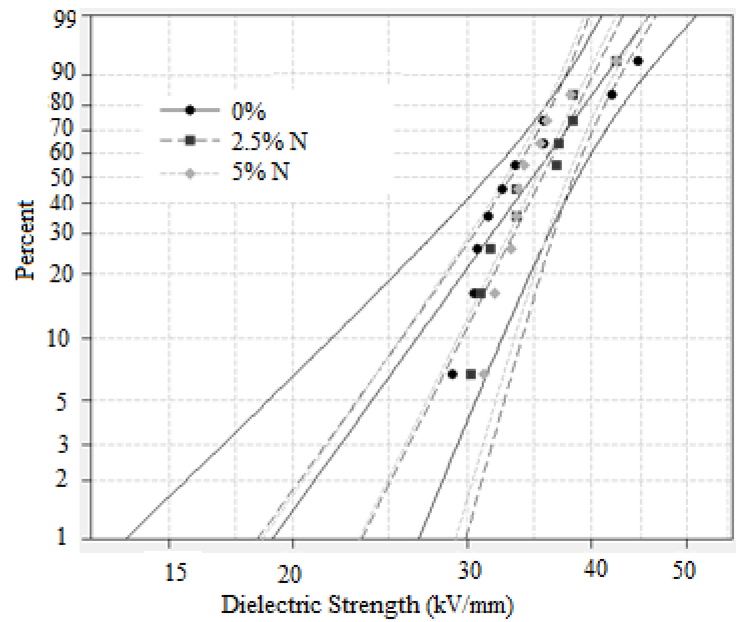

**Schematic for the experiment**

- Loss of the dielectric property of an insulator due to the application of an electric field greater than a certain critical magnitude is called dielectric breakdown.
- Critical magnitude of electric field - dielectric strength
- Voltage increased at a rate of 1 kV/s

# Dielectric Strength Experimental Results




65% M , micro+ nanofilled samples

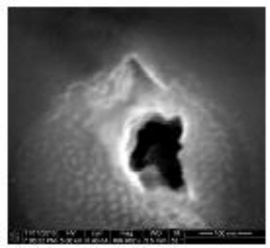



0% (unfilled), 2.5% N, 5% N

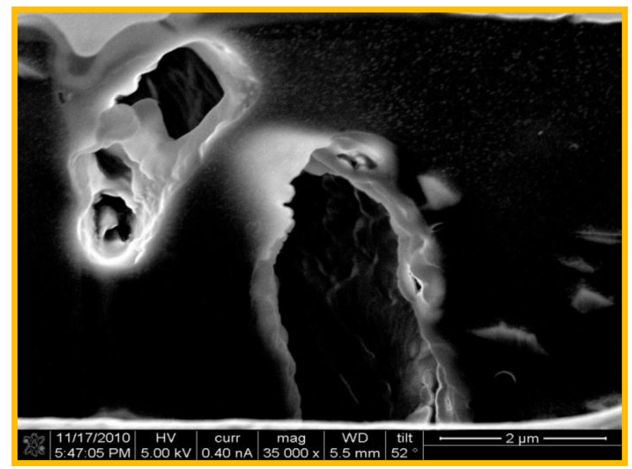
- Different Distributions- Weibull, Normal, Lognormal were tried. Weibull Distribution-chosen
- No significant difference in dielectric strength values of different samples

# Dielectric Strength Experiments - SEM Images

- High voltage applied using a quasi-homogenous field (sphere-sphere configuration) could be a reason
- Puncture could initiate at any spot in between the two spherical electrodes
- The short-term duration of the test could also be a factor

Particles displaced from the voids

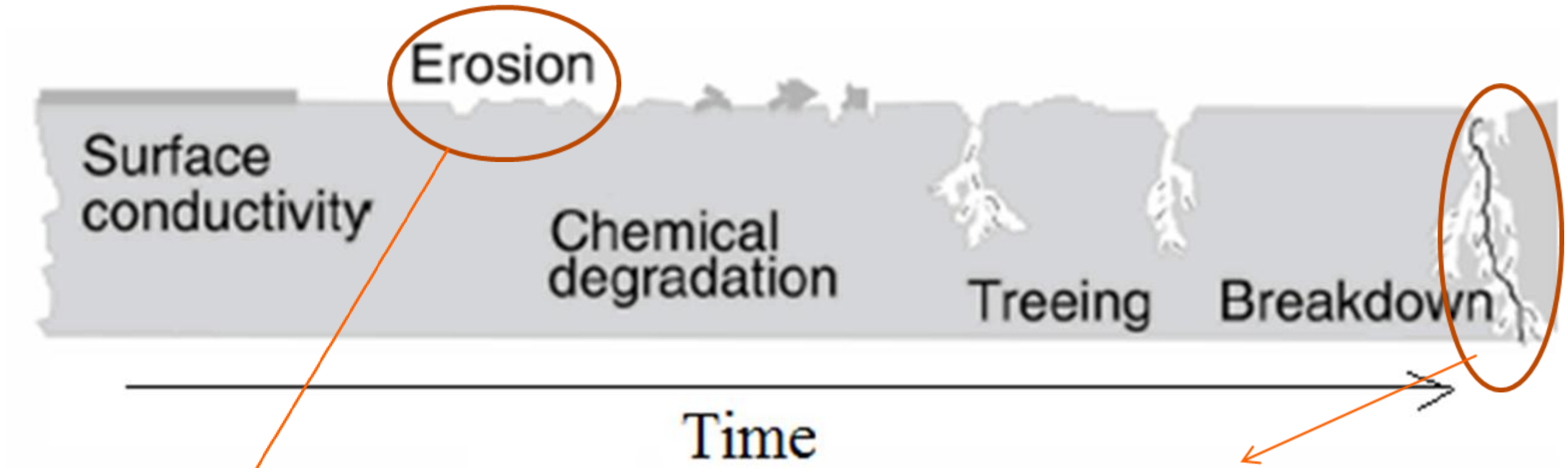



Voids in the bulk (micro + nano sample)

