Structural Engineering Research Group
(SERG)
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Dielectric Modeling of Hydrated Cement Paste Panels

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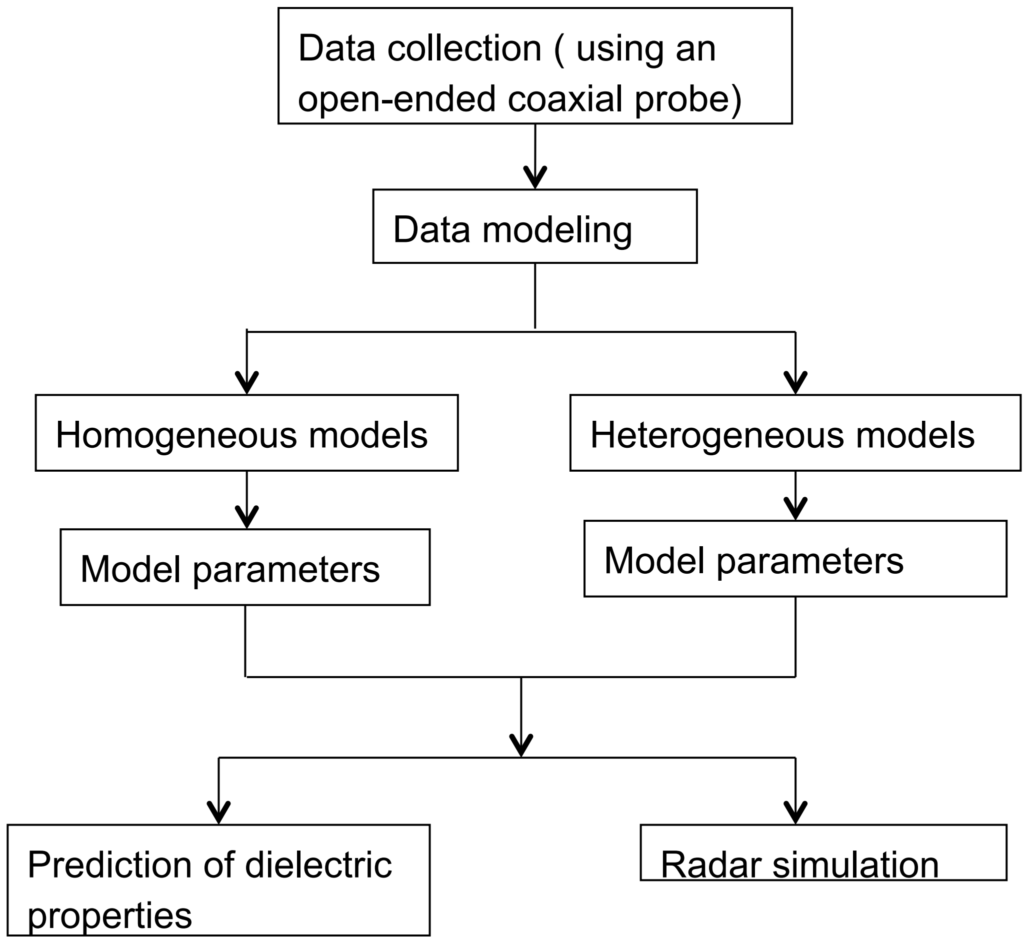
Outline

Objectives

- To apply existing dielectric models for dielectric properties of hydrated cement paste panels considering moisture content, water-to-cement (w/c) ratio and measurement frequency

- To better understand the inspection data using electromagnetic (EM) sensors

Thesis Roadmap



Dielectric Property

- Dielectric properties represent the ability of a material to permit an electric field passing through it, and are expressed by complex electric permittivity.

$\epsilon^{*} = \epsilon' - i\epsilon''$

where

ϵ = Complex electric permittivity (F/m),

ϵ' = Real part of complex electric permittivity (Dielectric constant, F/m), and

ϵ'' = Imaginary part of complex electric permittivity (Loss factor, F/m).

$\epsilon_r^{*} = \epsilon^{*} / \epsilon_0 = \epsilon_r' - i\epsilon_r''$

ϵ_r = Complex electric permittivity,

ϵ_r' = Real part of complex electric permittivity (Dielectric constant), and

ϵ_r'' = Imaginary part of complex electric permittivity (Loss factor).

Literature Review

1. Applications of Dielectric Properties in Civil Engineering

- Phase velocity of EM waves in construction materials
- Amplitude of EM waves
- Radius of reinforcing bars
- Moisture content in cementitious materials
- Thickness gauging of materials

2. Dielectric Measurements on Cementitious Materials

Experimental Methods

- Transmission line
- Free space
- Coaxial probe
- Waveguide
- Parallel plate capacitor

Influencing Factors from Coaxial Measurements

- Moisture content
- W/C ratio
- Measurement frequency
- External environment

Literature Review

3. Dielectric Modeling

Homogeneous Models

- Debye's model
- Havriliak-Negami's Model
- Yu's model

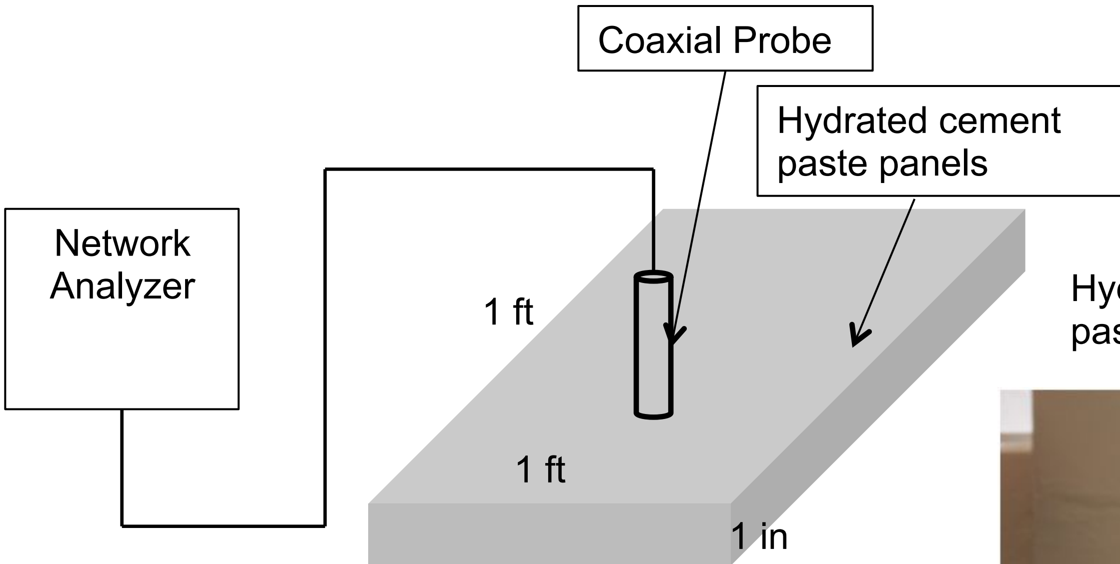
Heterogeneous Models

- Maxwell-Garnett's Model
- Wiener's Model
- Polder-van Santen's model

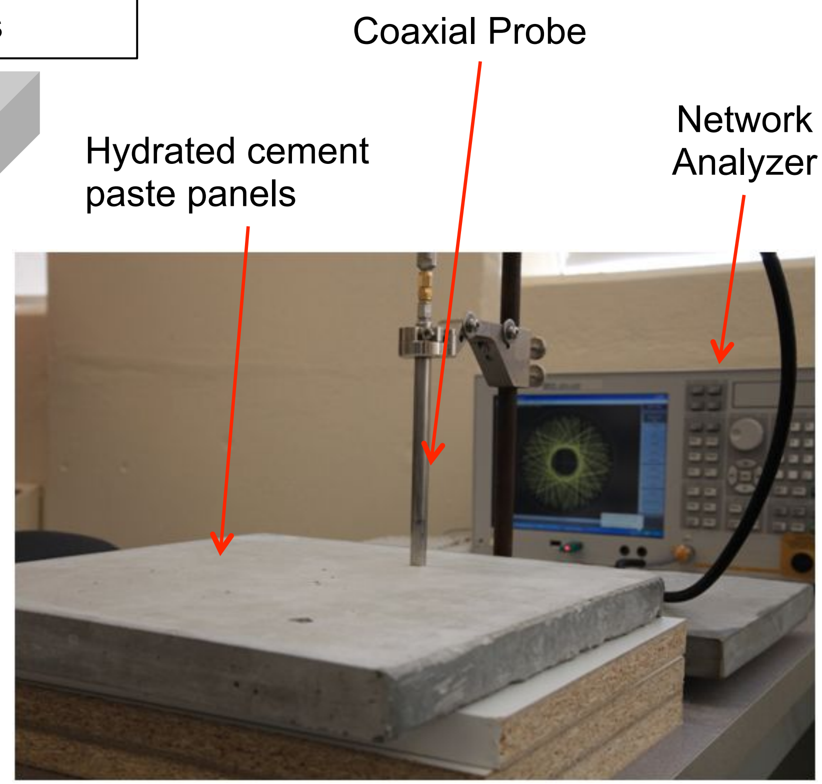
➢ **Three limitations**

- few models were applied on cementitious material
- not much dielectric data on cementitious materials
- not originally developed for cementitious materials

Experimental Setup



Schematic of experimental setup



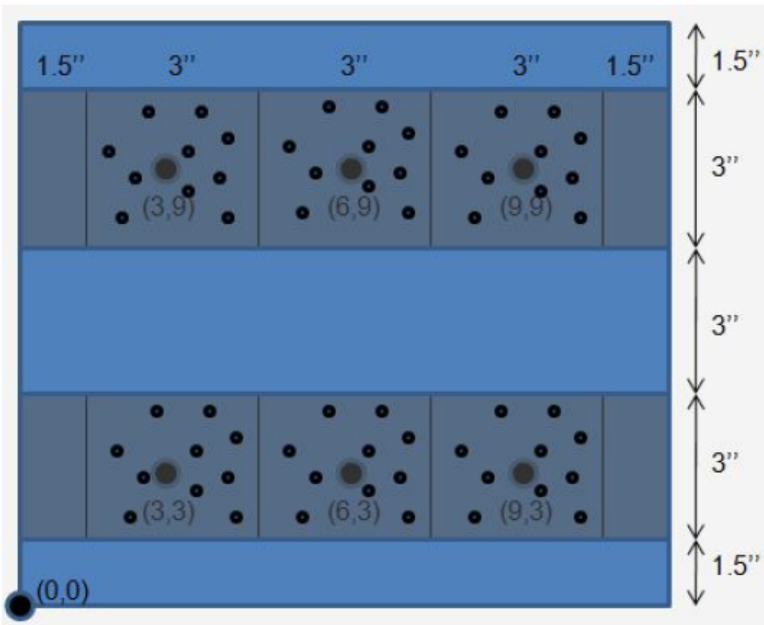
Experimental setup

- W/C ratios: 0.35, 0.4, 0.42, 0.45, 0.5, 0.55
- Moisture content: Dielectric measurements were taken on both room-conditioned and oven-dried panels.
- Frequency: 0.5 GHz to 4.5GHz with the interval of 0.04 GHz

Error Reduction

- Calibration at the tip of the probe
- Three main sources of error

Error Source	Solution
Air gap	1. Visual inspection 2. Make the surface smooth
Size of probe	Collected from 60 points and take the average
External environment	In relatively stable environment



Data points
(Source: Solak)

Calibration kit and probe
(Source: Agilent® Technologies)

Plexiglass

Mold

Outline

Equation of Debye's Model

- **Equation**

$$\epsilon(\omega)=\epsilon_{\infty}+\frac{\epsilon_{s}-\epsilon_{\infty}}{1+i\omega\tau}$$
(1)

$$\epsilon'(\omega)=\epsilon_{\infty}+\frac{\epsilon_{s}-\epsilon_{\infty}}{1+(\omega\tau)^{2}}$$
(2)

$$\epsilon'(\omega)=\frac{\omega\tau(\epsilon_{s}-\epsilon_{\infty})}{1+(\omega\tau)^{2}}$$
(3)

where

$\epsilon(\omega)$ = Dielectric properties from modeling,

ϵ_{∞} = Dielectric constant at infinite frequency,

- **Relaxation Time**

$$\tau=\frac{\epsilon_{r}''}{\omega\times(\epsilon_{r}'-\epsilon_{\infty})}$$
(4)

where

τ = Relaxation time (ns),

ϵ_{r}'' = Loss factor from measurements (Imaginary part of relative complex electric permittivity),

