Dielectric Deamplification of Multiphase Cementitious Composites in the Frequency Range of 0.5GHz to 4.5GHz

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***Abstract*—Dielectric properties (dielectric constant and loss factor) of hydrated cementitious composites (e.g., Portland cement paste and concrete) are the basis for the use of microwave and radar nondestructive testing/inspection techniques (such as GPR) in civil infrastructure systems (e.g., buildings and bridges). Among different types of cementitious composites, hydrated cement paste (hcp) is the major element providing the bonding strength in cementitious composites. Since hcp is porous and multiphase, its measured effective dielectric constant and loss factor are the function of not only frequency, temperature, and humidity but also its design parameters such as the water-to-cement (w/c) ratio. The removal of moisture content (liquid phase) in hcp materials is known as the dielectric deamplification in hcp and other cementitious composites. This phenomenon affects the performance of microwave/radar sensors when applied to concrete structures. It is also known that interactions among liquid phase (moisture), gaseous phase (voids), and solid phase (hcp) provide insightful information regarding material composition and structural integrity (e.g., cracking in hcp) of the composite.**

In this paper, the dependence of dielectric deamplification in hcp on the w/c ratio of hcp in the frequency range of 0.5$\sim$4.5 GHz at room temperature (25 C) is investigated. Panel specimens made of hcp designed with different w/c ratios (0.35, 0.40, 0.42, 0.45, 0.50, 0.55) and cured for 7 days were prepared. Some hcp panels were oven-dried at 105 C in order to remove non-chemically bound moisture in hcp. Dielectric constant and loss factor of hcp panels were measured using an open-ended coaxial probe system and a network analyzer. From the measurements, it is found that the dielectric deamplification in the measured dielectric constant of hcp exhibits a pattern different from the one in the loss factor of hcp, while both patterns are related to the w/c ratio of hcp. This finding can be useful in predicting the material composition of hcp and other cementitious composites using microwave/radar sensors.

Keywords: *Cementitious composites, hydrated cement paste, dielectric deamplification, w/c ratio*
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I. Introduction

In recent years, the use of microwave and radar techniques such as ground penetrating radar (GPR) for the nondestructive testing/inspection of civil infrastructure systems has been extensively reported [1], [2], [3], [4], [5], [6]. Among existing construction materials, Portland cement concrete (PCC) is widely used in buildings, bridges, tunnels, airports, roadways, pipelines, and other critical civil infrastructure systems. In view of the surface and subsurface sensing capabilities of electromagnetic waves in PCC structures, microwave and radar techniques can be used for material characterization [7], [8], moisture monitoring [9], void and crack detection [10], concrete cover thickness detection [11], rebar and corrosion detection [12], prestressing tendon failure detection [13], structural testing and remote sensing [14]. The electromagnetic wave-medium interaction phenomenon in PCC is governed by the electromagnetic properties of materials; the electric/complex permittivity and the magnetic/complex permeability. Since most PCC structures are non-magnetic (except for the purpose of electromagnetic shielding), it is the complex permittivity or the relative complex permittivity (dielectric constant and loss factor) of PCC that affects the performance and data interpretation of microwave and radar techniques. Hardened PCC is formed by the binding mechanism of hydrated cement paste (hcp) to combine filling materials like fine (sand) and coarse (gravel) aggregates in PCC. In addition, hardened PCC and hcp are both porous and multiphase cementitious composites, typically consisted of three phases; solid (hcp and aggregates), gaseous (air in voids), and liquid (moisture in voids). Since the porosity of PCC is mainly attributed to the porosity of hcp and subsequently affects the distributions of two other phases in PCC, it is important to study the dielectric dispersion of hcp in order to fully understand the dielectric properties of PCC. The objective of this paper is to investigate the dielectric deamplification of multiphase cementitious composites using hydrated cement paste (hcp) as an example, by considering different water-to-cement (w/c) ratios (0.35, 0.40, 0.42, 0.45, 0.50, 0.55) in hcp, in the frequency range of 0.5GHz to 4.5GHz. Hcp panel specimens were conditioned in room temperature and oven-dried to remove the moisture in the voids of hcp. In the following sections, specimen preparation and experimental setup are described. Measured dielectric properties of hcp specimens in different conditions were reported and discussed.