- Hence, corona resistance experiments using rod-plane geometry (divergent field) was conducted over 500 hours

# Corona Resistance Experiment

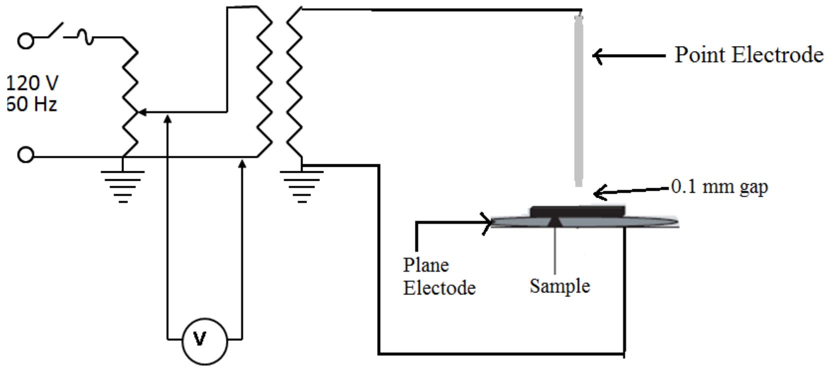
- Corona discharges originate due to ionization of air in locations of high electric stress
- Corona can be a significant threat to the performance of polymeric insulating equipments due to the organic nature of the housing material




**Corona experimental results** **Degradation model**

- Corona experiments measure the depth of erosion. Resistance is inversely proportional to depth