ω = Frequency (GHz),

ϵ_{r}' = Dielectric constant from measurements (Real part of relative complex electric permittivity), and

ϵ_{∞} = Dielectric constant at infinite

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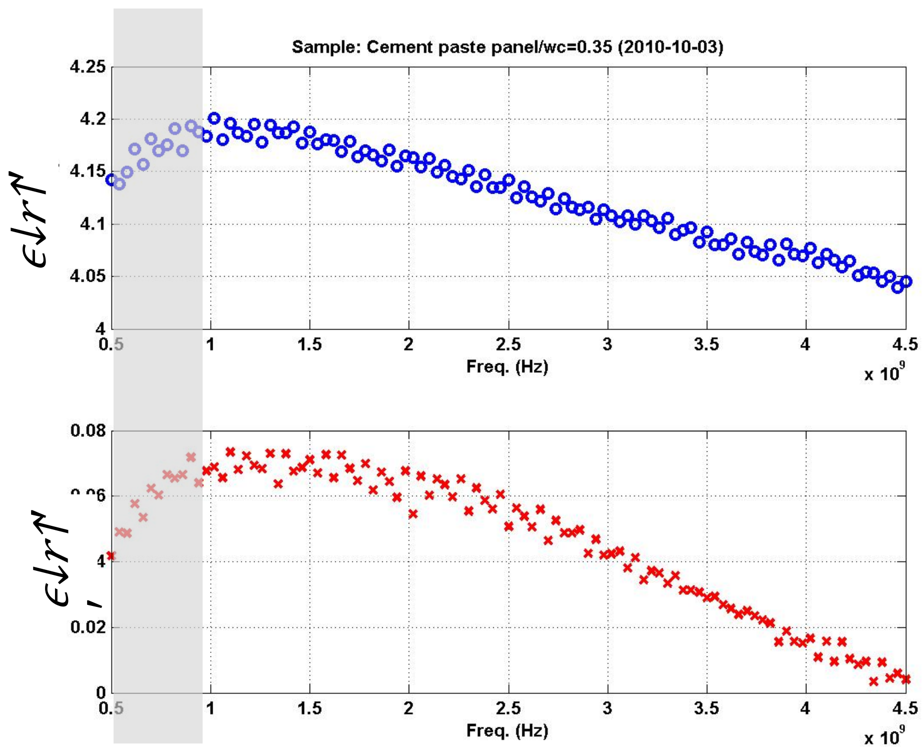
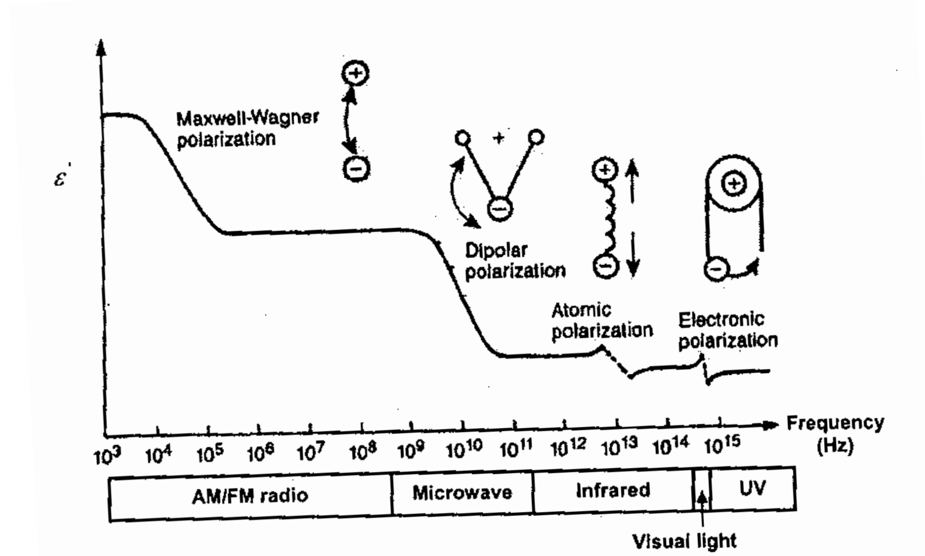
Experimental Results

- **Oven-dried Cement Paste Panels with W/C=0.35 (CP35)**



Experimental results on oven-dried CP35



Dielectric dispersion (Source: Yu)

The data from 0.5 GHz to 0.98 GHz was removed since it increases with the increase of frequency which is against with the theory of dielectric dispersion.

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Procedure of Debye's Model

Step 1: Calculate ϵ_∞

Step 1.1: $\tau = \epsilon_r'' / \omega \times (\epsilon_r' - \epsilon_\infty)$ by substituting assumed values of ϵ_∞, and plot τ with frequency.

Step 1.2: Look for the initial curve which shows that τ decreases at first and increases in the end with frequency, and refine ϵ_∞.

Step 1.3: Get the curve of τ with frequency at the determined value of ϵ_∞.

Step 2: $\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau}$ with different combinations of assumed ϵ_s and τ.

Step 3: Calculate the norm error (NE) between modeling and experiment results, and find ϵ_s and τ which lead to the minimum error.

where

$$NE = \sum \{ |\epsilon_{exp}'(\omega) - \epsilon_m'(\omega)| + |\epsilon_{exp}''(\omega) - \epsilon_m''(\omega)| \}$$

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Relaxation Time with. Frequency

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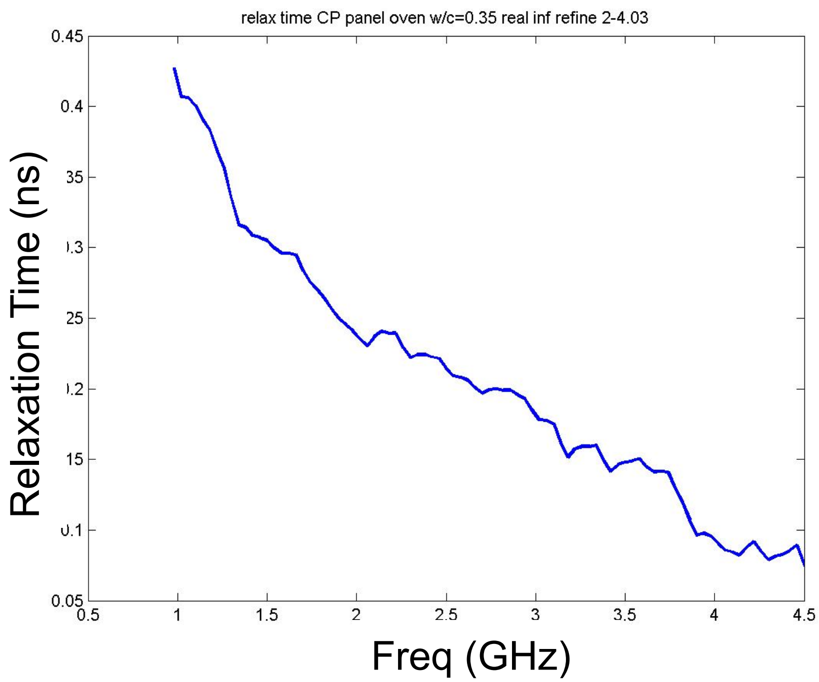
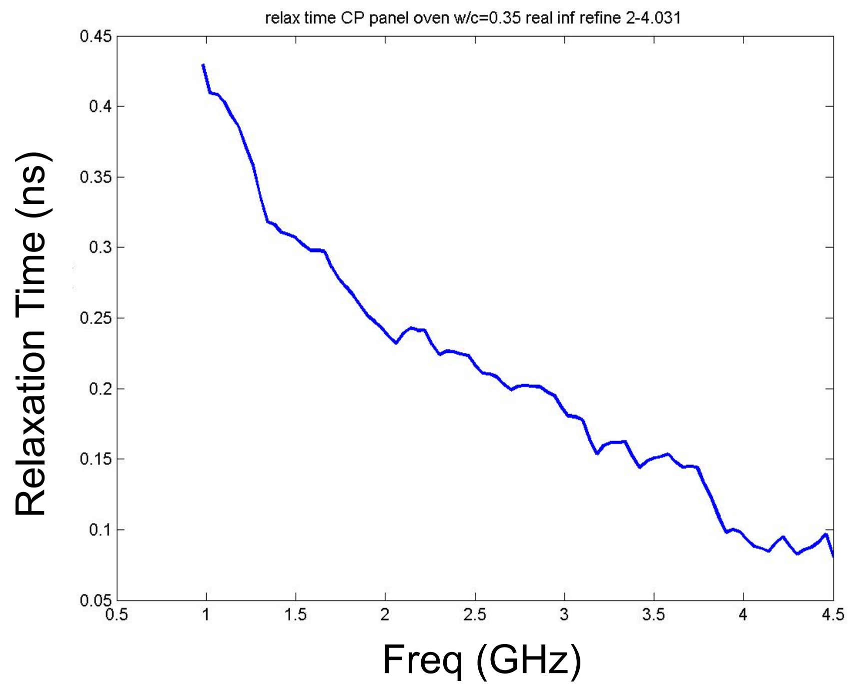
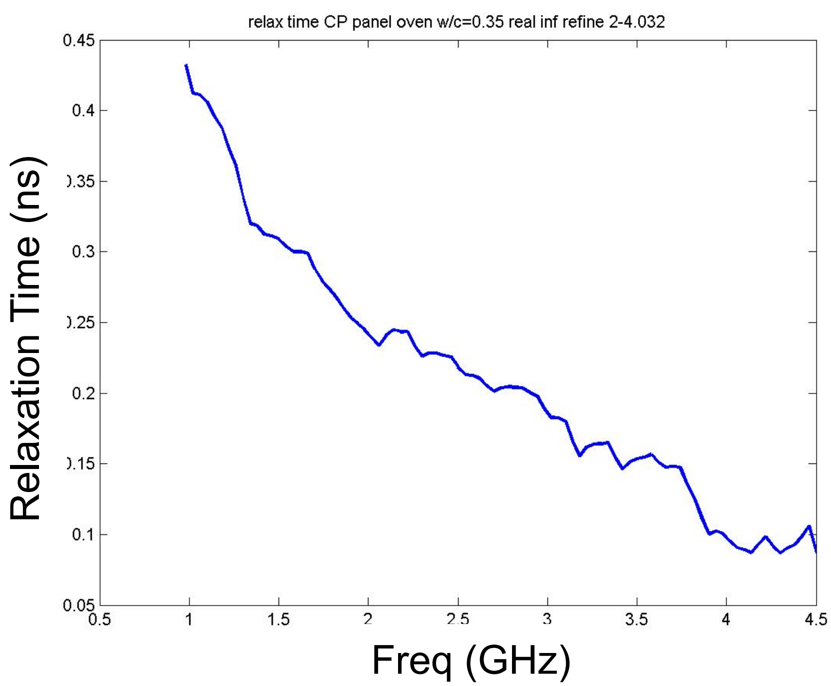