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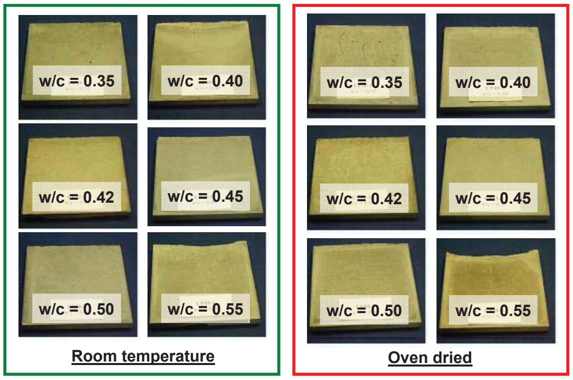

Figure 1. Manufactured and conditioned hcp panels

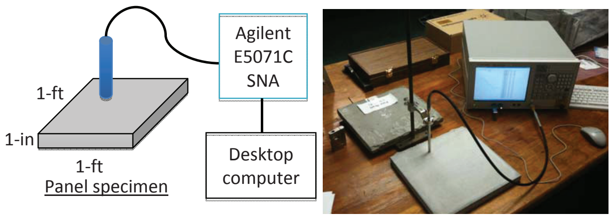

Figure 2. Contact dielectric measurement system and dimensions of hcp panels

II. Specimen Preparation

Twelve 1ft-by-1ft-by-1in hydrated cement paste (hcp) (Portland cement Type I/II plus water) panels with six water-to-cement (w/c) ratios (0.35, 0.40, 0.42, 0.45, 0.50, and 0.55; by weight) were manufactured, moist-cured for 28 days and conditioned in two different environments (room temperature and oven dried). In the room temperature environment, six hcp panels were conditioned at a temperature of 23°C and 50% RH (relative humidity) for seven days, while the other six hcp panels were oven dried at a temperature of 110°C and 0%RH. Plexiglass molds were used in casting the hcp panels to ensure a smooth surface for the accurate measurement of the coaxial probe. Fig. 1 shows the twelve hcp panels. Hcp panels are denoted by their w/c ratio and conditioning environment. For example, CP35rt is a hcp panel of w/c = 0.35 conditioned in room temperature and CP50od is an oven dried hcp panel of w/c = 0.50.

III. Experimental Setup

Contact dielectric measurements of hcp specimens were conducted by using an open-ended coaxial probe system and a series network analyzer (Agilent E5071C) in the frequency range of 0.5GHz to 4.5GHz. Fig 2 shows the experimental setup of the measurement system and the dimensions of hcp panels. Contact dielectric measurements were calibrated by a E-cal module and using reference materials (water and perfect electric conductor) before each measurement. Relative, complex permittivity (dielectric constant ϵ_r' and loss factor ϵ_r'') was converted from the S11 measurement using the Agilent 85071E Material Measurement software. In view of the spatial variation in localized contact dielectric measurements of hcp panels, sixty data points were randomly collected from each hcp panel within the 1ft-by-1ft surface area. Average values were calculated when determining the dielectric constant (ϵ_r') and loss factor (ϵ_r'') of each hcp panel.

Table I
Percentage of deviation of ϵ_r' – CP35, Room Temperature

Freq.(GHz)	0.5	1.0	1.5	2.0	2.5	3.5	4.5
Mean	6.25	6.06	6.05	5.92	5.82	5.74	5.68
Min.(%)	91	93	92	93	94	92	93
Max.(%)	116	116	114	114	115	114	113

Table II
Percentage of deviation of ϵ_r'' – CP35, Room Temperature

Freq.(GHz)	0.5	1.0	1.5	2.0	2.5	3.5	4.5
Mean	0.49	0.44	0.37	0.28	0.33	0.23	0.25
Min.(%)	81	85	85	75	86	85	91
Max.(%)	156	142	148	167	145	171	149

Table III
Percentage of deviation of ϵ_r' – CP55, Room Temperature

Freq.(GHz)	0.5	1.0	1.5	2.0	2.5	3.5	4.5
Mean	5.10	5.09	5.05	4.96	4.90	4.81	4.72
Min.(%)	92	92	92	92	92	93	93
Max.(%)	108	108	107	106	106	107	108

Table IV
Percentage of deviation of ϵ_r'' – CP55, Room Temperature

Freq.(GHz)	0.5	1.0	1.5	2.0	2.5	3.5	4.5
Mean	0.22	0.25	0.25	0.25	0.28	0.27	0.27
Min.(%)	44	64	77	71	74	72	74
Max.(%)	142	118	117	129	126	135	136