# Corona Resistance Experiments



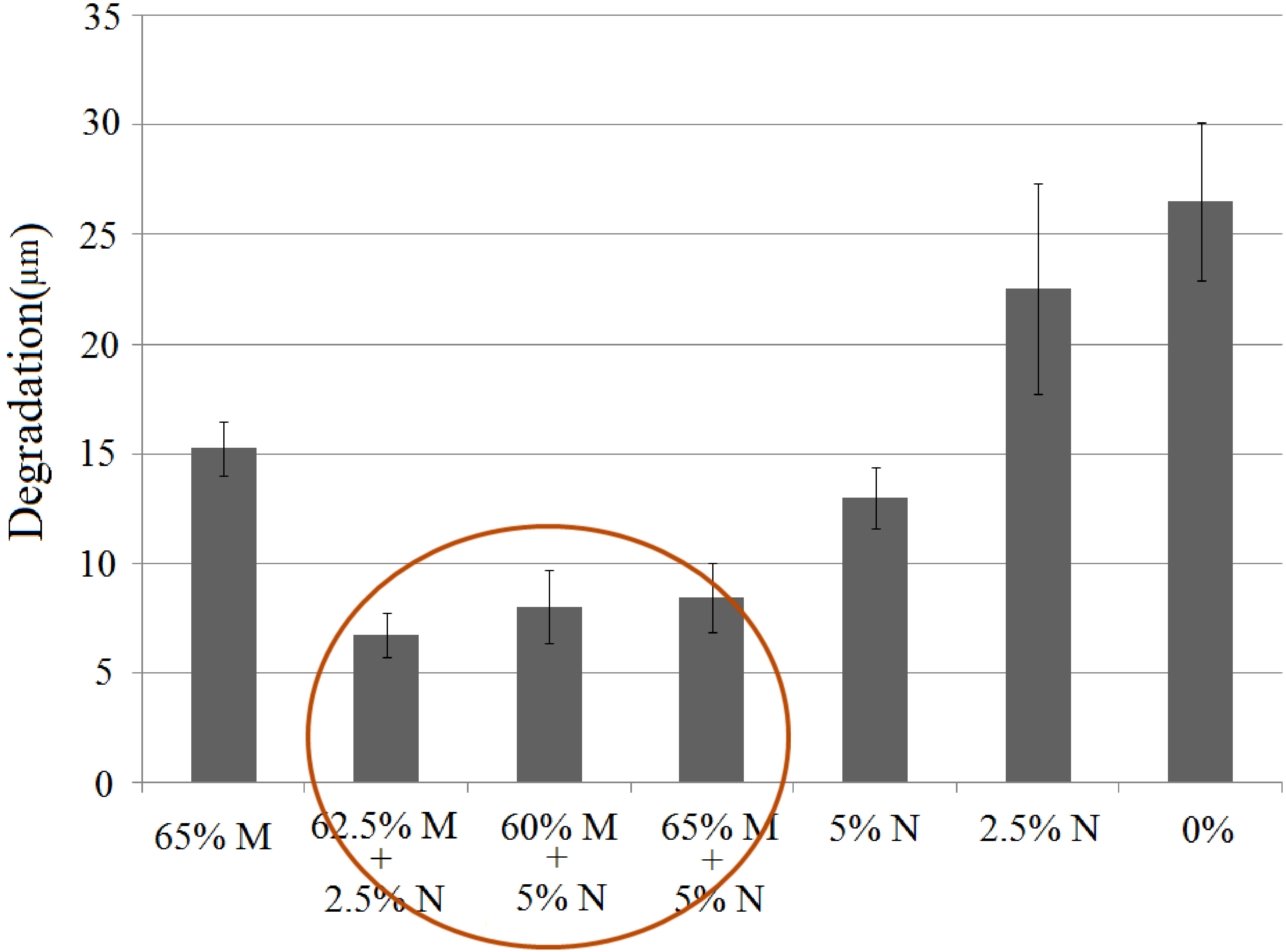

Schematic of the setup

Schematic of the setup

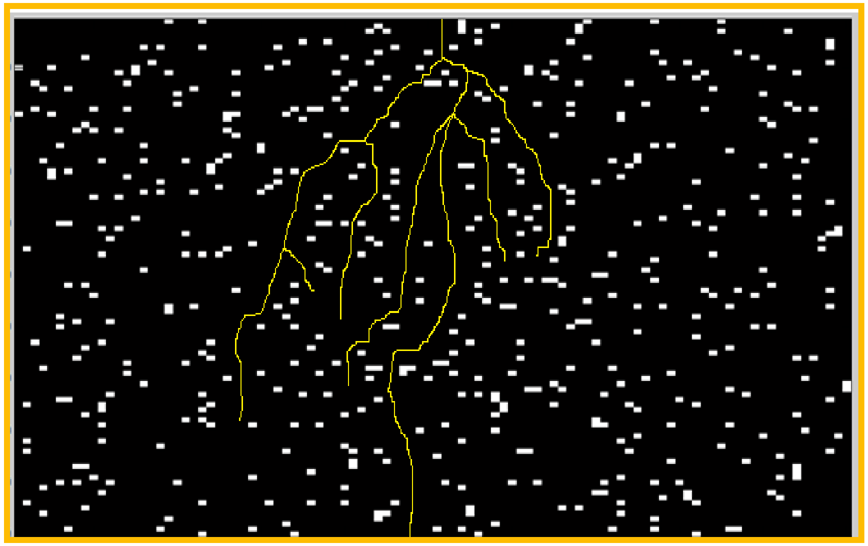
- 6 measurements for each sample type
- Erosion measured after every 100 hours

| Test Duration: 500 hours |
|---|
| Rod dimension : 1 mm diameter |
| Applied voltage : 5 kV |
| Gap between the rod tip and sample: 0.1 mm |

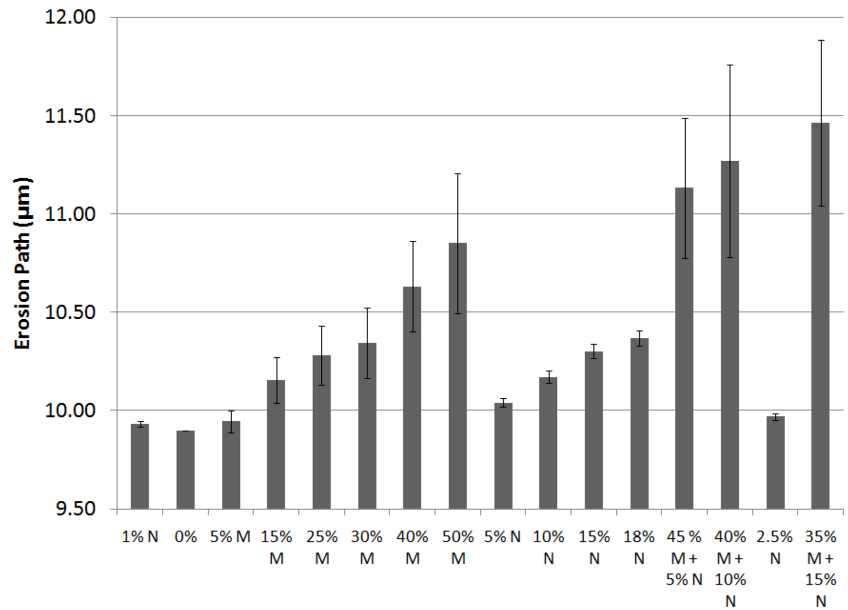
# Corona Experiment: Degradation Measurements after 500 hours



# Degradation Model: Dijkstra's Shortest Path Algorithm



Schematic showing the map of erosion path on a 5% N filled sample




Bar graph showing erosion path traversed over 100 samples

- Degradation model maps the erosion path. Longer erosion path means greater corona resistance
- Erosion paths obstructed due to the addition of filler particles

# Correlation between Experimental Results and Model

## Experiment

- Unfilled sample had the largest erosion depth
- Nano filled samples (2.5% N and 5% N) had smaller erosion depths than unfilled sample
- Micro filled sample had lower erosion depth than the unfilled sample
- Micro + nanofilled samples had the lowest erosion depth as compared to the microfilled sample for the same filler concentration (65% M, 62.5% M + 2.5% N and 60% M + 5% N)

## Model

- Unfilled sample had the shortest path ("straight line")- 9.9 um
- Nanofilled samples had longer short distance paths as compared to the unfilled sample
- Microfilled samples had longer erosion paths as compared to the unfilled sample
- Micro + nanofilled samples had longer erosion paths as compared to the microfilled sample for the same filler concentration (50% M, 45% M + 5% N, 40% M + 10% N and 35% M + 15% N)

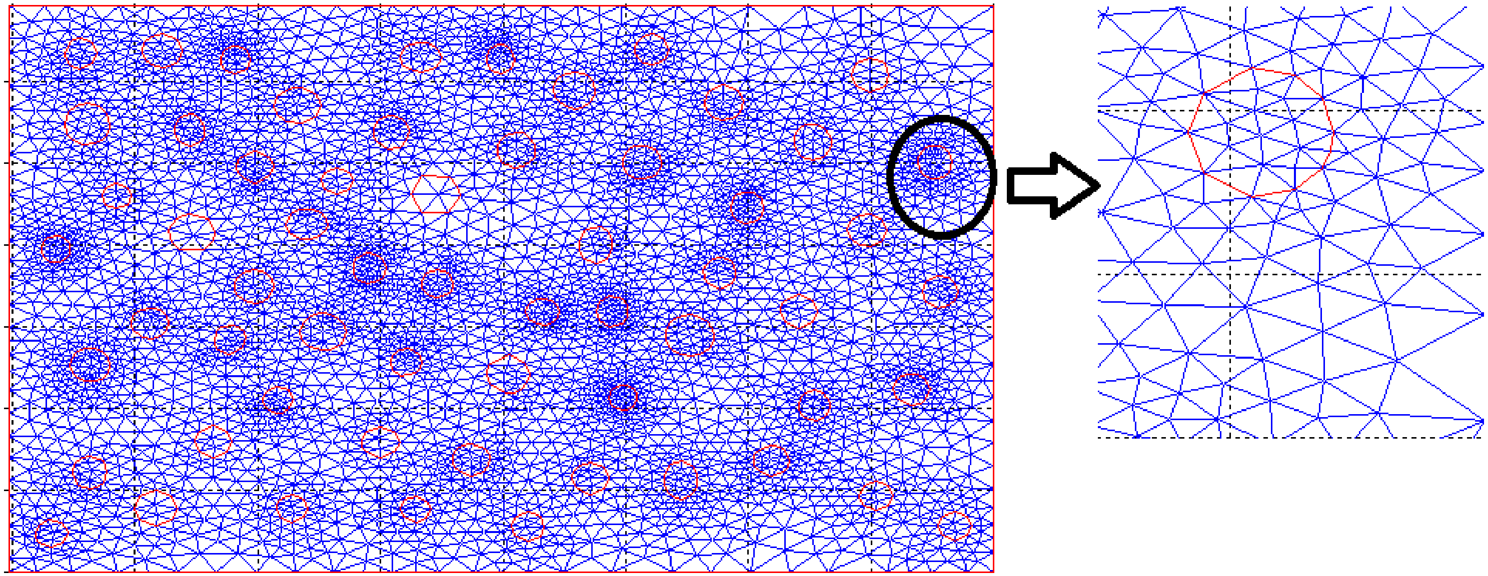
# Thermal Analysis: Thermal Conductivity Measurements & Calculations

