Article:

Smyl, D. orcid.org/0000-0002-6730-5277 (2020) Electrical tomography for characterizing transport properties in cement-based materials: A review. Construction and Building Materials, 244. 118299. ISSN 0950-0618

https://doi.org/10.1016/j.conbuildmat.2020.118299

Electrical tomography for characterizing transport properties in cement-based materials: a review

Danny Smyl[a,b,*]

[a]*Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK*
[b]*The Integrated Civil and Infrastructure Research Centre (ICAIR), Sheffield, UK*

Abstract

The ability to spatially and temporally quantify the state and distribution of moisture and ions is of central importance to understanding the durability of cement-based materials and structures. Owing to the heterogeneous nature of concrete and challenges associated with using point-based measurements in accomplishing such a task, the use of two- and three-dimensional tomography for quantifying transport properties has become the source of much research interest. Distinct from electromagnetic radiation-based modalities – Electrical Tomography (ET), including Electrical Resistance Tomography, Electrical Impedance Tomography, and Electrical Capacitance Tomography, has emerged as a viable means for characterizing transport in cement-based materials. In this work, we provide a technical overview of ET and the nature of ET inverse problems. We also review historical challenges and successes of ET for imaging transport properties in cement-based materials. Based on realizations from the review, challenges and opportunities afforded by ET for characterizing transport properties are provided and discussed.

Keywords: Cement-based materials, inverse problems, tomography, transport

---

[*] Corresponding author
Email address: `d.smyl@sheffield.ac.uk` (Danny Smyl)

Contents

1. Introduction

In the context of global climate change, cement production contributes approximately 5-8% of the total CO_2 emissions [1]. It is therefore imperative that researchers and industry are invested in developing sustainable cement binder systems and alternative cementitious materials [2–6]. All the while, it is important to (i) extend the service life of concrete structures thereby reducing the long-term demand for traditional cementitious binders and (ii) continually improve our understanding of the durability and transport mechanisms in novel cementitious materials [7].

Central in the discussion of a concrete structure's durability is moisture distribution and transport. This is because many degradation processes in concrete structures, such as reinforcement corrosion [8] and ASR [9], take place in the presence of moisture. Moreover, the transport of corrosion-promoting ions, such as chloride, is facilitated by moisture [10, 11]. Inasmuch, it is logical to use moisture transport properties, such as permeability or hydraulic conductivity, as metrics for concrete durability [12–15].

Concrete is, however, a highly heterogeneous material, rarely fully saturated, and often has some level of distributed cracking when exposed to environmental conditions [16–18]. As such, endeavoring to quantify the durability characteristics of an unsaturated, heterogeneous, and possibly damaged cement-based material by interpreting data from point-based measurements – alone – often leads to results that are highly variable and/or painfully frustrating to decipher. Moreover, the use of such parameters can lead to significant errors in numerical models [19] and life-cycle estimations using such models [20].

These realizations have encouraged researchers to adopt measurement regimes acquiring data from more than two points. Broadly speaking, these methods include direct and inverse methods. In direct methods, the user directly interprets a suite of measurements to gain information on the transport phenomenon of interest. The advantages of these methods are their speed, broad usage, and well-documented behavior. Within this family, multi-point resistivity methods using, e.g. Wenner probes, have proven useful in characterizing water content, pore fluid resistivity, and properties related to the pore-space tortuosity of cement-based materials [21]. One challenge in using such a method is that calibration using numerical models and precise knowledge of the samples' mix design and condition may be required to attain accurate quantitative results [22]. In the case of Wenner probes, an "apparent" resistivity (not the true concrete resistivity, but one affected by reinforcement, contact impedance, etc.) is calculated from the measurements using knowledge of the sample geometry, injected current, and assuming that the sample is homogeneous and semi-infinite [23–27].