IV. Measurement Result

A. Spatial distribution of ϵ_r' and ϵ_r''

Since the coaxial probe measurement system collects localized dielectric properties of hcp panels, it is necessary to measure multiple points from a hcp panel in order to obtain the representative values of dielectric constant and loss factor for each hcp panel. The spatial distribution of ϵ_r' and ϵ_r'' values in the frequency range of 0.5GHz to 4.5GHz is evaluated by the percentage of deviation (maximum and minimum) of sixty data points with respect to the mean value of the sixty data points at particular frequency. In tables I and II the percentage of deviation of ϵ_r' and ϵ_r'' for CP35rt panel is provided, respectively. Same evaluation is provided for CP55rt panel in tables III and IV.

It is found that the range of variation of ϵ_r' for CP35rt is from 20% to 25%, while the range of variation of ϵ_r'' for CP35rt is from 58% to 92%, both within 0.5GHz∼4.5GHz. When the w/c ratio is increased from 0.35 to 0.55, the range of variation of ϵ_r' is from 14% to 16% and the one of ϵ_r'' is from 40% to 98%. Although the increase of the w/c ratio creates additional

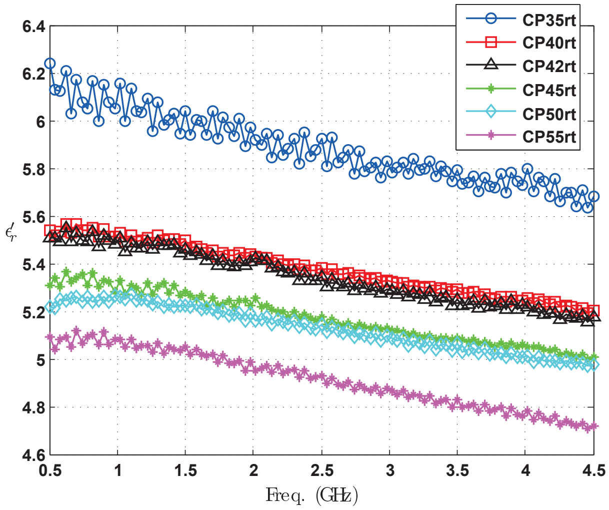

Figure 3. ϵ_r' of hcp panels – Room Temperature

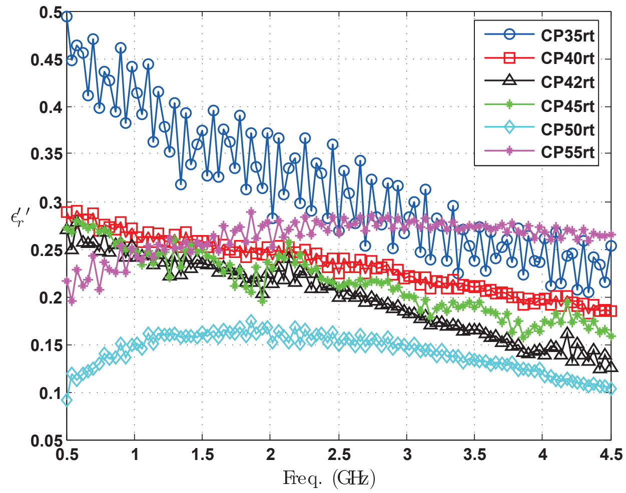

Figure 4. ϵ_r'' of hcp panels – Room Temperature

voids in hcp panels, the voids in hcp panels are not completely filled with either air or moisture, which is the reason why the ϵ_r' of the CP55rt panel varies to a greater range than the ϵ_r' of the CP35rt panel. Meanwhile, measured ϵ_r' values fluctuate to a less extent than measured ϵ_r'' values, due to the greater influence of moisture on ϵ_r'' than on ϵ_r'.

B. Room temperature conditioned hcp panels

Measured ϵ_r' and ϵ_r'' curves of hcp panels conditioned in room temperature are shown in figs. 3 and 4. The increase of the w/c ratio of hcp panels results in the decrease of ϵ_r'. It is clear that ϵ_r' decreases with an increasing frequency. On the other hand, the effect of an increasing w/c ratio on ϵ_r'' is not as conclusive as the one on ϵ_r'. In general, there is a trend for a decreasing ϵ_r'' when the frequency and the w/c ratio both increase. However, measured ϵ_r'' values fluctuate when w/c ratios = 0.35, 0.50 and 0.55 (fig.4). Also, it is found that, when the measurement frequency approaches 4.5GHz, difference in the ϵ_r'' values of various w/c ratios decreases. This phenomenon (fig.4) is very different from the one in ϵ_r' (fig.3).