- Thermal conductivity measurements were done using the laser flash method; while the calculations were done using rule of mixtures
- Macroscopic quantity such as thermal conductivity do not adequately explain the improvements in corona resistance measurements of nano-fillers

| Sample | Thermal conductivity (W/m-K) (experiment) | Thermal conductivity (W/m-K) (calculated) |
|---|---|---|
| 0% | 0.168 | 0.168 |
| 2.5% N | 0.173 | 0.183 |
| 5% N | 0.169 | 0.199 |
| 65% M | 0.892 | 0.781 |
| 62.5% M + 2.5% N | 0.933 | 0.781 |
| 60% M + 5% N | 0.798 | 0.781 |
| 65% M + 5% N | 0.832 | 0.852 |

# Thermal Analysis: Model

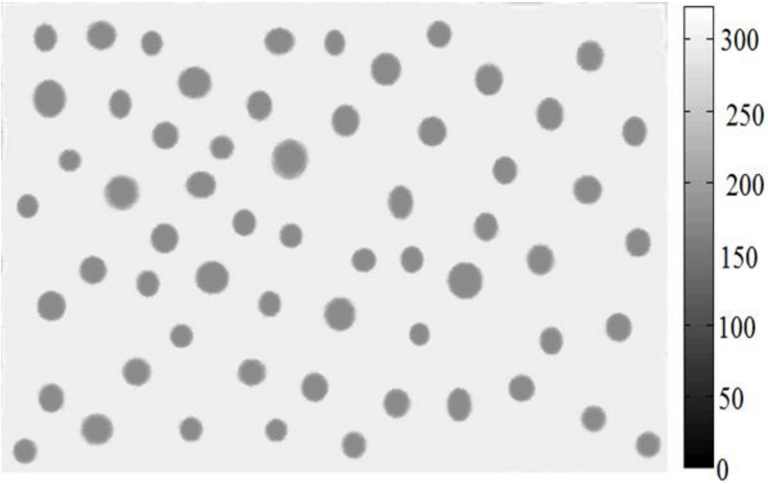
- Thermal model developed using PDE toolbox in MATLAB
- Model uses Finite Element Method to calculate the localized temperatures of micro and nanofilled samples



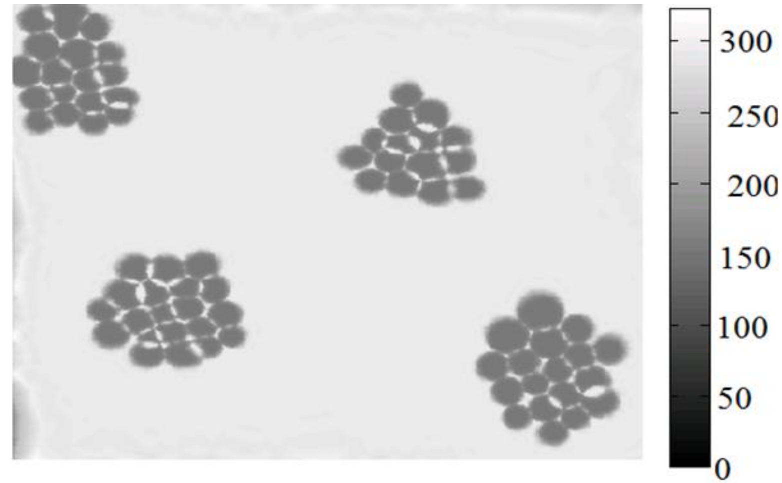
**Finite Element Method showing the formulation of triangular elements in a nano-filled sample**