A significant body of research has addressed challenges associated with the calibration of direct electrical methods used in characterizing durability properties of cement-based materials and structures. For example, the effects of geometry [24], reinforcement [25], air content [28], temperature [29], and curing [30] – among numerous other variables – has been considered. Meanwhile, other researchers have focused on the development of new measuring apparatuses, including, e.g. multi-ring devices [31], embedded sensors [32, 33], and near-surface electrode grids [34]. As a whole, this body of research has significantly improved the robustness of direct methods to the point that direct methods have become standard in field and laboratory characterization of cement-based materials [35].

Tomographic methods are an alternative to direct methods, wherein researchers aim to gain spatial and/or temporal information on transport properties by solving an inverse problem using distributed data. In general, tomographic methods use input data to reconstruct properties such as moisture distribution, flow rates, ingress, and conductivity [36, 37]. The use of tomography for characterizing transport properties and transport-related properties in cement-based material is extensive. Broadly speaking, these methods have included radiation-based modalities such as X-ray [38–40] and γ-ray [41] tomography, neutron imaging [42–44], magnetic resonance imaging [45, 46], and electrical tomography (ET) [47].

Of the tomographic modalities, each have their respective strengths and weaknesses for characterizing transport properties and transport-related properties of cement-based materials. For example, X-ray tomography is often considered the modality of choice for characterizing the solid pore space of cement-based materials, while neutron tomography is arguably better suited for characterizing unsaturated flow [48]. It is important to recognize that the imaging capabilities of X-ray and neutron tomography are driven by the underlying physics of each modality. As it pertains to this work, the physical differences lie in the X-ray and neutron cross sections of hydrogen [49]. Since hydrogen has a large neutron cross section, neutron tomography is well-suite for characterizing water ingress. On the other hand, hydrogen has a small X-ray cross section, therefore X-ray tomography is not ideal for imaging water ingress. In contrast, while X-ray and neutron tomography are based on measurements from beams passing through a sample more-or-less linearly, electrical-based modalities rely on diffusive electric fields flowing through the cementitious medium [50]. As such, ET may be categorized as “diffusive” [50].

We may then conclude that the use of ET for characterizing transport properties in cement-based materials results in fundamentally different imaging characteristics compared to the aforementioned radiation-based modalities. The primary differences between ET and radiation-based modalities derive from (i) the diffusive nature on electrical fields in porous media and (ii) the contrasting behaviors of electrical and radiation-based inverse problems [51]. In principle, (i) and (ii) are relatively straightforward to conceptualize; in practice these differences result in fundamentally different abilities of electrical- and radiation-based modalities for characterizing transport in cement-based materials. To summarize, rather qualitatively, the tomographic features of popular modalities used for characterizing transport in cement-based materials are provided in Table 1.

Modality	**Modality type**	**Diffusive**	**Non-diffusive**	**Resolution**	**Sample size**
Neutron tomography	neutron attenuation-based		X	high, sub-millimetric [52]	small-medium
X-ray tomogrpahy	X-ray attenuation-based		X	high, sub-millimetric [53]	small-medium
γ-ray tomography	γ-ray attenuation-based		X	medium, millimetric [54]	small-medium
Electrical impedance tomography	electrical-based	X		low, sub-centimetric [55]	small - large
Electrical resistance tomography	electrical-based	X		low, sub-centimetric [55]	small - large
Electrical capacitance tomography	electrical-based	X		low, sub-centimetric [56]	small - large
Magnetic resonance imaging	magnetic-based		X	high, sub-millimetric [57]	small

Table 1: Summary highlighting important tomographic features of popular modalities used for characterizing transport in cement-based materials.

