

Data-Driven Modeling of Concrete Complex Dielectric Permittivity by Gaussian Process Regression

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Cracks in concrete affect its structural integrity and related performance. Accordingly, concrete diagnosis results in a task of primary importance in making informed decisions about reconstructing or repairing buildings. Among the different approaches for evaluating concrete characteristics, methods based on electromagnetic waves have been proposed. In this context, the characterization of the concrete complex dielectric permittivity $\epsilon_{eff}(\omega)$ has received significant attention, and within this framework the Debye, the Jonscher model and its variants have been intensively used. Although the above are consolidated models, recently, data-driven techniques have emerged as alternatives for material property modeling because of their regression and generalization potential. In this study, we investigate the ability of Gaussian Process Regression to effectively model $\epsilon_{eff}(\omega)$ by comparing its performance with that of the standard Debye and Jonscher models.

Index Terms—Concrete, Permittivity, Gaussian Processes, Data-driven modeling.

I. INTRODUCTION

DUE to environmental factors and dynamic loads, building structures are vulnerable to damage [1]. In ordinary cement concrete, cracks are inevitable due to several natural or manufactured factors, causing the decline of the compressive strength performance and leading to structure deformation, affecting structural integrity performance [1]. Accordingly, concrete diagnosis results are of primary importance for practitioners in the field in making informed decisions about reconstructing or repairing buildings [1]. During the decades, monitoring concrete mechanical properties has become an area of cross-disciplinary research, and numerous non-destructive testing evaluation (NDT) methods have been developed for this aim [1]. Alongside techniques using elastic waves, methods based on electromagnetic waves for surface moisture detection, porosity, and concrete compressive strength estimation have been proposed over the years [2]. Accordingly, the characterization of the complex dielectric permittivity of concrete has received significant attention [2]. Although concrete is an aggregate of water, sand, and cement, resulting in a heterogeneous material from an electromagnetic point of view, it has been modeled by considering it as a homogeneous material, i.e., assuming that the size of its heterogeneities is small compared to the wavelength of the external electromagnetic field to model its electromagnetic properties [3]. Considering the above scenario, the Debye model was used [3] to characterize the concrete complex permittivity $\epsilon_{eff}(\omega)$, where ω is the angular frequency. Afterwards, the Jonscher model was alternately used [4]. While these models have been developed considering a frequency range up to 2GHz, in [5], this range has been extended until 10GHz using appropriate variants of the Jonscher model. Although the above models are well-established, we point out that data-driven techniques have recently begun taking hold as alternatives for building models for property prediction and material design due to

their ability to regress and generalize [6]. Based on the latter consideration, in this work, we investigate the ability of a data-driven model exploiting Gaussian process regression (GPR) to characterize the concrete complex dielectric permittivity $\epsilon_{eff}(\omega)$ by comparing its performance with that of the standard Debye and Jonscher models.

II. THEORY

The aim of GPR is to exploit a set $\{\mathbf{x}_i, y_i\}_{i=1}^N$, where $\mathbf{x}_i \in \mathbb{R}^d$ are the data sites and $y_i \in \mathbb{R}$ are the data values, for obtaining an estimator that can predict the value of the function $y_\beta = y(\mathbf{x}_\beta)$ in correspondence to $\mathbf{x}_\beta$, $\mathbf{x}_\beta \notin \{\mathbf{x}_i\}_{i=1}^N$, quantifying the expected error [7]. The fundamental assumption underlying the GPR approach is that the data values y_i are the realizations of a Gaussian random process $\bar{\mathcal{Y}} = \{Y(\mathbf{x}, \omega), \mathbf{x} \in \Omega\}$, with mean $\boldsymbol{\mu} = \mathbb{E}[\mathbf{Y}] = 0$ and covariance $\sigma^2 [\exp(-\varepsilon^2 \|\mathbf{x}_i - \mathbf{x}_j\|)]_{i,j \in \{1, \dots, N\}} = \sigma^2 \mathbf{K}$, where σ^2 and $\mathbf{K}$ are the process variance and the covariance kernel matrix, respectively [7]. The Gaussian process $\bar{\mathcal{Y}}$ can be used for regression as follows; let $\bar{\mathbf{Y}}_{\mathbf{x}}$:

$$\bar{\mathbf{Y}}_{\mathbf{x}} = \mathbf{w}(\mathbf{x})^t \cdot \bar{\mathbf{Y}} \quad (1)$$

a linear predictor belonging to $\bar{\mathcal{Y}}$, where $\mathbf{w}(\mathbf{x})^t$ are the unknowns weight functions values $w_i(\cdot)$ assumed in $\mathbf{x}$, which must be determined through the minimization of the mean squared error of $\bar{\mathbf{Y}}_{\mathbf{x}}$ defined as:

$$\epsilon_{\bar{\mathbf{Y}}_{\mathbf{x}}} = \mathbb{E} \left[\left(\bar{\mathbf{Y}}_{\mathbf{x}} - \mathbf{w}(\mathbf{x})^t \cdot \bar{\mathbf{Y}} \right)^2 \right] \quad (2)$$