$$\rho C_p \frac{\partial T}{\partial t} + \Delta(-k\Delta T) = Q$$

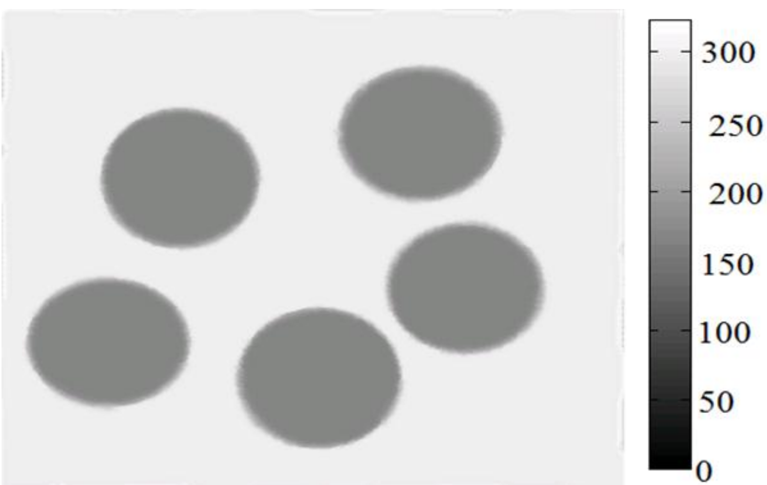
# Thermal Analysis: Model Results



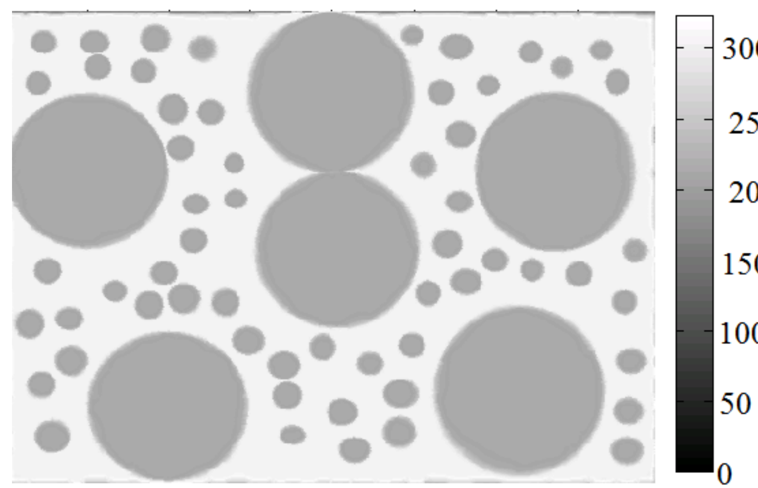

**Localized Temperature for 2.5% N sample (dispersed)**




**Localized Temperature for 2.5% N sample (agglomerated)**

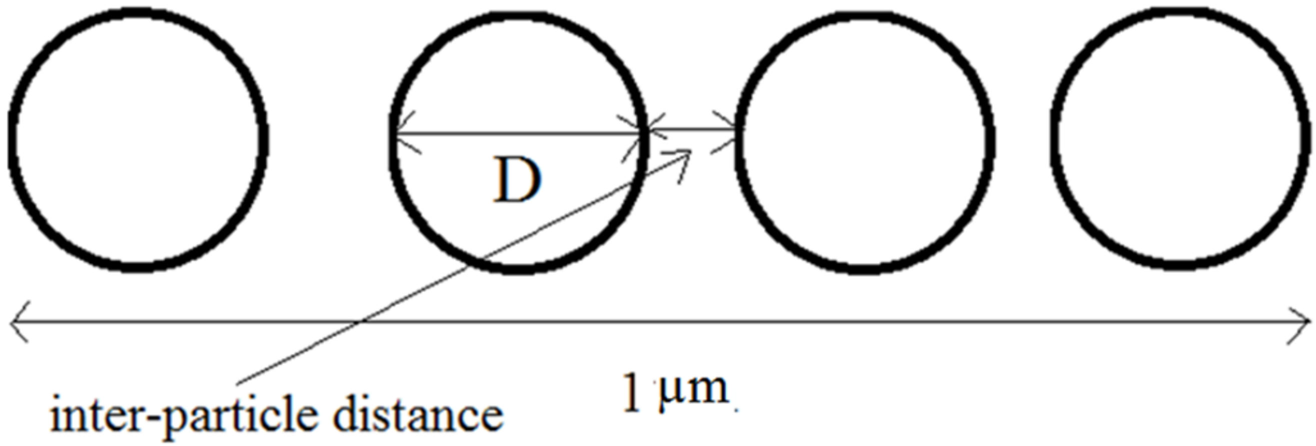



**Localized Temperature for 30% M sample**




**Localized Temperature for 40% M + 2.5% N sample**

# Localized Temperature Calculations




| Sample | Length covered by filler (μm) | Length covered by the matrix (μm) | Average Temperature (°C) |
|---|---|---|---|
| 0% | - | - | 300 |
| 30% M | 297 | 703 | 255.4 |
| 50% M | 720 | 280 | 192 |
| 2.5% N | 320 | 680 | 252 |
| 5% N | 440 | 560 | 234 |
| 40% M+ 2.5% N | 748 | 252 | 187.8 |
| 40% M + 5% N | 767 | 233 | 185 |

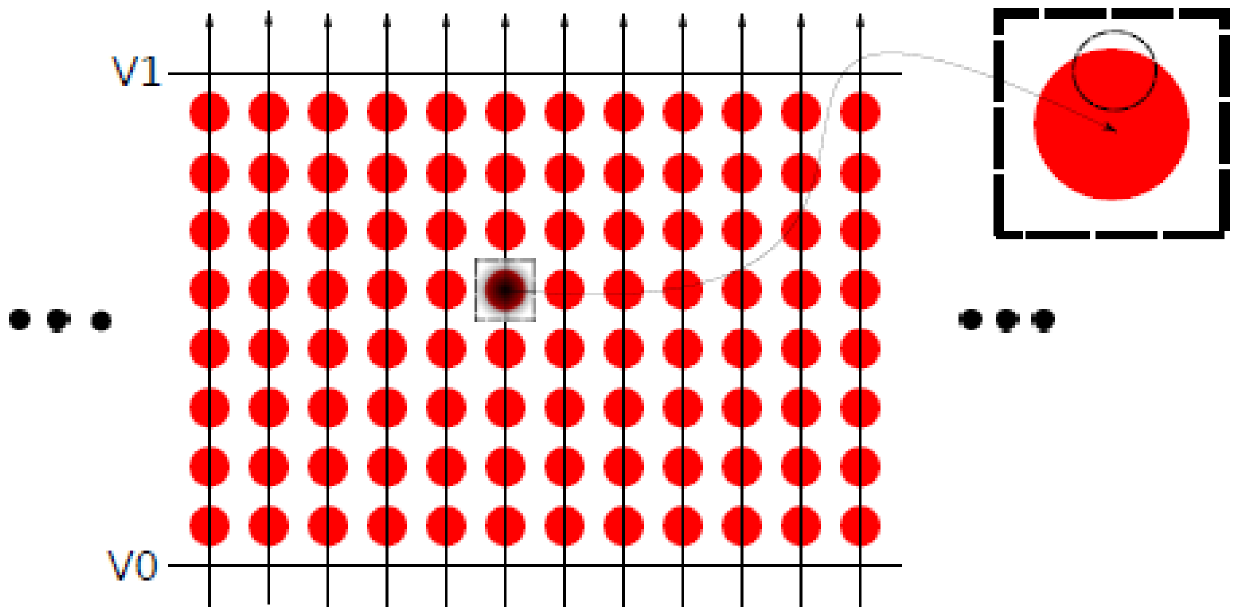
# Thermo Gravimetric Analysis (TGA)