The summary shown in Table 1 generally indicates that electromagnetic radiation-based modalities are powerful tools for characterizing transport properties at high resolution when the sample is small. The small-medium sample size range required for high-resolution imaging[1] using electromagnetic radiation-based tomography results from the high attenuation of concrete [58], which has been shown experimentally in e.g. [59]. In other words, the distinguishability of electromagnetic radiation-based measurements decrease significantly as sample size increases, which is of course proportional to the loss in resolution. On the other hand, electrical-based modalities are shown to be effective for imaging large specimens at the cost of resolution, which is fundamentally linked to the diffusive nature of electrical tomography. In either case, both electromagnetic radiation- and electric-based modalities both have implementation limitations that should be noted. For example, radiation-based tomography requires a radiation source, i.e. a reactor, synchrotron, etc. which usually requires a dedicated facility. Meanwhile, electrical-based tomography is relatively easy to implement, but

---

[1] The following criteria are used herein to qualify imaging modalities resolution for imaging moisture: sub-millimetric (high resolution), millimetric (medium resolution), and centimetric/sub-centimetric (low resolution).

quantitative interpretation of results can be difficult and prior knowledge of the electrical-transport properties of interest may be required. Nonetheless, the purpose of this article is not to contrast the performance of electrical- and electromagnetic radiation-based tomographic modalities. Indeed, each modality has its strengths and weaknesses – therefore the use of a given modality should be selected based on application-specific criteria.

In this paper, we provide a first review of ET applications used for characterizing transport properties in cement-based materials. Here, we distinguish between "transport" in the holistic sense and "transport properties," where we refer to "transport properties" as physical phenomena directly or indirectly related to the spatial-temporal movement and evolution of water, ions, etc. in the pore space of cement-based materials. Additionally, we discuss some challenges and opportunities in using for ET for investigating transport-related processes in cement-based materials. We begin by providing a necessary technical background highlighting ET imaging regimes and their corresponding inverse problems. Following, we overview applications of two- and three-dimensional ET for investigating and characterizing transport properties in cement-based materials. Lastly, a discussion of the challenges and opportunities remaining in this field is provided.

2. Electrical tomography

2.1. Background

Broadly speaking, ET is a family of imaging modalities aiming to reconstruct one or more distributed electrical properties from electrical measurements. By electrical property, we generally refer to physical properties such and resistivity ρ, conductivity $\sigma = 1/\rho$, and permittivity ϵ. When cement-based materials are exposed to a time-harmonic field, these properties are related via the admittivity function [60] written as

$$Y = \sigma(x, y, z) + \mathrm{i}\omega\epsilon(x, y, z) \tag{1}$$

where electrical impedance is the inverse of Y, $\mathrm{i} = \sqrt{-1}$, x, y, and z are the spatial coordinates for the generalized three-dimensional case, and ω is the angular frequency of the applied current. Based on this preliminary, we can now define the imaging modalities (and their corresponding assumptions) within ET in the following itemization.

- Electrical Impedance Tomography (EIT): reconstruct $\rho(x,y,z)$ (or $\sigma(x,y,z)$) and $\epsilon(x,y,z)$ from $V(\omega)$ and $I(\omega)$. Assumption: the quasistatic relation $\nabla \cdot ((\sigma + \mathrm{i}\omega\epsilon)\nabla u) = 0$, where u is the electric field and $[u, \sigma, \epsilon \in (x,y,z)]$, holds. The quasistatic assumption results from neglecting wave propagation effects/time dependence of the magnetic potential [61, 62].

- Electrical Resistance Tomography (ERT): reconstruct $\rho(x,y,z)$ (or $\sigma(x,y,z)$) from measured voltages V and knowledge of the excitation currents I. Assumption: $\nabla \cdot (\sigma \nabla u) = 0$ holds [63], i.e. ϵ may be neglected.

- Electrical Capacitance Tomography (ECT): reconstruct $\epsilon(x,y,z)$ from capacitance measurements C. Assumption: $\nabla \cdot (\epsilon \nabla u) = 0$ holds, i.e. σ may be neglected [61].