C. Oven dried hcp panels

In the oven drying process (110°C) applied to the hcp panels, physically-bonded moisture was removed and it resulted in the volumetric phase exchange between the liquid phase (moisture) and the gaseous phase (air) in the hcp panels. Reduction of mass was measured by Eq.(1) and listed in table V.

$$\phi(\%) = \frac{W_{rt} - W_{od}}{W_{od}} \times 100\% \qquad (1)$$

where $\phi(\%)$ is the percentage of mass reduction, W_{rt} is the weight of room temperature conditioned hcp panels and W_{od} the weight of oven-dried hcp panels. Measured ϵ_r' and ϵ_r'' curves of oven-dried hcp panels are shown in figs. 5 and 6.

Table V
REDUCTION OF MASS IN OVEN-DRIED HCP PANELS

w/c ratio	0.35	0.40	0.42	0.45	0.50	0.55
$\phi(\%)$	5.66	5.13	4.93	4.86	2.70	4.71

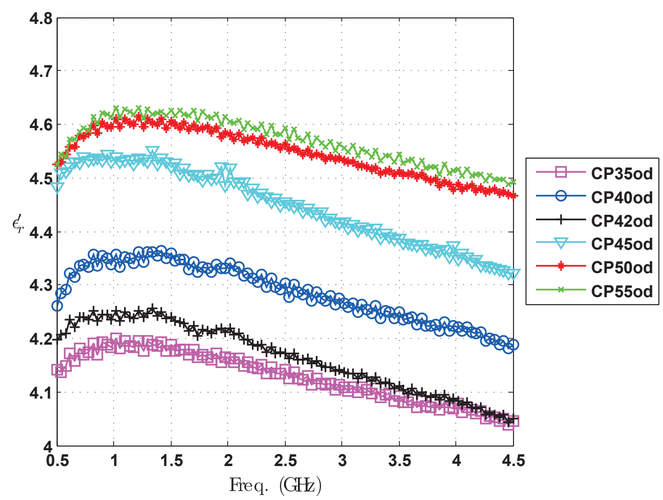

Figure 5. ϵ_r' of hcp panels – Oven Dried

D. Dielectric deamplification of multiphase hcp panels

Dielectric deamplification is usually observed in multiphase cementitious composites once internal moisture is removed. Such phenomenon is related to the structure of the solid phase which is formed by the cement hydration process and determined by design parameters such as the w/c ratio. Dielectric deamplification of multiphase hcp panels can be used to understand the solid/void structure, along with other measurement parameters such as frequency and temperature. Measured dielectric deamplification curves for hcp panels of w/c ratios = 0.35(fig.7), 0.40(fig.8), 0.42(fig.9), 0.45(fig.10), 0.50(fig.11), and 0.55(fig.12) are illustrated.