- TGA measurements conducted on the samples to measure the weight loss initiation temperature
- Measurements showed higher weight loss initiation temperatures for samples containing nanofillers as compared to unfilled and microfilled samples
- Measurements supported partial discharge endurance results

| Sample Type | Temperature for weight loss initiation (°C) |
|---|---|
| 65% M | 259 |
| 62.5% M + 2.5% N | 285.5 |
| 60% M + 5% N | 290 |
| 65% M + 5% N | 280 |
| 5% N | 214 |
| 2.5% N | 85.8 |
| 0% | 87.6 |

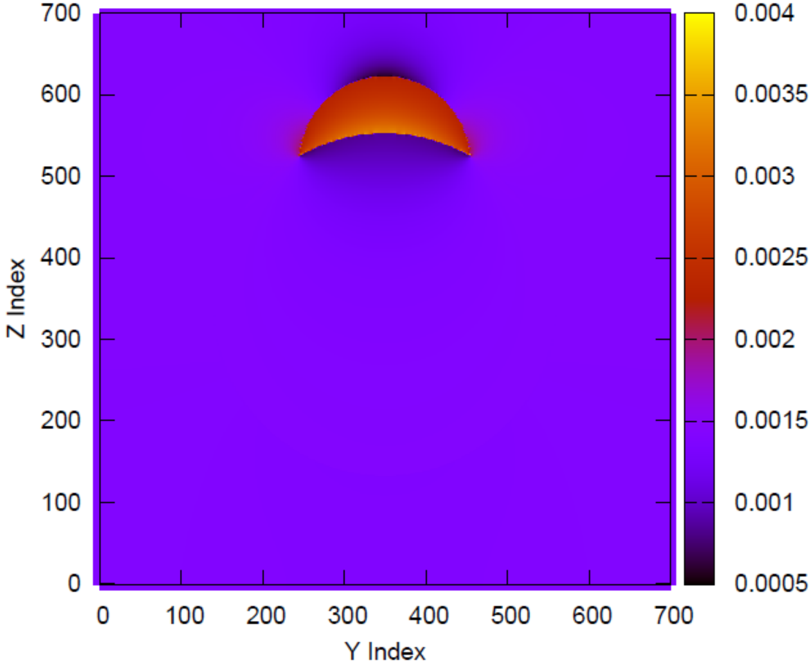
# Electric Field Calculations

- Electric field calculations done to explain corona resistance performance
- Numerical model to calculate electric field in a periodic array of cells
- **Electric field calculations conducted on spherical particles with voids on the side and the top of the particle**
- Onset of partial discharges can be predicted based on the electric field calculations