Relaxation time with frequency for oven-dried CP35 - ϵ_{∞} **=4.030**

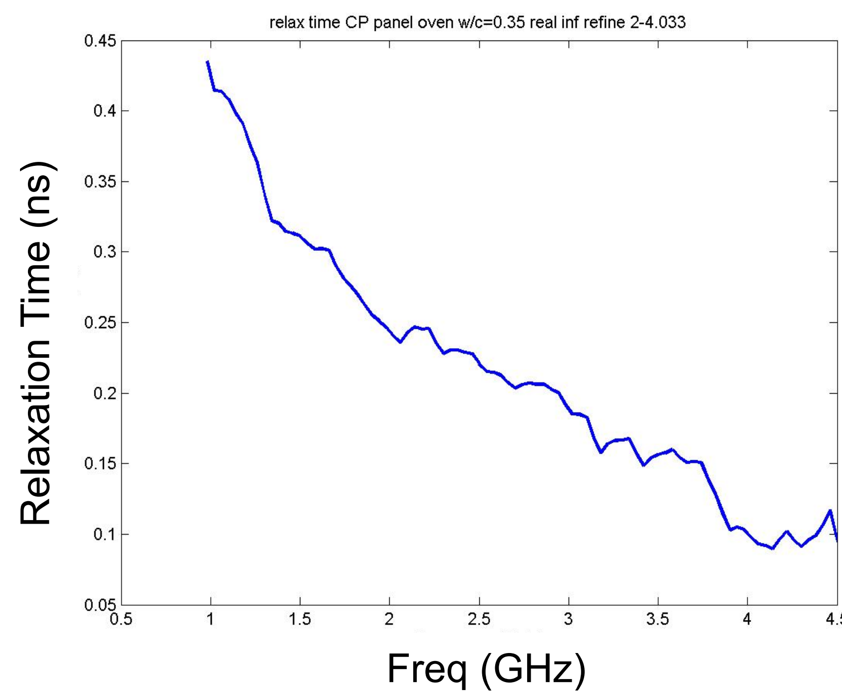


Relaxation time with frequency for oven-dried CP35 - ϵ_{∞} **=4.031**

Relaxation Time with. Frequency



Relaxation time with frequency for oven-dried CP35 - ϵ_∞ **=4.032**



Relaxation time with frequency for oven-dried CP35 - ϵ_∞ **=4.033**

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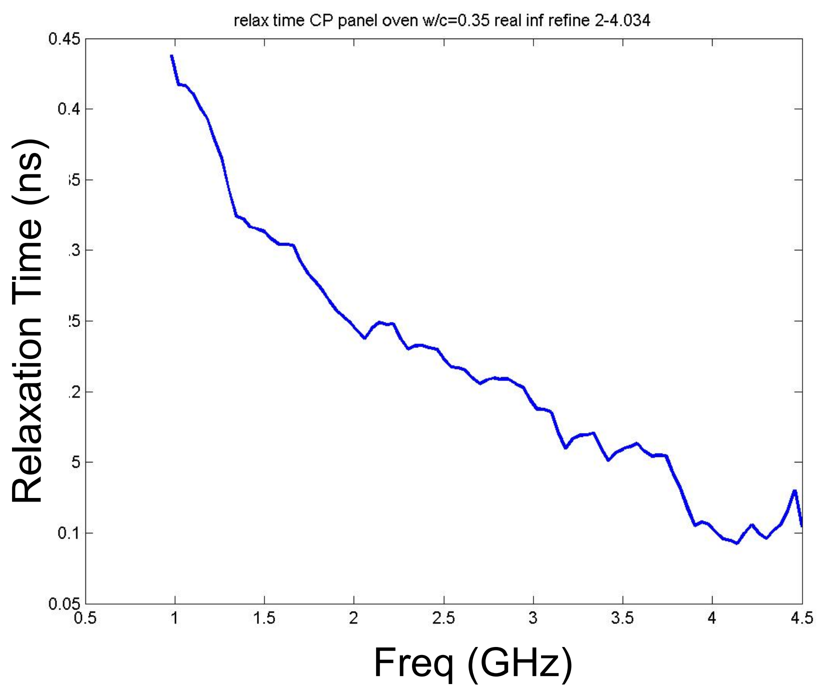
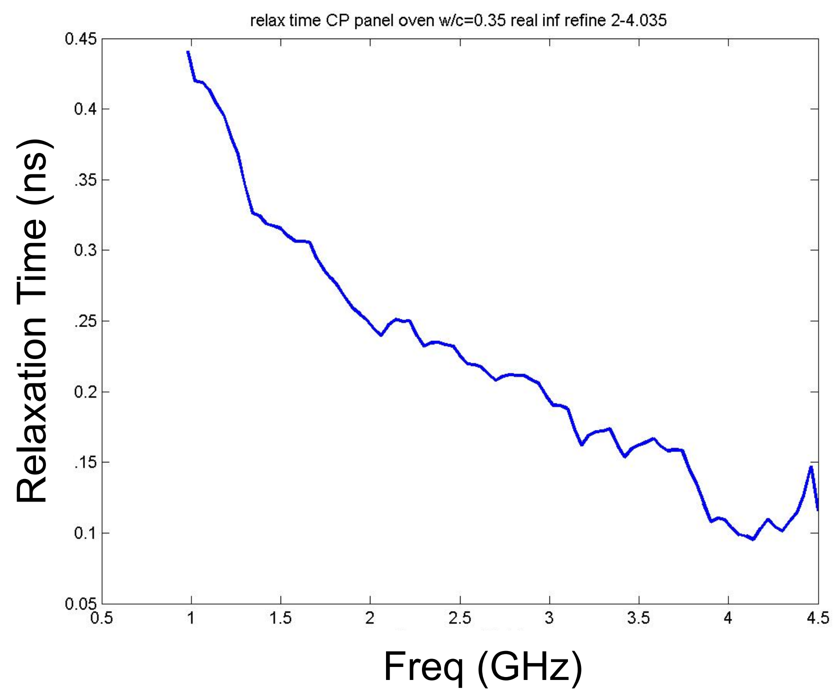
Relaxation Time with. Frequency



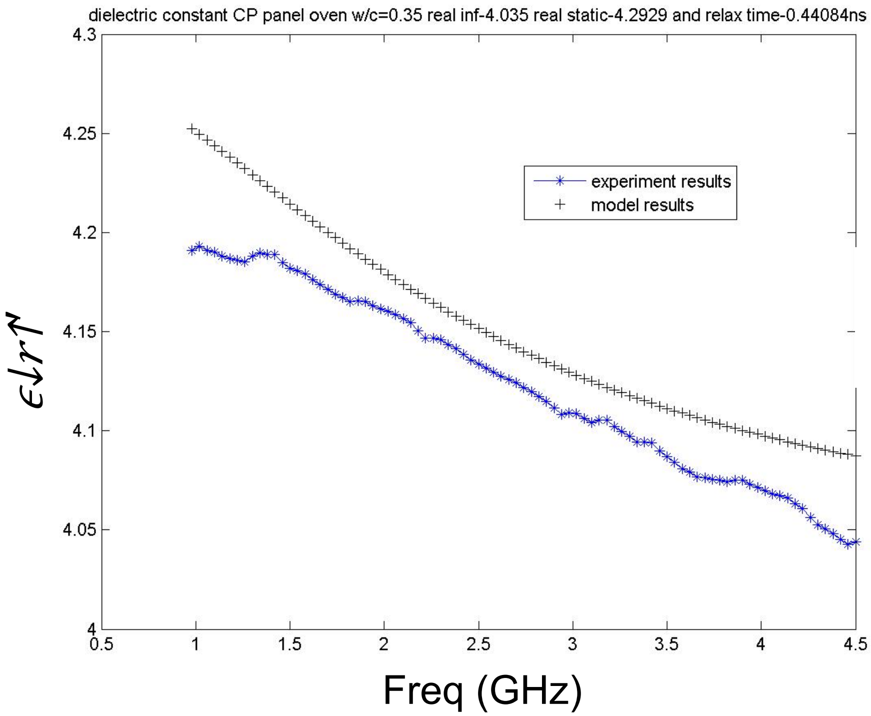
Relaxation time with frequency for oven-dried CP35 - ϵ_∞ **=4.034**



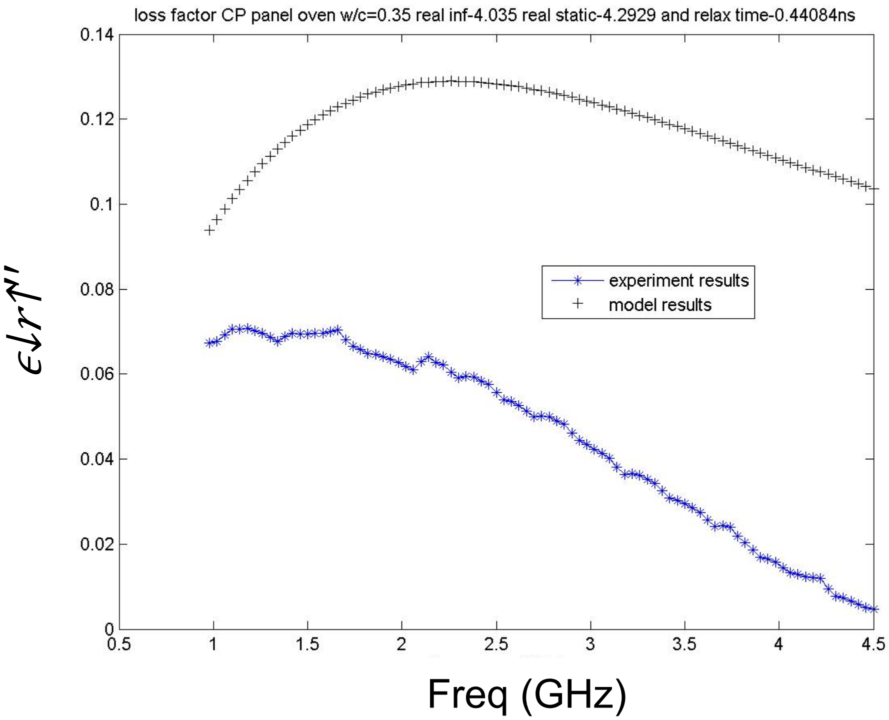
Relaxation time with frequency for oven-dried CP35 – **final value of** ϵ_∞ **=4.035 Final curve of** τ

Results of Debye's Model

- **Oven-dried Cement Paste Panels**



Dielectric constant – model vs experiment (CP35)



Loss factor – model vs experiment (CP35)

Determined values:

ϵ_s =4.2929, τ=0.4408 ns

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Results of Debye's Model

In summary, the modeling results of dielectric constant is close to experimental results, but loss factor on oven-dried CP35 does not match experimental data on the trend of the curve as well as the values. This is due to the mathematical expression of the imaginary part.

$$\epsilon''(\omega) = \frac{\epsilon_s - \epsilon_\infty}{\frac{1}{\omega\tau} + \omega\tau}$$

where

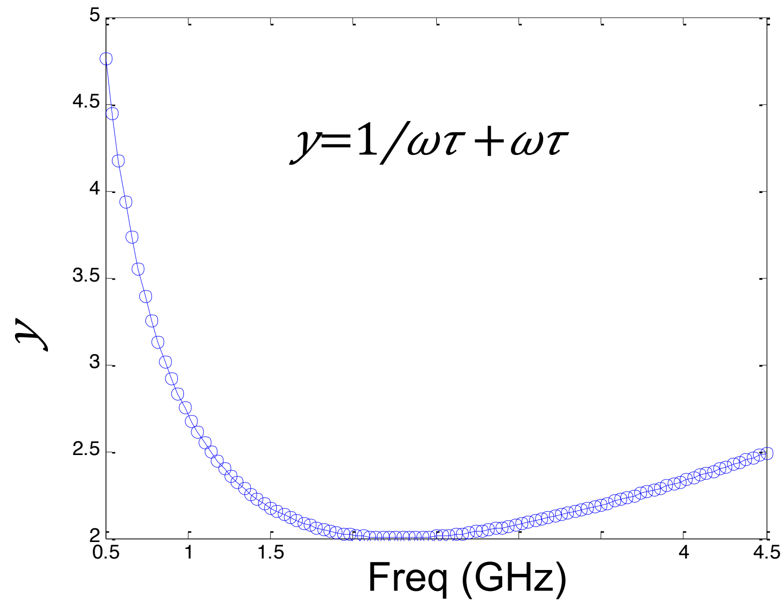
$\epsilon''(\omega)$ = Loss factor from modeling,

ϵ_∞ = Dielectric constant at infinite frequenc

ϵ_s = Dielectric constant at zero frequency,

$\omega = Frequency\ (GHz)$, and

τ = Relaxation time (ns).