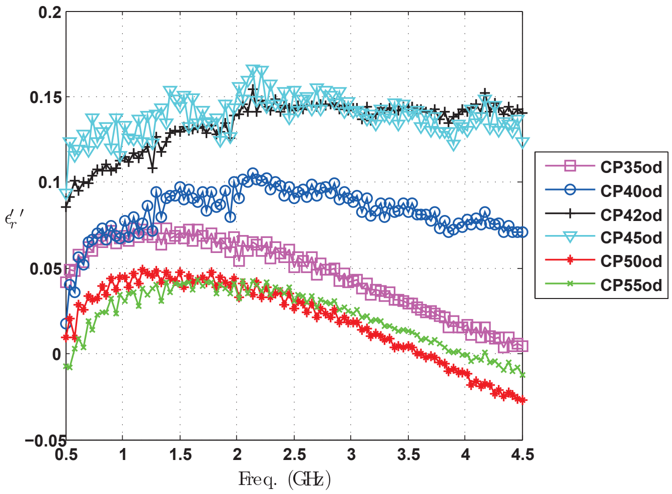

Figure 6. ϵ_r'' of hcp panels – Oven Dried

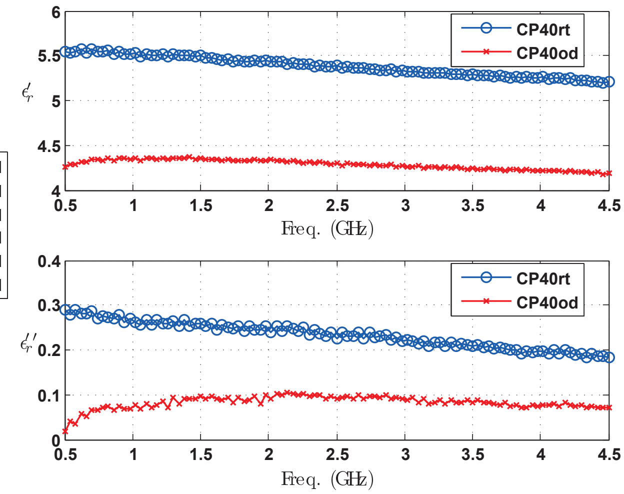

Figure 8. Dielectric deamplification of the CP40 panels

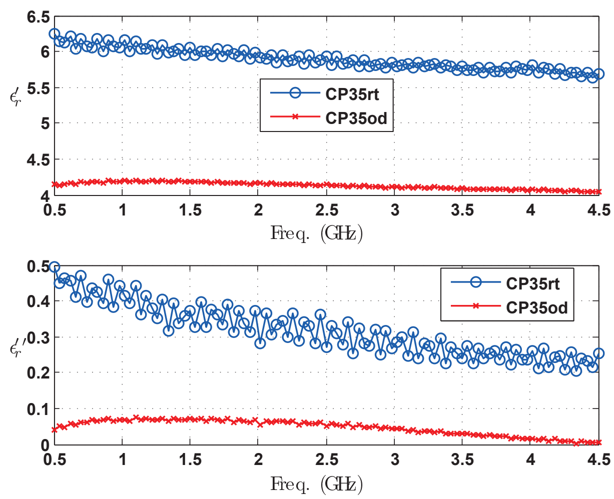

Figure 7. Dielectric deamplification of the CP35 panels

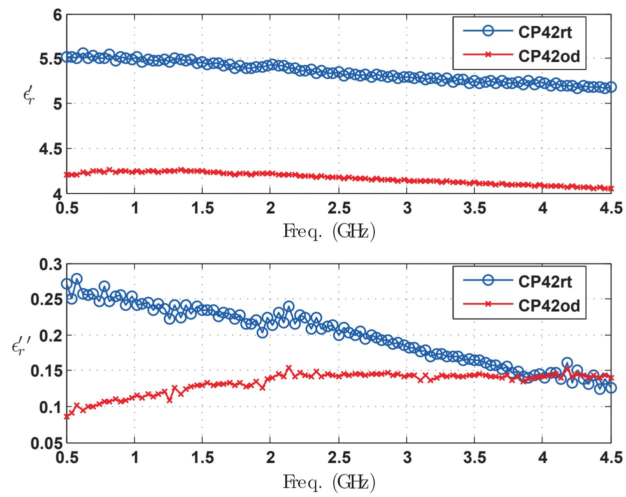

Figure 9. Dielectric deamplification of the CP42 panels

V. Discussion

A. Effect of the w/c ratio

For both room temperature conditioned and oven dried hcp panels, increasing the w/c ratio in hcp results in dielectric deamplification for ϵ_r' and ϵ_r'', as observed from the experimental data in the frequency range of 0.5GHz to 4.5GHz. It is also found that the deamplification pattern of ϵ_r' ,) is different from the one of ϵ_r'' , for both room temperature conditioned (figs.3, 4) and oven dried (figs.5, 6) hcp panels.

B. Effect of moisture

Presence of moisture (ϵ_r'=78∼81 in 0.5GHz∼4.5GHz) in multiphase hcp can increase both the measured dielectric constant and loss factor of hcp, and the removal of moisture in hcp leads to dielectric deamplification. At 0.5GHz frequency, the ϵ_r' of CP35 drops ∼33% and the ϵ_r'' drops ∼90%, while ϵ_r' drops ∼28% and ϵ_r'' ∼96% at 4.5GHz frequency, after the removal of 5.66% mass of moisture in the CP35 hcp panel. We also observed that the dielectric deamplification of ϵ_r' is approximately uniform for CP35, CP40, CP42, CP45, and CP50, except CP55. On the other hand, the dielectric deamplification of ϵ_r'' for all hcp panels does not exhibit any clear pattern. Additionally, it is worthy of mentioning that the dielectric deamplification of ϵ_r' is only qualitatively but quantitatively uniform. This information can be used to better understand the internal structure of hcp.