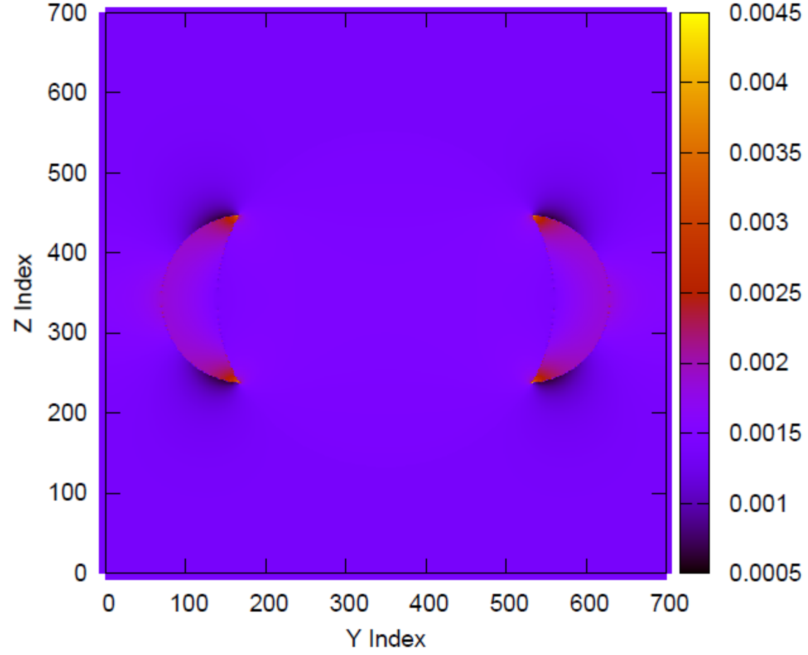



**Cell with spherical dielectrics, voids shown as darker regions around each cell**

# Electric Field Results



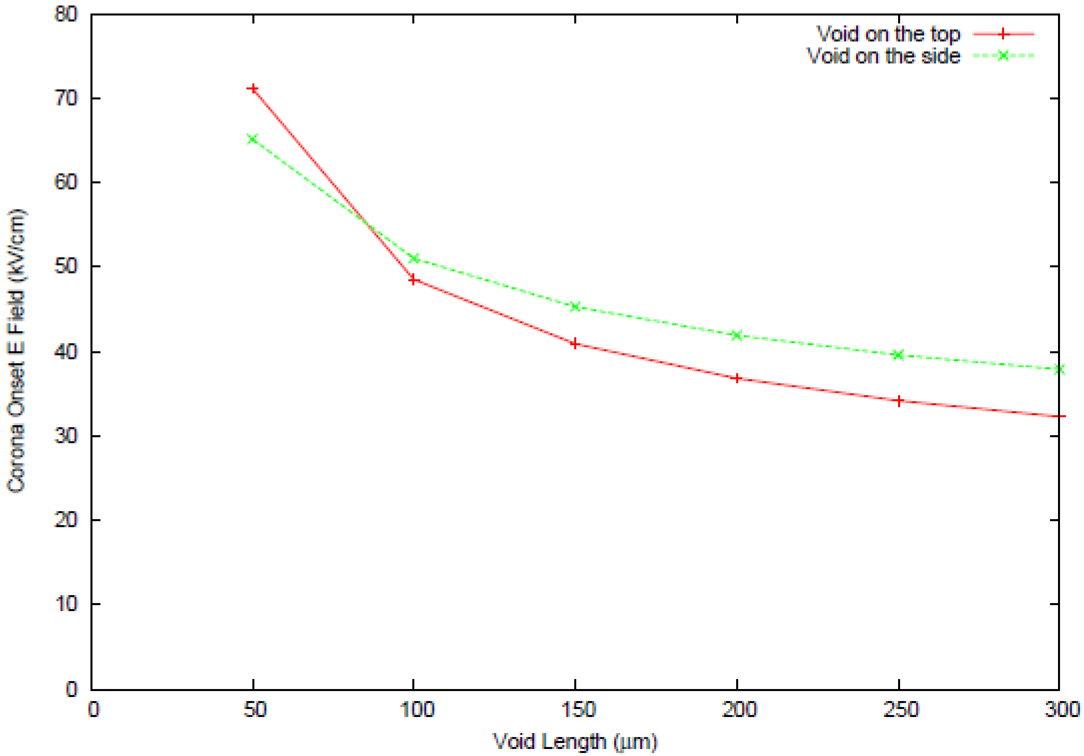

**Electric field in z direction with void on top of the particle**




**Electric field in z direction with void on sides of the particle**

- Electrons provided with a longer free path when the voids as compared to the top of the sphere

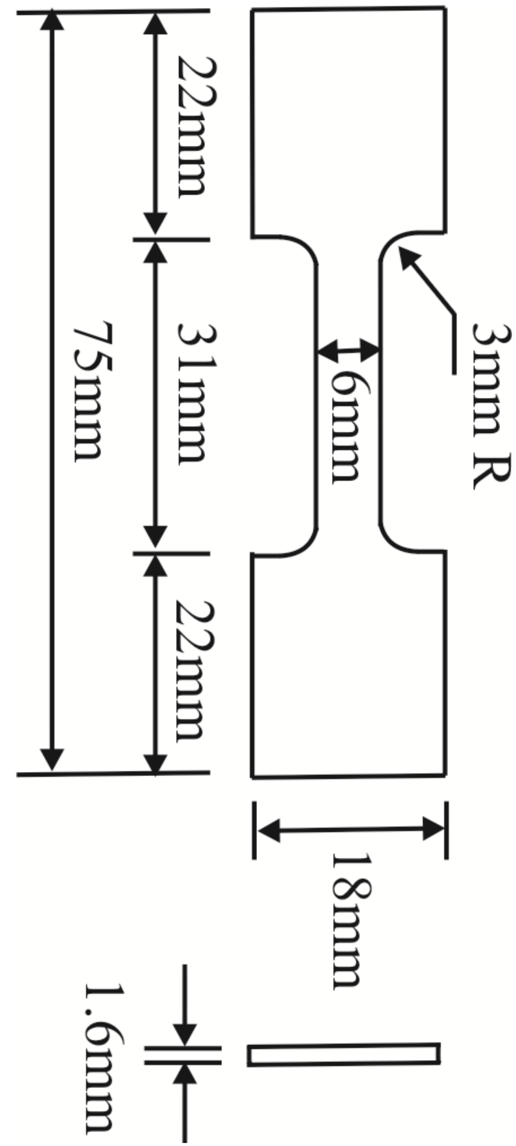
# Electric Field Results




**Corona onset electric field for different void sizes**

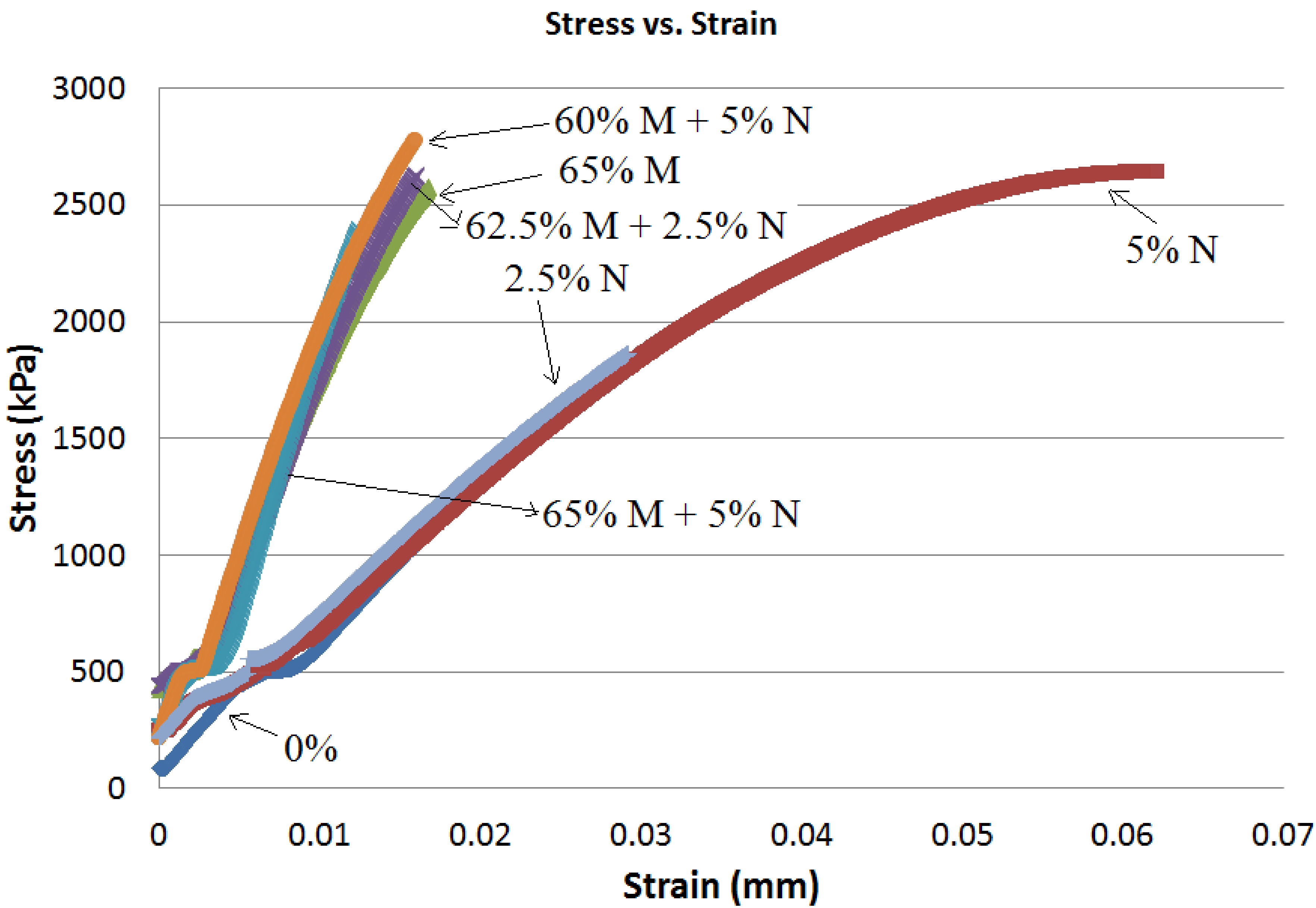
- Larger cells provide a greater void length for electrons to avalanche
- However, voids on the side have corona onset at a higher electric field (compared to when the void on the top) even though the geometry has a longer free path because the field inside the side void is lower than the top void