Debye's Parameters

- **Oven-dried Cement Paste Panels**

W/C ratio	ϵ_∞	ϵ_s	τ (ns)	NE
0.35	4.035	4.2929	0.4408	0.9970
0.40	4.086	4.4621	0.2788	1.2626
0.42	3.887	4.3562	0.3146	0.9399
0.45	4.180	4.6422	0.3399	0.8920
0.50	4.446	4.7047	0.5640	0.4189
0.55	4.449	4.7242	0.4755	0.4859

From modeling parameters, ϵ_∞ and ϵ_s generally increase with the increase of w/c ratio, but τ does not have obvious trend.

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Results of Debye's Model

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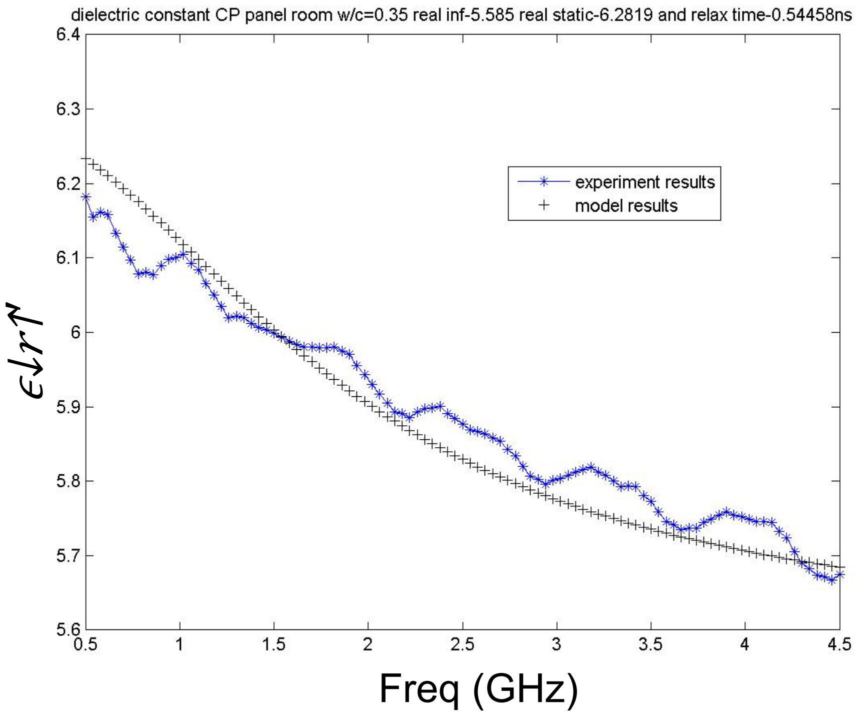
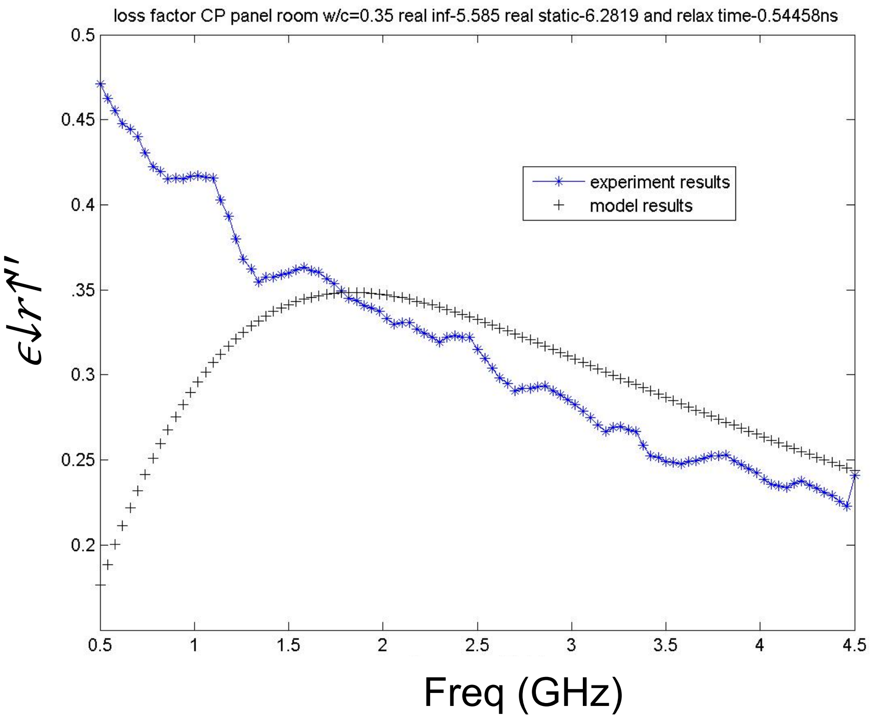
- **Room-conditioned Cement Paste Panels**



Dielectric constant – model vs experiment (CP35)



Loss factor – model vs experiment (CP35)

Determined values:

ϵ_∞ =5.585, ϵ_s =6.2819, τ=0.5446 ns

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Debye's Parameters

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- **Room-conditioned Cement Paste Panels**

W/C ratio	ϵ_{∞}	ϵ_{s}	τ (ns)	NE
0.35	5.585	6.2819	0.5446	1.2110
0.40	5.147	5.6573	0.4975	0.739
0.42	5.123	5.6331	0.5365	0.8066
0.45	4.956	5.4472	0.5111	0.7316
0.50	4.907	5.3661	0.4499	0.9475
0.55	4.618	5.1963	0.4120	0.5622

From modeling parameters, ϵ_{∞} and ϵ_{s} show the descending trend with the increase of w/c ratio, which is in contrast with the results from oven-dried cement paste panels. In addition, τ generally decreases with the increase of the w/c ratio.

Outline

Havriliak-Negami's Model

$$\epsilon(\omega)=\epsilon_{\infty}+\frac{\epsilon_{s}-\epsilon_{\infty}}{(1+(i\omega\tau)^{\alpha_{2}})^{\gamma}}$$

where

$\epsilon(\omega)$ = Dielectric properties from modeling,

ϵ_{∞} = Dielectric constant at infinite frequency,

ϵ_{s} = Dielectric constant at zero frequency,

i = Imaginary number,

ω = Frequency (GHz),

τ = Relaxation time (ns), and

α_{2} and γ : Empirical parameters.

Procedure

Step 1: Calculate ϵ_∞

Step 1.1: $\tau = \epsilon_r'' / \omega \times (\epsilon_r' - \epsilon_\infty)$ by substituting assumed values of ϵ_∞, and plot τ with frequency.

Step 1.2: Look for the initial curve which shows that τ decreases at first and increases in the end with frequency, and refine ϵ_∞.

Step 1.3: Get the curve of τ with frequency at the determined value of ϵ_∞.

Step 2: $\epsilon(\omega) = \epsilon_\infty + \epsilon_s - \epsilon_\infty / 1 + i\omega\tau$ with different combinations of possible ϵ_s, τ, α_2 and γ.

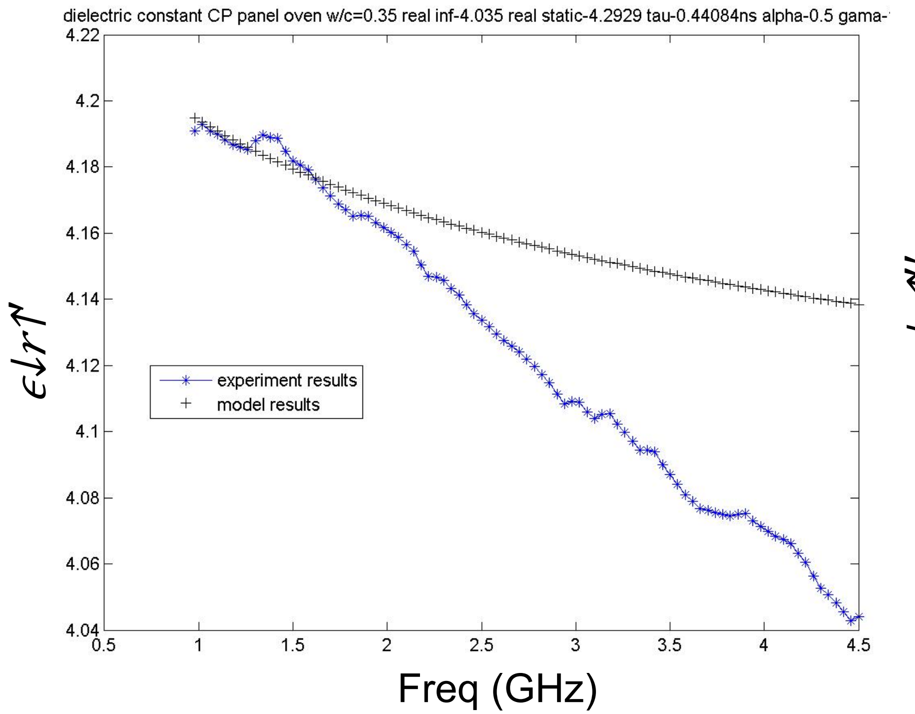
Step 3: Calculate the norm error (NE) between modeling and experiment results, and find ϵ_s, τ, α_2 and γ which lead to the smallest error.

where

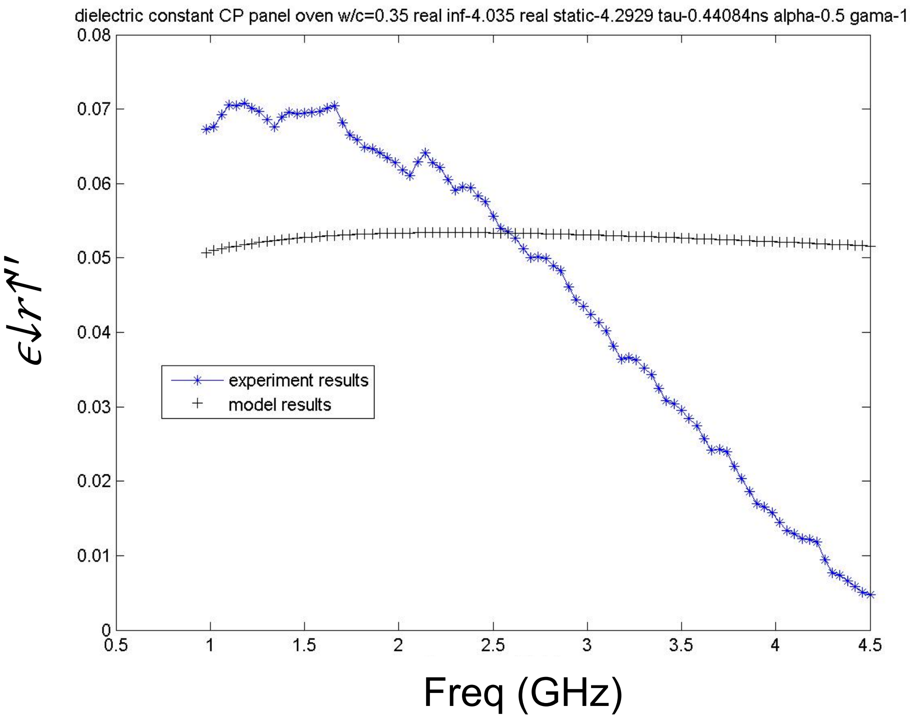
$$NE = \sum \{ |\epsilon_{exp}'(\omega) - \epsilon_m'(\omega)| + |\epsilon_{exp}''(\omega) - \epsilon_m''(\omega)| \}$$

Results

- **Oven-dried Cement Paste Panels**



Dielectric constant – model vs experiment (CP35)



Loss factor – model vs experiment (CP35)

Determined values:

ϵ_∞ **=4.035,** ϵ_s **=4.2929,** τ**=0.4408ns,** α_2 **=0.5,** γ**=1**

Model Parameters

- **Oven-dried Cement Paste Panels**

W/C	ϵ_∞	ϵ_s	τ (ns)	α_2	γ	NE	NE (Debye)
0.35	4.035	4.2929	0.4408	0.5	1	0.6675	1.2110
0.40	4.086	4.4621	0.2788	0.55	1	0.3947	0.739
0.42	3.887	4.3562	0.2845	0.7	1	0.2364	0.8066
0.45	4.180	4.6422	0.3487	0.75	0.85	0.3161	0.7316
0.50	4.446	4.7047	0.7070	0.9	0.9	0.3084	0.9475
0.55	4.449	4.7242	0.5967	0.85	0.9	0.2620	0.5622

- H-N's model provides better modeling results from smaller NE. This is due to the two more parameters in H-N's model.
- τ in H-N's model is different from that obtained by Debye's model. For CP42 and CP45, it is decreases, and it is increased for CP50 and CP55.
- α_2 shows a generally ascending trend with the increase of w/c ratio, and γ remains to be stable.