In ET used for characterizing transport properties in cement-based materials, measurements V and C are generally taken from the boundary. This is done for two primary reasons, (i) the practicality of placing electrodes on the specimen's exterior and (ii) to avoid disturbing internal transport processes. Moreover, to solve the reconstruction problem and avoid unnecessary modeling errors, precise knowledge of the electrode locations and physical domain Ω are required. To illustrate this and summarize the ET modalities discussed in this subsection pictorially, a schematic is provided in Fig. 1. In Fig. 1, representative measurement protocols are shown. In Fig. 1a, for example, we see the most common EIT/ERT electrode measurement protocol – adjacent electrode measurements – coupled with opposite current injections, which are also commonplace. Meanwhile, Fig. 1b shows a rather non-conventional protocol while Fig. 1c demonstrates that ERT/EIT measurements can be taken quite arbitrarily (such as when current injections are taken from all electrodes against a common ground). On the other hand, fewer measurement combinations are (generally) possible for ECT as inferred from the right-hand column of Fig. 1; nonetheless, the ECT measurement protocol shown in Fig. 1c has proven robust in recent work [64].

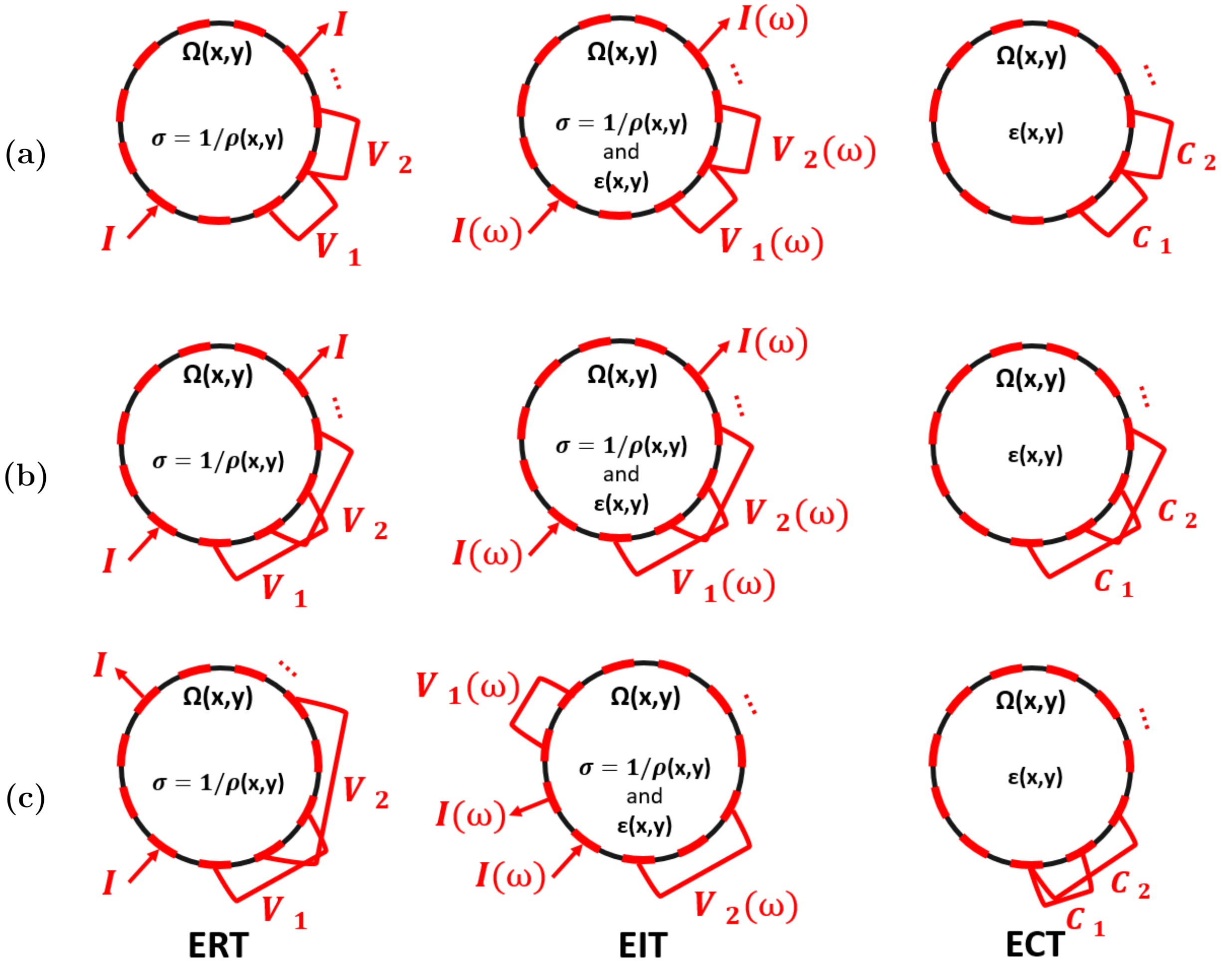


Figure 1: Schematic two-dimensional ($\Omega(x, y)$) illustration of electrical tomography imaging modalities: Electrical Resistance Tomography (left column), Electrical Impedance Tomography (middle column), and Electrical Capacitance Tomography (right column). Representative measurements protocols are shown for (a) opposite current injection (ERT/EIT) and adjacent measurements (ERT/EIT/ECT), (b) opposite current injection (ERT/EIT) and non-adjacent measurements skipping one electrode (ERT/EIT/ECT) and (c) arbitrary injection and measurement configurations (ERT/EIT) and a common ECT excitation protocol following [64].

2.2. ET inverse problems

As with the majority of tomographic modalities, obtaining an image of the quantity of interest results from the solution to an inverse problem [51]. The need to solve an inverse problem in the first place, however, stems from the need to estimate distributed parameters (a parameter field) from data. Such a problem, estimating causes (parameters) from effects (data) is referred to as an inverse problem. An inverse problem is the reverse of a so-called "forward