# Tensile Strength Measurements

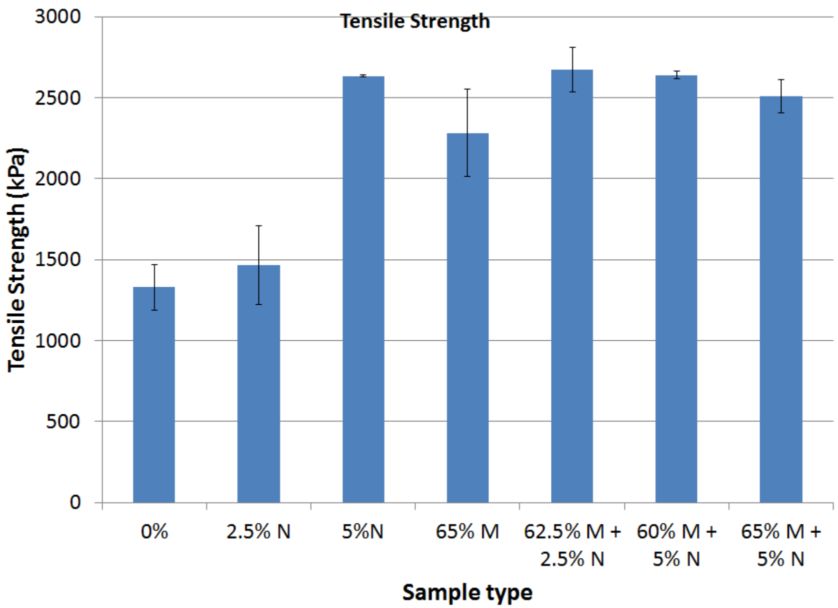



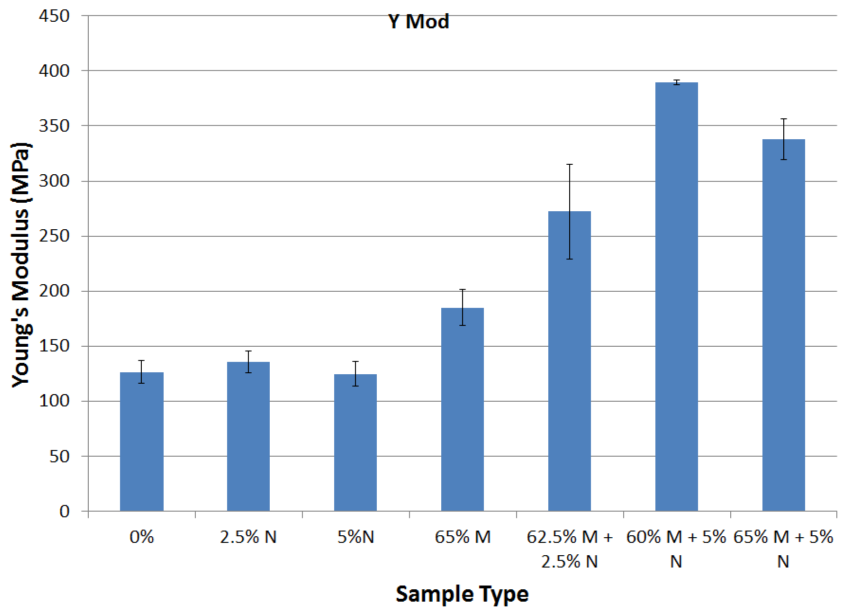

- Three samples of each type were tested
- The samples were cut in dog bone shape
- The rate of deformation was set at 0.1 mm/min

# Tensile Strength Results



# Tensile Strength Results




**Tensile Strength** **Young's Modulus**

- Addition of nano-fillers improves the tensile strength of the samples
- Samples containing micro-fillers have more rigidity and stiffness as compared to nanofilled and the unfilled samples
- So improvement in electrical properties of the micro+ nanofilled samples compared to microcomposites is not at the cost of mechanical strength

# Conclusions

- Nano filled epoxies show superior performance when compared with unfilled and micro filled samples (of the same filler concentration)
- Uniform filler dispersion is the key to good electrical performance. Quite difficult to achieve in large samples.
- Mixture of micro and nanofillers can provide improvement in electrical performance when compared with micro fillers only.
- Extensive experimentation required to establish superior performance of nanocomposites. Traditional short term experiments may not be adequate
- Theoretical models have been developed to complement experimental results
- Much work needs to be done to fully exploit advantages of nanodielectrics.