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Results

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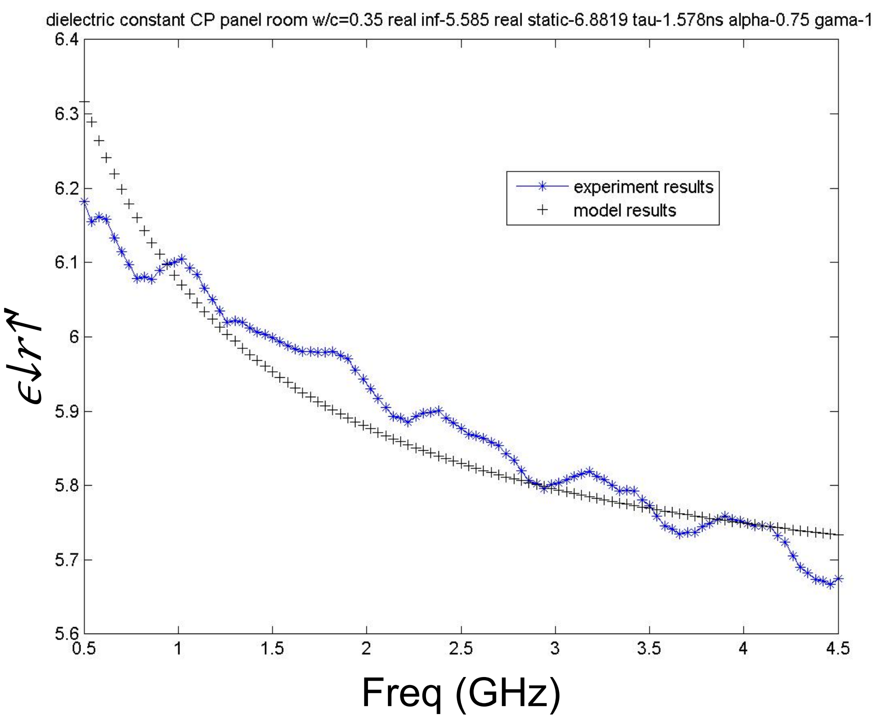
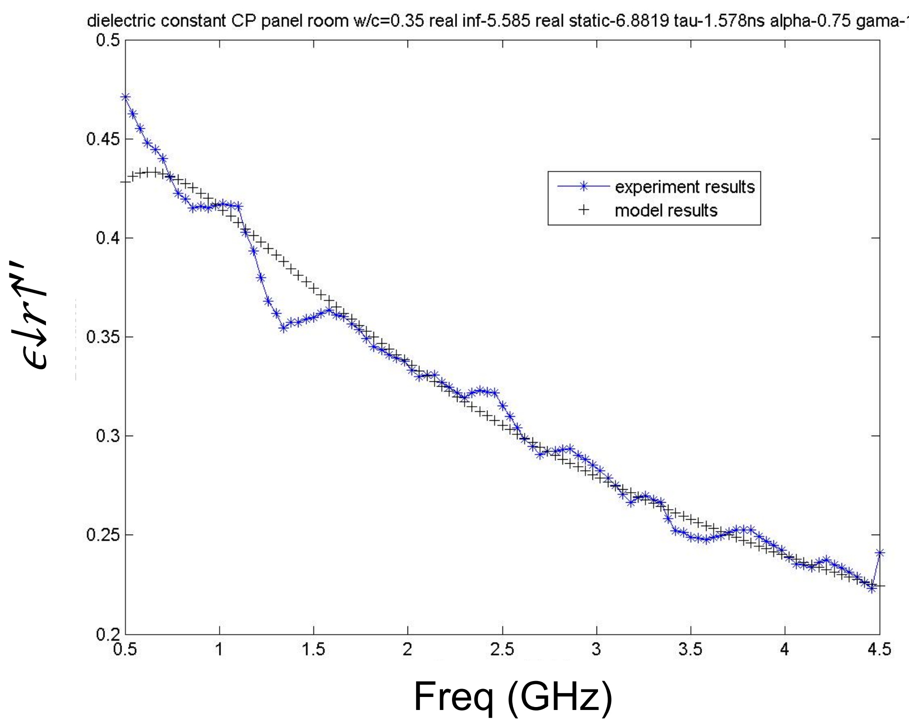
- **Room-conditioned Cement Paste Panels** ★



Dielectric constant – model vs experiment (CP35)



Loss factor – model vs experiment (CP35)

Determined values:

ϵ_∞ **=5.585,** ϵ_s **=6.8819,** τ**=1.578ns,** α_2 **=0.75,** γ**=1**

Model Parameters

➢ **Room-conditioned Cement Paste Panels**

Description	ϵ_∞	ϵ_s	τ (ns)	α_2	γ	NE
CP35	5.585	6.8819	1.578	0.75	1	0.5815
CP40	5.147	5.9573	1.052	0.75	1	0.5262
CP42	5.123	5.9331	1.363	0.7	1	0.5568
CP45	4.956	5.7472	1.146	0.75	1	0.5115
CP50	4.907	5.3661	0.646	0.8	0.85	0.4933
CP55	4.618	5.1963	0.412	1	1	0.5622

- H-N's model provides better modeling results from smaller NE, except CP55. This is due to the two more parameters in H-N's model.
- τ and ϵ_s in H-N's model is different from that obtained by Debye's model.
- α_2 and γ generally remain to be stable.

⇨ α_2 is a more important parameter which can lead the improvement.

Outline

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Yu's Model

$$\epsilon(\omega)=\epsilon_{\infty}+\frac{\epsilon_{s}-\epsilon_{\infty}}{1+(i\omega\tau)^{(\alpha*\varphi)}}=\frac{\gamma}{(C_{1}+\varphi)}*C_{2}+\frac{\frac{\gamma}{(C_{3}+\varphi)}*C_{4}}{1+(i\omega\tau)^{(\alpha*\varphi)}}$$

where

$\epsilon(\omega)$ = Dielectric properties from modeling,

ϵ_{∞} = Dielectric constant at infinite frequency,

ϵ_{s} = Dielectric constant at zero frequency,

i = Imaginary number,

ω = Frequency (GHz),

τ = Relaxation time (ns),

***φ* = W/C ratio**, and

C_1, C_2, C_3, C_4, γ, **and α = Parameters determined by experiment.**

This is an improved version of Debye's model for oven dried cement paste panels

Procedure

Step 1: Fix C_1 and C_2 as negative numbers, calculate γ based on ϵ_∞ obtained from Debye's and H-N's model. Fix C_3 as a negative numbers and calculate C_4 from $\epsilon_s - \epsilon_\infty$ obtained by Debye's and H-N's model

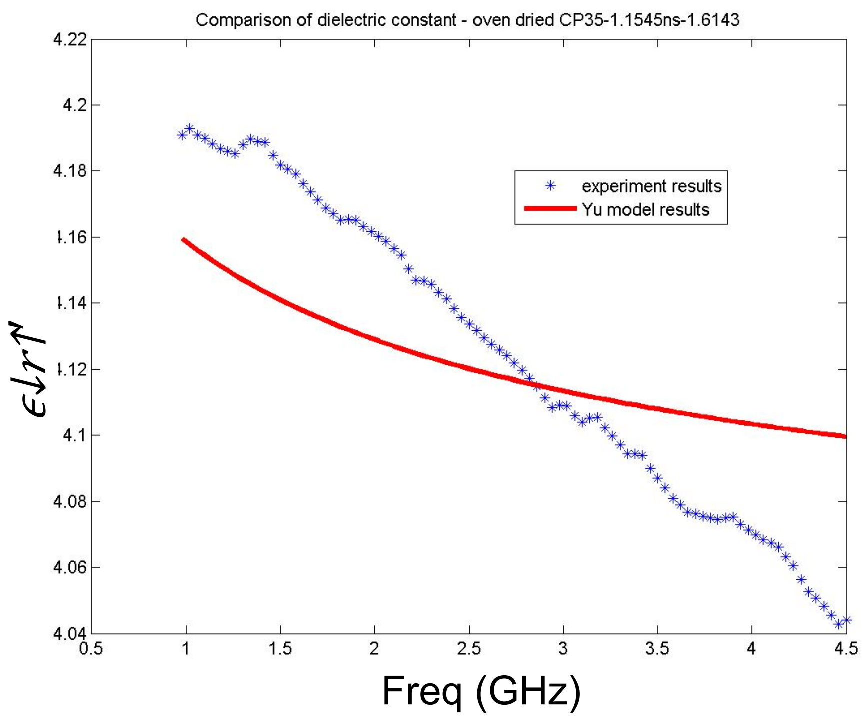
↓

Step 2: Assume τ and α, plug assumed τ and α into Yu's model, and calculate dielectric properties using Yu's model from different combinations of τ and α.

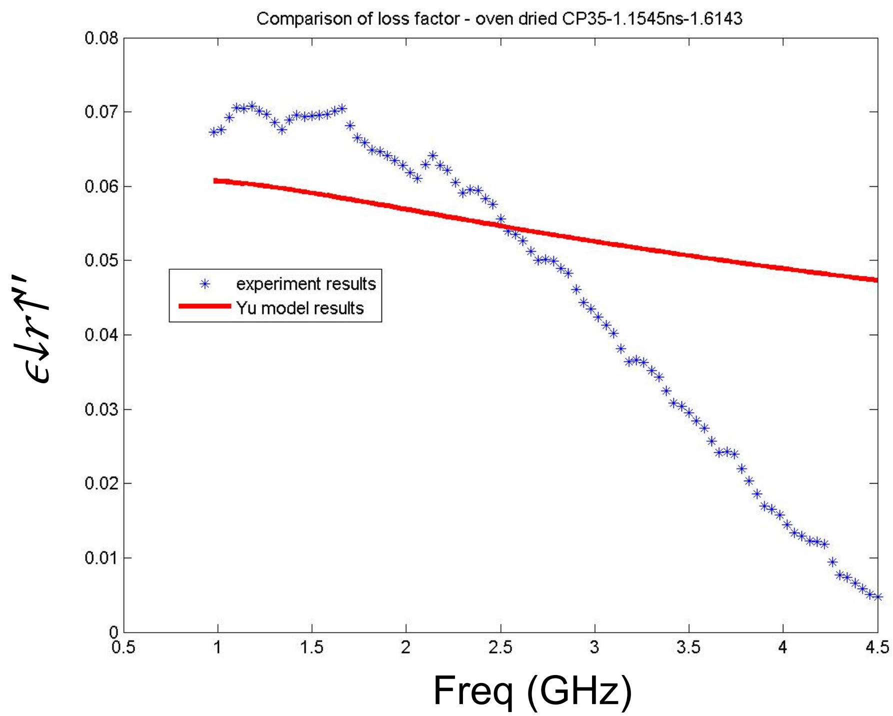
↓

Step 3: Calculate the norm error between modeling results and experiment results, and find τ and α which lead to smallest error.

Results



Dielectric constant – model vs experiment (CP35)



Loss factor – model vs experiment (CP35)

Determined values:

C_1 =-1.25, C_2 =-0.4, C_3 = -1, C_4 =-8.7370, γ=1.4533, τ=1.1415ns, $\alpha*\varphi$=0.57

Model Parameters

W/C ratio	$\alpha*\varphi$	τ(ns)	γ	C_1	C_2	C_3	C_4	NE	NE (H-N)
0.35	0.565	1.155	1.453	-1.25	-0.4	-1.0	-8.737	0.4755	0.6675
0.40	0.6	0.430	1.394				-6.435	0.3422	0.3947
0.42	0.8	0.392	1.314				-5.674	0.2277	0.2364
0.45	0.823	0.421	1.359				-6.270	0.2630	0.3161
0.50	0.9	0.650	1.337				-10.705	0.3006	0.3084
0.55	0.9	0.545	1.252				-11.034	0.2474	0.2620

- C_4 shows a descending trend with the increase of w/c ratio, except for CP35
- $\alpha*\varphi$ increases with the increase of w/c ratio.