problem" where we obtain effects from causes (e.g. obtaining a displacement field from knowledge of stiffness and boundary conditions). Inasmuch, in order to obtain an ET image, the former reality is also holds, where where we aim to reconstruct an electrical property (in general, an electrical parameter field) from ET data. We must, however, note that in order to asses transport properties in cement-based materials, a relation between the reconstructed electrical property and a transport property should be quantified or qualified. For this, one may use a number of models available in the literature [65–68]. As a simple illustrative example, one may begin by quantitatively relating the degree of saturation S to σ (i.e. $S = S(\sigma)$). Using this corroboration and information on the time dependence of S (i.e. $\frac{\partial S(x,y,z)}{\partial t}$) generated from ET reconstructions one could, for example, estimate the hydraulic conductivity K using analytic relations from [69].

To accomplish the latter, however, one needs to take the first step in solving an ET problem: clearly writing down the model that links the electrical data, call it d, and the electrical parameter field of interest, call it θ[2]. This is referred to as an observation model and is written as

$$d = U(\theta) + e \tag{2}$$

where e is an error term including modeling and measurement errors and U is the *forward model*. Technically speaking, U maps the parameter θ to the data space d. For the purposes of clarity, the relation between the ET forward and inverse problems are shown schematically in Fig. 2. Practically speaking, U is a numerical model, which inputs θ, Ω, and source terms (such as I) and outputs data (V, C, etc.). Since the geometry of Ω is in general arbitrary, we typically adopt a discretized solution for U. Most commonly, in ERT/EIT/ECT, the finite element method is used in solving the forward model U [62, 64, 70, 71]. For this, numerous finite element regimes have been proposed for ET, ranging from classical point-electrode models [72, 73] to modern smoothed (reduced-order) [74] and *hp*-adaptive models [75]. For further details on the ET numerical forward models, including the pervasive Complete Electrode Model, the reader is referred to [76] and [77] for ERT/EIT and ECT, respectively.

---

[2] In practice, we simply substitute the appropriate electrical data and parameter field into the generalized placeholders d and θ, respectively.