VI. Conclusion

In this paper, dependance of dielectric deamplification in hcp in the frequency range of 0.5GHz∼4.5GHz is investigated. Contact dielectric measurements using an open-ended coaxial probe system are reported. Considering the effects of measurement frequency, the w/c ratio, and the presence of moisture, it is found that the presence of moisture in hcp plays the most significant role in the dielectric deamplification of hcp. The

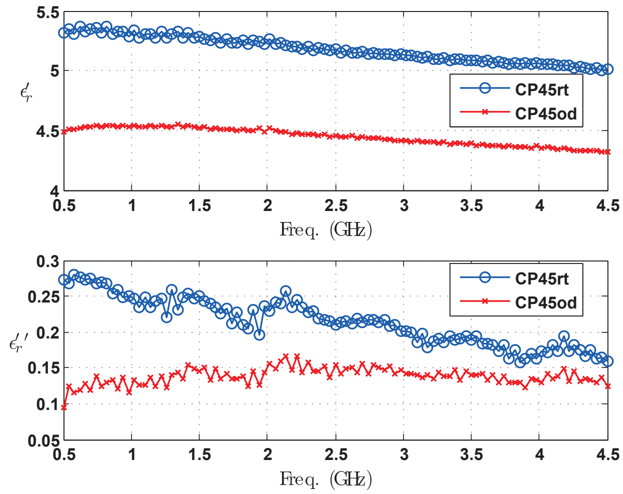

Figure 10. Dielectric deamplification of the CP45 panels

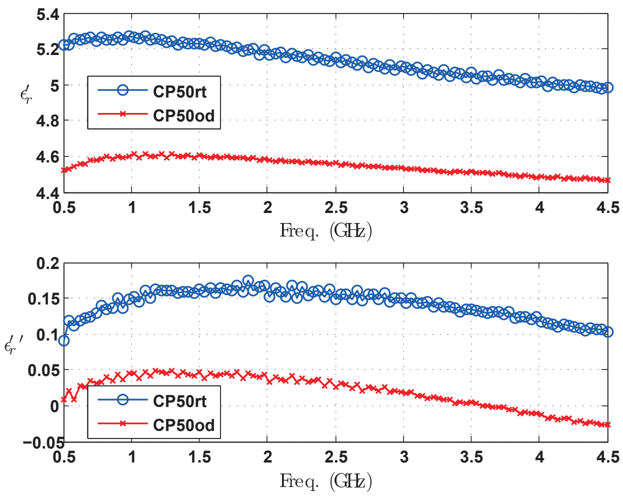

Figure 11. Dielectric deamplification of the CP50 panels

increase of the w/c ratio of hcp can result in the dielectric deamplification of hcp. Deamplifcation patterns of ϵ_r' and ϵ_r'' of hcp are different. Measurement frequency plays a relatively minor role in the dielectric deamplification of ϵ_r' but can be significant in the one of ϵ_r''.

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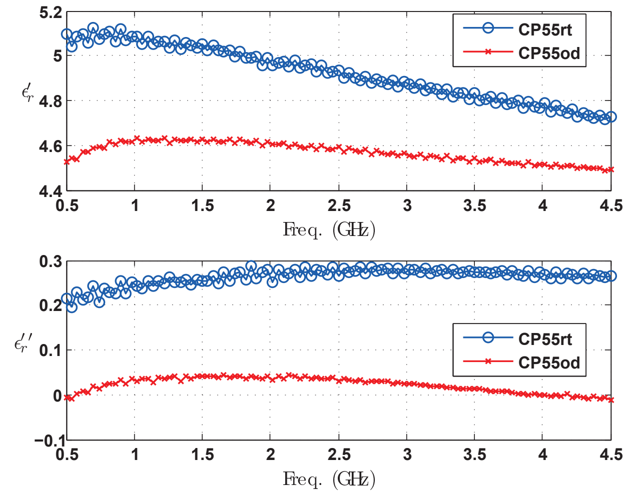

Figure 12. Dielectric deamplification of the CP55 panels

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