Comparison

- **Comparison of Different Models on Oven-dried Cement Paste Panels**

$$PE^{\prime}(\omega)=100\%*\epsilon_{m}^{\prime}(\omega)-\epsilon_{exp}^{\prime}(\omega)/\epsilon_{exp}^{\prime}(\omega)$$

$$PE^{\prime\prime}(\omega)=100\%*\epsilon_{m}^{\prime\prime}(\omega)-\epsilon_{exp}^{\prime\prime}(\omega)/\epsilon_{exp}^{\prime\prime}(\omega)$$

where

$\boldsymbol{PE^{\prime}(\omega)}$ ***= Percentage error of dielectric constant,***

$\boldsymbol{PE^{\prime\prime}(\omega)}$ ***= Percentage error of loss factor,***

$\epsilon_{m}^{\prime}(\omega)$ = Dielectric constant from modeling at a certain frequency,

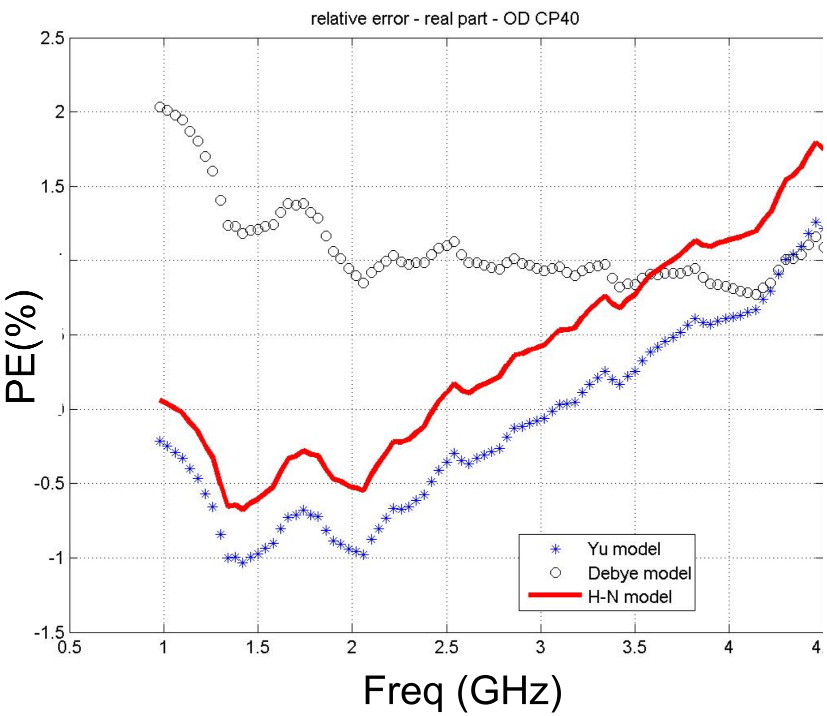
$\epsilon_{exp}^{\prime}(\omega)$ = Dielectric constant from experimental measurements at a certain frequency,

$\epsilon_{m}^{\prime\prime}(\omega)$ = Loss factor from modeling at a certain frequency, and

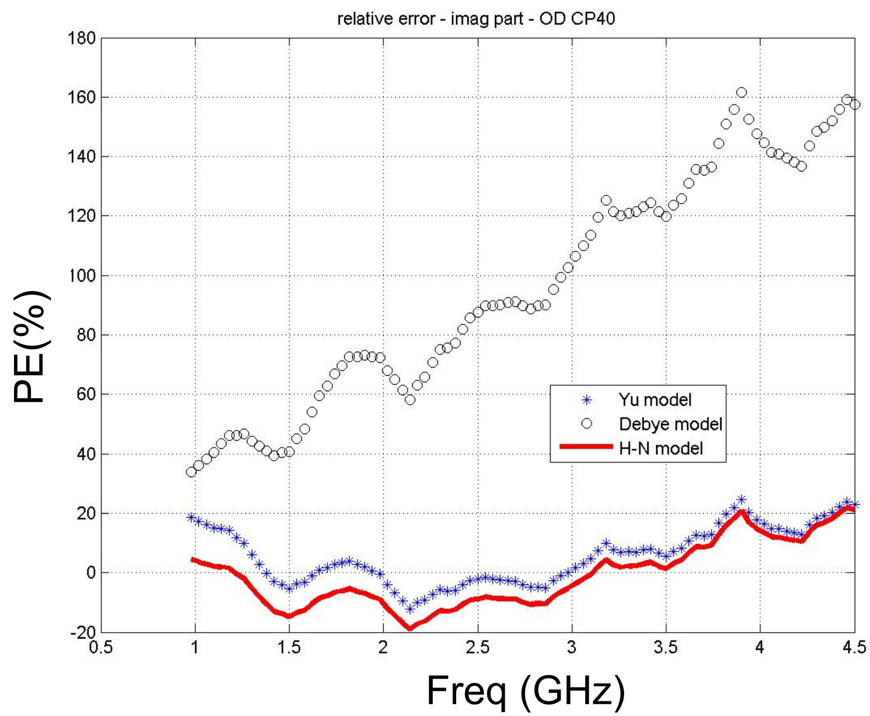
$\epsilon_{exp}^{\prime\prime}(\omega)$ = Loss factor from experimental measurements at a certain frequency.

Comparison

➢ **Comparison of Different Models on Oven-dried Cement Paste Panels**



Dielectric constant – PE (CP40)



Loss factor – PE (CP40)

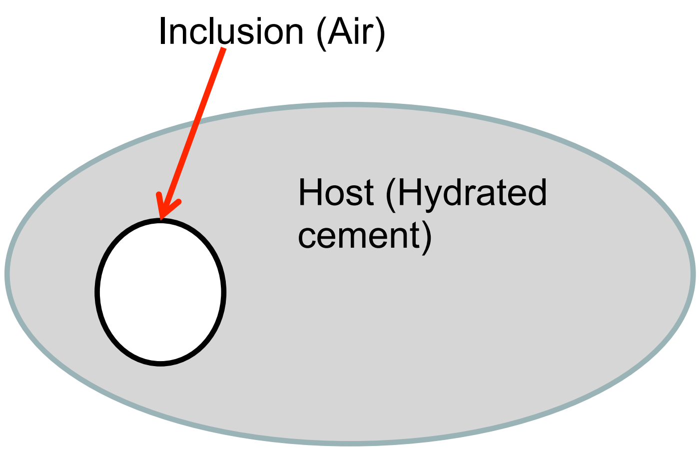
- PE for dielectric constant are all within ±3%.
- PE for loss factor from Debye's model is very large, but H-N's model and Yu's model provide much smaller PE. Yu's model is slightly better than H-N's model.

Summary of Homogeneous Models

- **Oven-dried Cement Paste Panels**
  - Yu's model can provide the best overall performance, and the performance of H-N's model is close to Yu's model.
  - These three models provide small PE for dielectric constant. Debye's model does not work for loss factor, nevertheless H-N's model and Yu's model provide better results on loss factor even though the results still do not match.
  - The common parameters for Debye's model and H-N's model, ϵ_∞ and ϵ_s, generally increase with the increase of w/c ratio.
- **Room-conditioned Cement Paste Panels**
  - The results from H-N's model are in good agreement with experimental results on both dielectric constant and loss factor. Debye's model can provide similar results on dielectric constant, but are not in good agreement on loss factor.
  - The common parameters for Debye's model and H-N's model, ϵ_∞ and ϵ_s, decrease with the increase of w/c ratio.

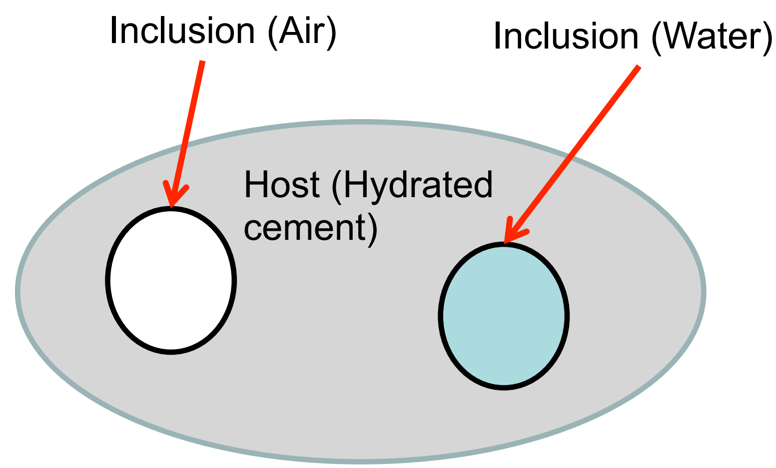
Outline

Heterogeneous Dielectric Models



Oven-dried

- Maxwell-Garnett's Model
- Wiener's Model



Room-conditioned

- Polder-van Santen's Model

Outline

Maxwell-Garnett's Model

$$\epsilon = \epsilon_h + 3 * V_i * \epsilon_h / \epsilon_i + 2 * \epsilon_h / \epsilon_i - \epsilon_h - V_i$$

where

ϵ = Dielectric properties of the mixing material,

ϵ_h = Dielectric properties of the host material,

ϵ_i = Dielectric properties of the inclusion material, and

V_i = Volumetric ratio of the inclusion material (Determined experimentally by ASTM C642).

The shape of inclusion material is assumed to be ***sphere.***

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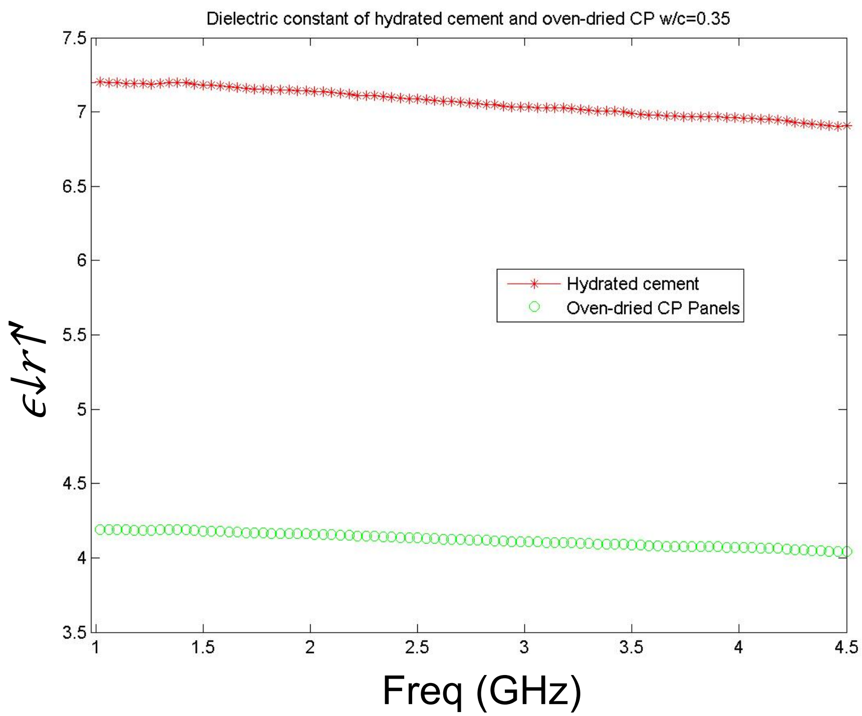
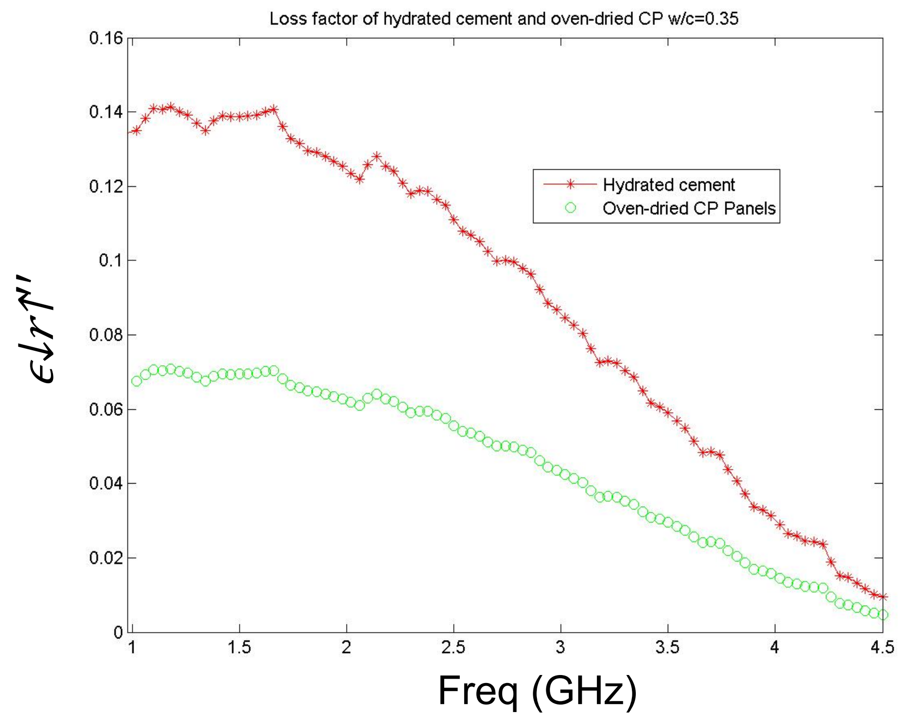
Results



Dielectric constant (w/c=0.35)



Loss factor (w/c=0.35)

Dielectric constant of the host material is larger than that of the mixing material.