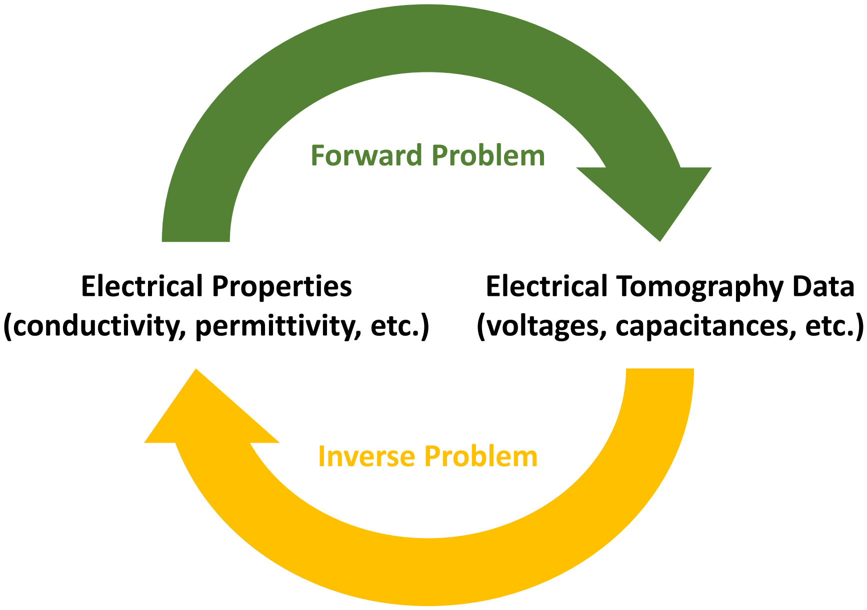


Figure 2: Schematic depicting the relationship between the ET forward and inverse problems.

As a whole, the goal of the ET inverse problem is to match the left and right hand sides of Eq. 2 as closely as possible. In reality, achieving $d - U(\theta) - e = 0$ is not feasible or pragmatically possible due to modeling errors, noise, uniqueness, etc. This was realized in classical works such as in [78–80], where the authors showed unique solutions to electrostatic inverse problems in general do not exist. However, we may aim to minimize an objective functional to a satisfactory level; in the least-squares (LS) sense, using a functional such as the following:

$$\Psi_{\text{ET}} = ||L_e(d - U(\theta))||^2 + R(\theta) \tag{3}$$

where $|| \cdot ||$ is the Euclidean norm, L_e is a matrix (noise model) generated from the noise covariance matrix using $L_e^T L_e = W^{-1}$, and R is a regularization term. The need for $R(\theta)$ is predicated on the fact that standard LS approaches to ET are unstable due to the ill-posed nature of ET. One method for conceptualizing the ill-posed nature of ET problems is to first write down the standard (non-regularized) LS estimator used in updating a Gauss-Newton optimization scheme (required for solving the LS-based inverse problem):

$$\delta\theta = (J^T J)^{-1} J^T (d - U(\theta)) \tag{4}$$

where $J = \frac{\partial U(\theta)}{\partial \theta}$ is the Jacobian (or sensitivity matrix) and $\delta\theta$ is the LS estimator (sometimes referred to as a minimizer or shift vector) computed during each iteration of the optimization regime. The problem with Eq. 4 is that the matrix $J^T J$, an approximation of the Hessian matrix, is ill-conditioned. This means that output values computed using the Hessian may vary significantly even when changes to the input values are small; thus, traditional LS solutions (e.g. schemes using the estimator presented in Eq. 4) are unstable [81]. To deal with this, incorporation of $R(\theta)$ brings stability to the LS solution and, when used properly, incorporates prior information into the LS solution [82]. Taking, for example, the most simple form of regularization (Tikhonov regularization), we can stabilize LS solutions by simply adding a multiple of the identity matrix to Eq. 4 thereby making the LS problem conditionally well-posed:

$$\delta\theta = (J^T J + \lambda I)^{-1} J^T (d - U(\theta)) \tag{5}$$

Of course, incorporating the Tikhonov regularization term, and its hyperparameter λ biases solutions – in this case biasing towards either the data fit or smoothness. However, when the structure of R can be accurately assumed *a priori*, regularization is a powerful tool in the inversion process [83]. There are numerous choices for $R(\theta)$ [84], such as (i) edge-promoting regularization which is popular in detecting cracks in concrete members [85] and (ii) smoothness-promoting regularization, which is popular in characterizing unsaturated moisture flow due to the diffusive nature of moisture in unsaturated cement-based materials [86]. For (ii), the most popular smoothness-promoting regularizers have been standard Tikhonov regularization and weighed smoothness regularization. If one is interested in the physical meaning of R, statistical interpretations of these regularizers are detailed in [82].

In addition to regularization techniques, the use of noise modeling is usually very effective in determining reliable solutions to ET inverse problems (as alluded to by the noise terms in Eq. 3). Noise modeling is typically included in ET when electrical measurements are not equally reliable. Hence, we utilize the noise covariance model W, which is typically formed as a diagonal matrix using the reciprocals of the anticipated noise variances. This information can be readily incorporated in the LS formulations, such as ones using the regularized estimator described in Eq. 5, by writing

$$\delta\theta = (J^T W J + \lambda I)^{-1} J^T W (d - U(\theta)). \tag{6}$$

By adding the noise model terms W and L_e (cost functional), we essentially gain the ability to weight solutions as a function of the anticipated noise. From a statistical viewpoint, this means that we can weigh the relative certainty of measurements $(d - U(\theta))$ against prior information ($R(\theta)$, or in the Tikhonov case, $R(\theta) = \lambda||\theta||^2$). In many situations, the use of noise modeling is essential for reducing the effect of large/inaccurate measurements on LS solutions [87].

Inverse methods aiming to minimize the functional in Eq. 3 are often referred to as *absolute imaging* and require an iterative optimization algorithm. Commonly, solutions to ET absolute imaging problems have utilized projection methods to ensure the parameter θ is physically realistic (e.g. $\sigma > 0$); however, the use of projection methods (e.g. numerically forcing $\sigma > 0$) often results in poorly-behaved problems. As a response, researchers have recently begun implementing constrained optimization regimes to ensure parameters are within physically-realistic bounds [47, 56]. These days, there are numerous regimes available for optimizing, constraining, and regularizing the LS ET problems; for these and references to many others, the reader is referred to [88–91].

The primary advantages of absolute imaging are that it is quantitative and has potential for producing high-quality reconstructions since the full nonlinear ET problem is solved. On the other hand, absolute imaging is computationally demanding since it requires and iterative algorithm to minimize Eq. 8. Moreover, when data from only one state is used, reconstructions are highly sensitive to measurement noise and modeling errors [36].

The main alternative to absolute imaging is *difference imaging*, where the observation model is linearized and usually solved with a one-step procedure. The difference imaging observation model is formulated by writing

$$\Delta d = J_d \Delta\theta + \Delta e \tag{7}$$

where $J_d = \frac{\partial U(\theta_0)}{\partial \theta}$ is the difference imaging Jacobian computed at the linearization point θ_0

and we also collect the difference terms corresponding to current and "reference" measurements $\Delta d = d - d_{\text{ref}}$, parameter fields $\Delta\theta = \theta - \theta_{\text{ref}}$, and error $\Delta e = e - e_{\text{ref}}$. In solving the difference imaging problem, we seek the minimum to the functional

$$\Psi_{\Delta \text{ET}} = ||L_{\Delta e}(\Delta d - J\Delta\theta)||^2 + R(\Delta\theta) \tag{8}$$

where $L_{\Delta e}^T L_{\Delta e} = W_{\Delta e}^{-1}$. Aside from the obvious computational speed-up in using a one-step regime; we also note that since we have adopted Δe, much of the measurement error is subtracted between the current and reference state. However, not all errors are subtracted since modeling errors in $U(\theta)$ and $U(\theta_0)$ are not the same due to the non-linearity of the forward model U in θ. As a result, difference imaging generally delivers qualitative results in ET imaging of, e.g. transient unsaturated flow [92]. Nonetheless, difference imaging remains a powerful in tool in qualitatively assessing transport properties in cement-based materials.