Because of the stationarity of $\bar{\mathcal{Y}}$, it results that $\sigma^2 K(\mathbf{x}, \mathbf{x}') = \mathbb{E} [\bar{\mathbf{Y}}_{\mathbf{x}} \bar{\mathbf{Y}}_{\mathbf{x}'}]$. Using this last relation in (2), we obtain that:

$$\epsilon_{\bar{\mathbf{Y}}_{\mathbf{x}}} = \sigma^2 K(\mathbf{x}, \mathbf{x}') - 2\mathbf{w}(\mathbf{x})^t (\sigma \mathbf{k}(\mathbf{x})) + \mathbf{w}(\mathbf{x})^t \cdot \sigma^2 \mathbf{K} \cdot \mathbf{w}(\mathbf{x}) \quad (3)$$

where $\mathbf{k}(\mathbf{x}) = [K(\mathbf{x}, \mathbf{x}_1), \dots, K(\mathbf{x}, \mathbf{x}_N)]^T$. The differentiation of (3) gives the following stationary point for $\epsilon_{\bar{\mathbf{Y}}_{\mathbf{x}}}$:

$$\mathbf{w}(\mathbf{x}) = \mathbf{K}^{-1} \cdot \mathbf{k}(\mathbf{x}) \quad (4)$$

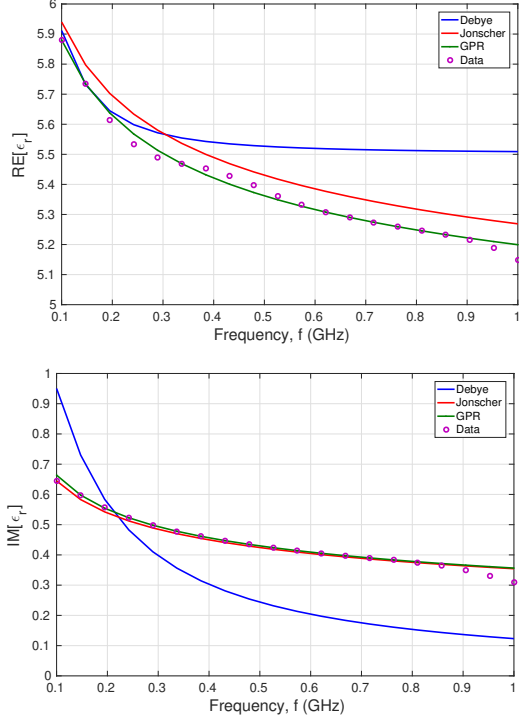


Fig. 1. Comparison among the values of the complex permittivity ϵ_{eff} provided by Debye, Jonscher, and Gaussian process regression models. Top: $\text{Re}[\epsilon_{eff}]$. Bottom: $\text{Im}[\epsilon_{eff}]$.

Using (4) in (1), and fixing the value of ϵ^2 , the following realization of the predictor $\bar{Y}_x$ is obtained:

$$\bar{y}_x = \mathbf{k}(x)^t \cdot \mathbf{K}^{-1} \cdot \bar{y} \quad (5)$$

which provides the GPR value in correspondence of x [7].

III. RESULTS

In this section, we present some preliminary results on the validity of the GPR approach to modeling the complex dielectric permittivity of concrete. The dataset $\mathcal{D} = \{\omega_\alpha, \epsilon_{eff}(\omega_\alpha)\}_{\alpha=1}^n$, used to build the GPR model has been extracted from the experimental data reported in [8], and consisted of $n = 20$ tuples. The dataset is relevant to a concrete specimens made of sand, gravel aggregate with a maximum size of 10 mm, and Ordinary Portland cement (concrete moisture content 2.8%) [8]. $\mathcal{D}$ has been randomly divided into training and test sets. The training set consisted of 80% of the tuples belonging to $\mathcal{D}$, while the test set consisted of the remaining 20 %. The coefficient of determination R^2 was used to assess the model performance. To implement the data-driven GPR model, the built-in functions `fitrgp` and `predict` of MATLAB 2023b © STATISTICS AND MACHINE LEARNING TOOLBOX have been used. In Fig. (1), a comparison among the values of ϵ_{eff} provided by the Debye, Jonscher, and GPR model in the range $[0.1, 1]$ GHz is reported. A visual analysis of the trends shown in Fig.(1) shows that the three models behave in a qualitatively similar manner, although the GRP model, in the permittivity results provided for both the real and imaginary part, deviates from the results offered by the

TABLE I
REGRESSION GOODNESS FOR THE CONSIDERED MODELS OF $\epsilon_{eff}(\omega)$.

Method	R^2
Debye	0.74
Jonscher	0.82
GPR	0.87

Debye and Jonscher models, especially the real part of the permittivity at high frequencies. Table (I) provides a more quantitative assessment of the different models' performance. It shows the value of the coefficient of determination obtained on the data contained in the test set. For the case considered in this study, the prediction quality of the GPR model turns out to be better than that of the Debye and Jonscher models.

IV. CONCLUSIONS

Data-driven techniques have recently been used to build models for predicting material properties due to their ability to regress and generalize [6]. Following this line of research, in this work, we present the results of a data-driven-based GPR model employed to characterize the complex dielectric permittivity $\epsilon_{eff}(\omega)$ of a specific type of concrete [8]. Although the study was only preliminary, the performance offered by the GPR model appears promising and worthy of further investigation to better define its potential and limitations.

ACKNOWLEDGEMENT

This research has been supported by the Italian Ministry of University and Research under the Program PRIN 2022: "Integration of Artificial Intelligence and Ultrasonic Techniques for Monitoring Control and Self-Repair of Civil Concrete Structures (CAIUS)", Code 2022AZPLL8.

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