Outline

Wiener's Model

$$\frac{\epsilon-\epsilon_h}{\epsilon+u}=V_i*\frac{\epsilon_i-\epsilon_h}{\epsilon_i+u}$$

where

ϵ = Dielectric properties of the mixing material,

ϵ_h = Dielectric properties of the host material,

ϵ_i = Dielectric properties of the inclusion material,

V_i = Volumetric ratio of the inclusion material, and

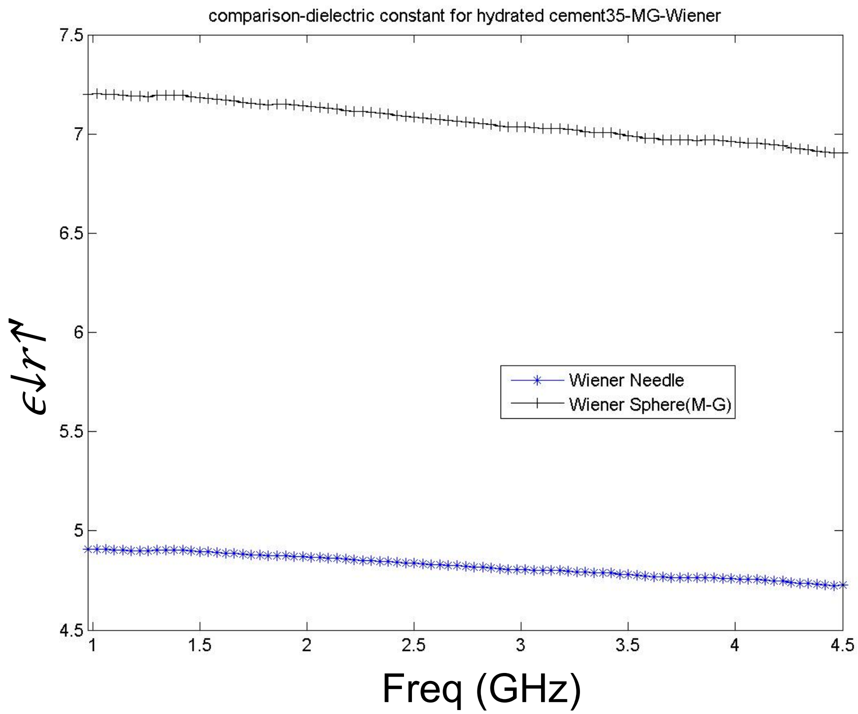
u = Form factor of the inclusion material.

The **shape** of inclusion material is assumed to be arbitrary.

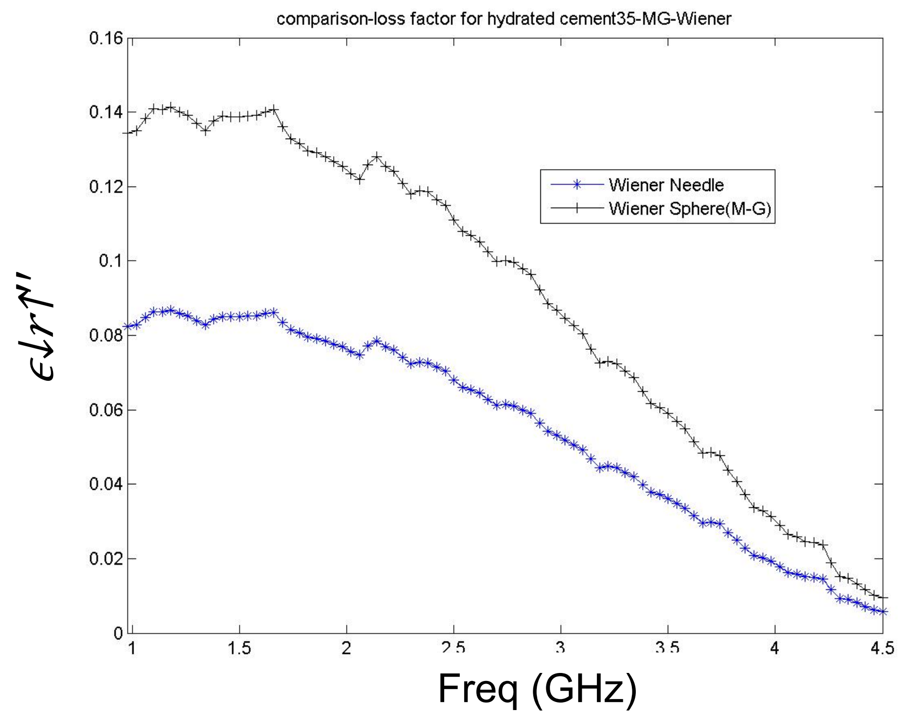
★

- Sphere inclusion $u=2*\epsilon_h$ (equal to M-G's model)
- Disk inclusion $u=2*\epsilon_i$ (not true, since ϵ_r' of the host material is negative)

Results – Needle-like Inclusion



Dielectric constant
(M-G vs Wiener)



Loss factor
(M-G vs Wiener)

Both dielectric constant and loss factor of the host material from M-G's model (sphere inclusion) are larger than those from Wiener's model (needle inclusion).

Outline

1. Introduction
2. Literature Review
3. Experimental Measurements
4. Results of Homogeneous Dielectric Models
   4.1 Debye's Model
   4.2 Havriliak-Negami's Model
   4.3 Yu's Model
5. Results of Heterogeneous Dielectric Models
   5.1 Maxwell-Garnett's Model
   5.2 Wiener's Model
   5.3 **Polder-van Santen's Model**
6. Conclusion, Contribution and Future Work

Polder-van Santen's Model

$$\epsilon - \epsilon_h = \sum_{i=1}^{N} V_i * (\epsilon_i - \epsilon_h) * \frac{1}{3} * \sum_{j=1}^{3} \frac{\epsilon}{\epsilon + N_j * (\epsilon_i - \epsilon)}$$

where

ϵ = Dielectric properties of the mixing material,

ϵ_h = Dielectric properties of the host material,

ϵ_i = Dielectric properties of the i^{th} inclusion material,

V_i = Volumetric ratio of the i^{th} inclusion material, and

N_j = Depolarization factors for the i^{th} inclusion material.

For sphere inclusion, (N_1, N_2, N_3)=(1/3, 1/3, 1/3);

Procedure

- ϵ_h from M-G's model
- ϵ_i of air
- N_j of spherical inclusion of air
- ϵ_i of water
- V_i of air and water
- ***Assumed N_j of water***

→ Polder-van Santen's Model → see which N_j of water can lead to the smallest norm error between left-hand-side and right-hand-side.

- ϵ_h from Wiener's model
- ϵ_i of air
- N_j of needle-like inclusion of air
- ϵ_i of water
- V_i of air and water
- ***Assumed N_j of water***

→ Polder-van Santen's Model → see which N_j of water can lead to the smallest norm error between left-hand-side and right-hand-side.

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Results

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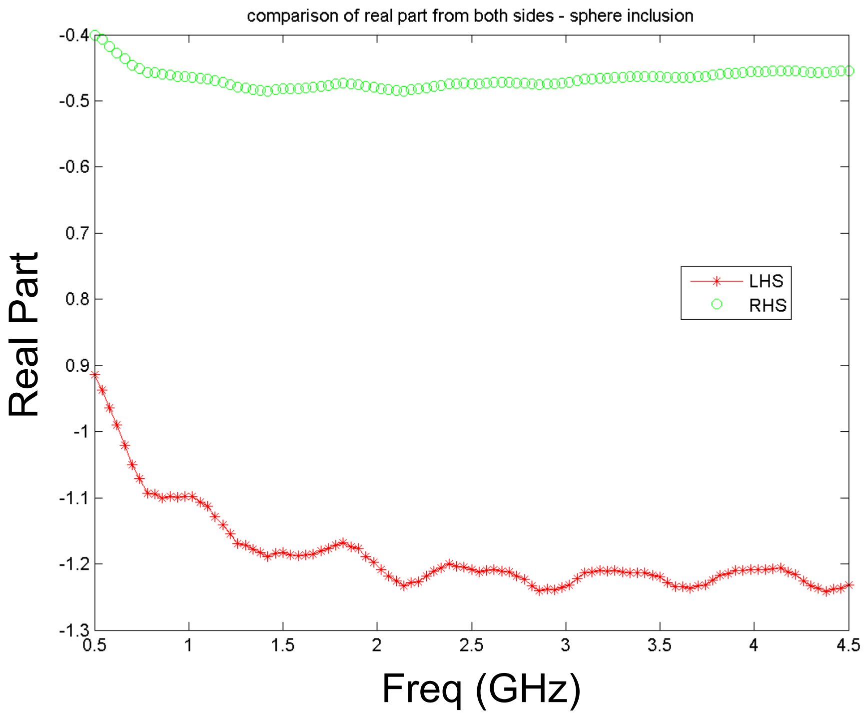
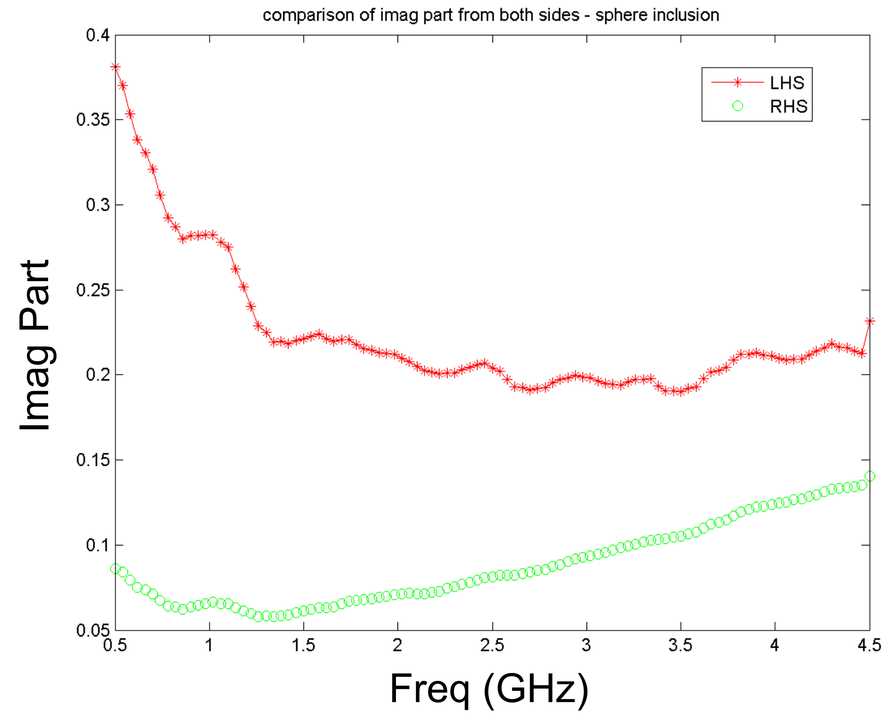
➢ Spherical Inclusion of Air



Real part (CP35)



Imaginary Part (CP35)

Determined depolarization factor of water (0.35,0.35,0.3).

Depolarization Factors of Water

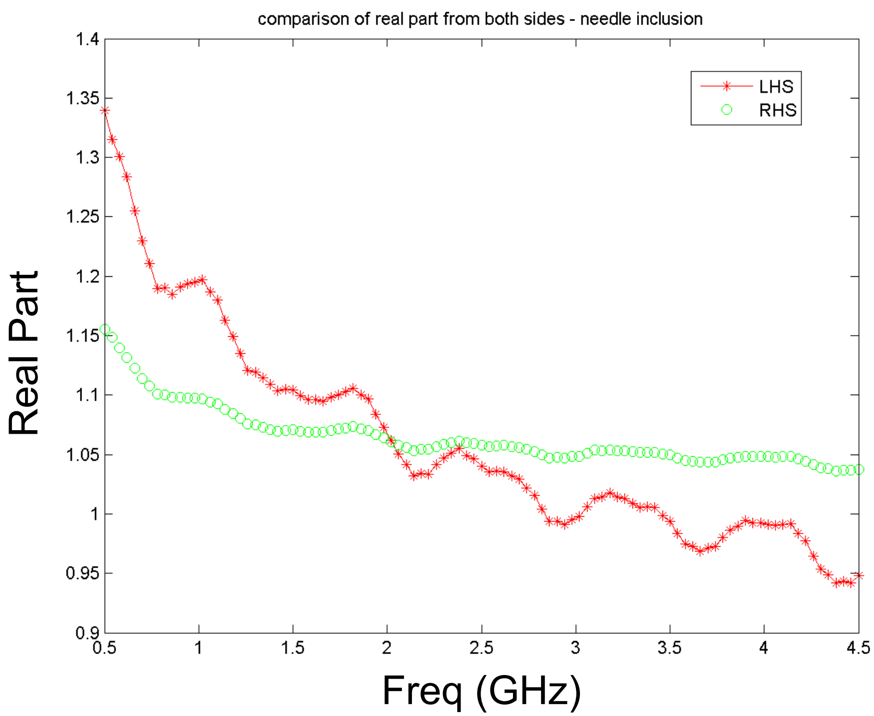
- **Spherical Inclusion of Air**

W/C ratio	Depolarization factors
0.35	(0.35,0.35,0.3)
0.40	(0.3,0.35,0.35)
0.42	(0.3,0.35,0.35)
0.45	(0.35,0.45,0.2)
0.50	(0.3,0.3,0.4)
0.55	(0.35,0.3,0.35)

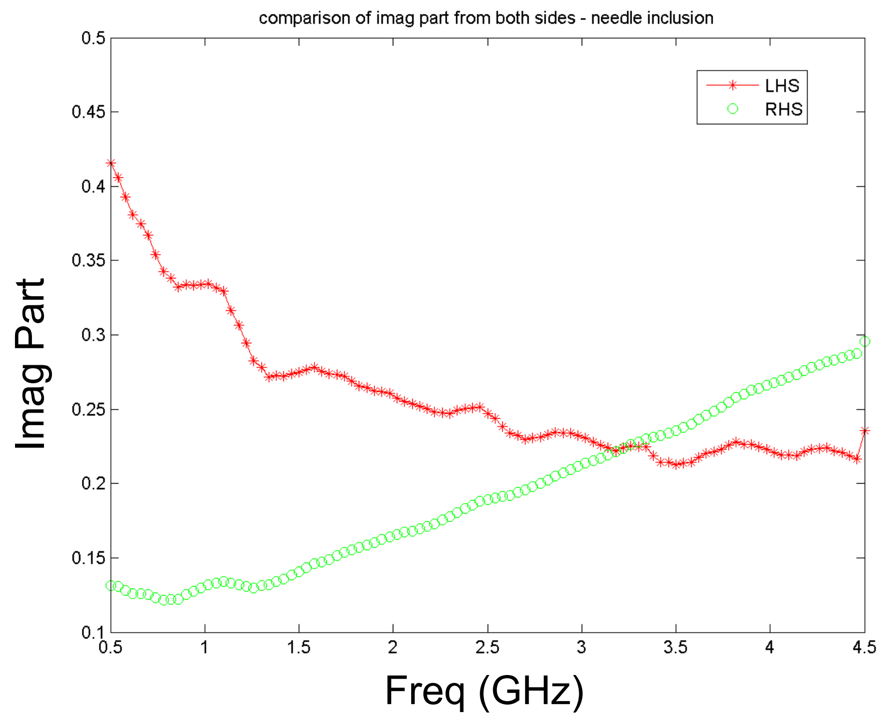
The depolarization factors of water are all close to sphere.

Results

- **Needle-like Inclusion of Air**



Real part (CP35)



Imaginary Part (CP35)

Determined depolarization factor of water (0.75,0.15,0.1).

Depolarization Factors of Water

- **Needle-like Inclusion of Air**

W/C ratio	Depolarization factors
0.35	(0.75,0.15,0.1)
0.40	(0.05,0.85,0.1)
0.42	(0.05,0.85,0.1)
0.45	(0.2,0,0.8)
0.50	(0,0.8,0.2)
0.55	(0.3,0.7,0)

The depolarization factors of water are close to each other for different w/c ratios.

Comparison

W/C ratio	Norm error (Spherical)	Norm error (Needle-like)
0.35	7.1	1.2
0.40	7.0	3.1
0.42	2.9	3.1
0.45	5.7	2.9
0.50	6.2	3.2
0.55	9.1	2.2

The results from needle air are generally better.

Conclusions

1. Yu's model provides the best overall performance on oven-dried cement paste panels even though the loss factor part still are not in good agreement with experimental results. H-N's model performs well for room-conditioned cement paste panels.

2. The model parameters, ϵ_{∞} and ϵ_{s} are same from Debye's model and H-N's model for oven-dried and similar for room-conditioned. However, τ values are different.

3. The dielectric properties of host material calculated from spherical inclusion are different from needle-like inclusion.

4. From the results of Polder-van Santen's model, the dielectric properties of host material by assuming the shape of air to be needle-like leads to better performance on room-conditioned cement paste panels.

Contributions

1. Introduced a new procedure to apply Debye's model on cement paste panels and to calculate model parameters.

2. Included the w/c ratio in Yu's model, which is a specific parameter for cementitious materials.

3. The results from heterogeneous models showed good potential for dielectric modeling on cement paste panels.

Future Work

1. The algorithm to determine τ has to be improved.
2. Include moisture content in dielectric modeling.
3. Better understanding and more applications are necessary to use heterogeneous dielectric models.
4. More experimental data is needed to improve the accuracy of dielectric models.

Thank you!

Questions?

Effectiveness

Step 1: Find one mathematical equation to fit the modeling data in the frequency range of [0.98, 3.5]GHz.

Step 2: Apply the same equation for the data in the frequency range of [3.5, 4.5]GHz and see the norm error between the results from M-G's model and the mathematical model.

Exponential function was used.

$$\epsilon_r'(\omega) = a * e^{(b*\omega)}$$

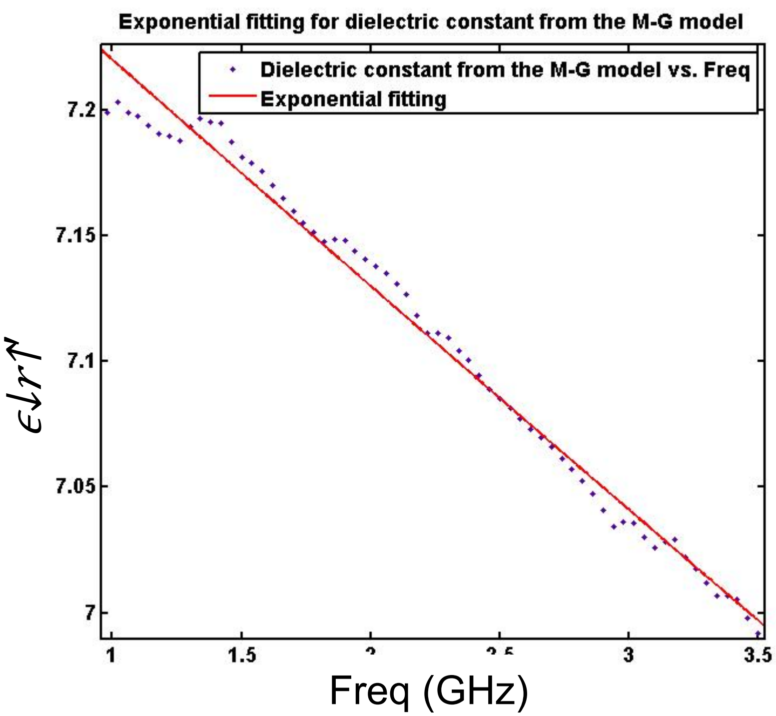
where

$\epsilon_r'(\omega)$ = Dielectric constant from mathematical equation,

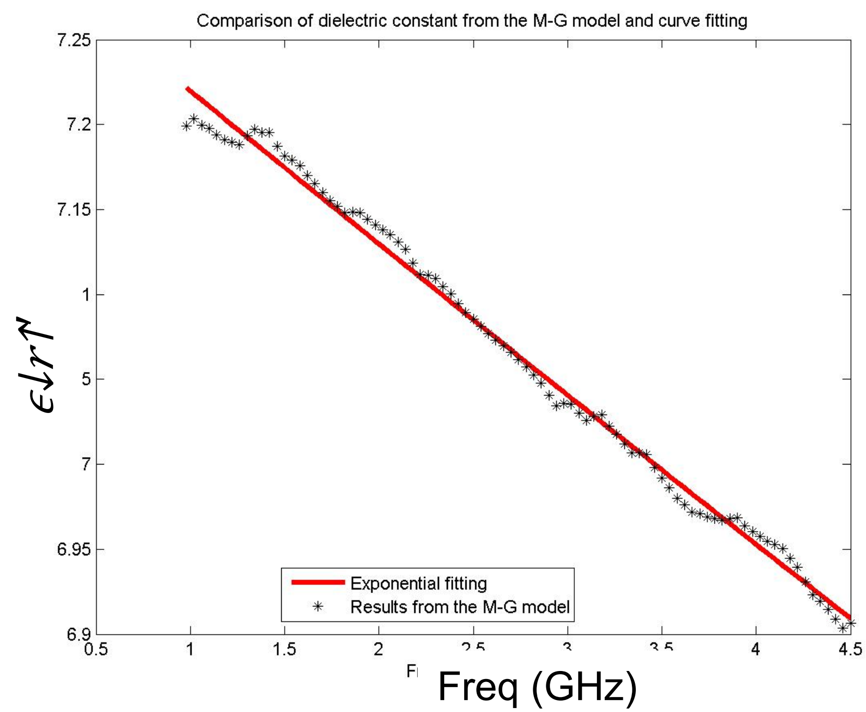
ω = Frequency (GHz), and

a and b = Coefficients of mathematical equation.

Effectiveness



Curve fitting (0.98~3.5GHz)



M-G's model vs Math Function

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Effectiveness

For CP35, the equation and coefficients are as following:

$$\epsilon_r'(\omega) = 7.311 * e^{(-0.01256 * \omega)}$$

where

$\epsilon_r'(\omega)$ = Dielectric constant from mathematical equation,

ω = Frequency (GHz), and

$a = 7.311$ and $\mathrm{b} = -0.01256$ = Coefficients of mathematical equation.

Coef. of Math Function

W/C ratio	a	b
0.35	7.311	-0.01256
0.40	10.28	-0.01575
0.42	9.158	-0.01845
0.45	9.915	-0.01906
0.50	10.02	-0.01252
0.55	11.76	-0.01231