To this point, we have covered the primary ET reconstruction methods used for characterizing transport properties in cement-based materials to date. In the field of ET as a whole, there exist a multitude of reconstruction algorithms far more sophisticated than standard difference or absolute imaging. Opportunities related to the implementation of these algorithms will be discussed in the final section of this article.

3. Electrical tomography as a modality for characterizing transport properties

3.1. Early works inspiring the use of ET for characterizing transport properties

The technical and conceptual basis of transport in cement-based materials is largely rooted in work done by researchers in geophysics, soil science, physics, mathematics, and civil engineering in the 19th century. Transport, as we understand it today, dates back to the seminal works of the 1850s, including Fick's law (1855) [93] and Darcy's law (1856) [94]. The laws governing transport in unsaturated porous media, partial differential equations usually solved numerically, were later updated and enriched to include, e.g. gravity (1931) [95], dual porosity (1976) [96], and dual permeability (1993) [97]. Of course, no numerical transport model is useful without a material model. For this, geophysical/soil science researchers have developed numerous unsaturated material models, e.g. the Burdine (1953) [98], Brooks and

Corey (1966) [99], Mualem (1976) [100], van Genuchten (1980) [101], and Kosugi (1996) [102] models. Obviously, cement-based materials are a new material relative to geologic and human histories; therefore, it is rather intuitive that transport research in geologic materials was well established before transport research in cement-based materials. As such, the modern understanding of unsaturated transport in cement-based materials is largely owed to researchers in geophysics and soil science [69]. In the following, we will jump forward from the fundamentals of transport in porous media and continue by reviewing the developments leading to modern-day usage of ET for characterizing transport in cement-based materials.

3.2. 1980s - 2010

The contemporary use of electrical measurements for characterizing transport properties in cement-based materials dates back to the mid-late 1980, where authors such as McCarter and Garvin formulated fundamental relationships between electrical properties and moisture content [103]. Shortly thereafter, other researchers began delving into the topic [104, 105], perhaps realizing the potential in using electrical-transport relations in characterizing, e.g., the microstructure and durability of cement-based materials.

It was not long thereafter when researchers, some of which are still active in the field of geophysical imaging, caught on and began developing ERT for nondestructive characterization of moisture distribution in concrete pavements and structures [106, 107]. After this early influx of literature, there was a lull in published activity using ET to study transport processes between 1996 and 2008, with the exception of works addressing technical issues related to the implementation of ERT measurement systems during moisture ingress or related measurements [108, 109]. Another exception is a work published in 2005, which was the first substantial work discussing the use of 3D ET for monitoring unsaturated moisture flow in a concrete wall [110]. Meanwhile, significant research progress was made during the ET lull period with regards to the tools used for electrical characterization and improvements in our fundamental understanding of cement-based material electrical properties (e.g., see [111], [112], and [113] for relevant era overviews on the aforementioned characterization tools and understanding of cement-based material electrical properties). Furthermore, significant research effort in the (non-ET) areas of multi-modality electrical methods for characterizing cement-based materials and structures [114–116] and impedance-based methods for characterizing the the pore space structure of hardened cement [117–119] were realized. These works (among numerous others) led to subsequent research significantly increasing the field's ability to characterize and understand transport properties in cement-based materials using electrical methods. Some representative example include quantifying the influence of salt in cement-stabilized geotechnical applications [120, 121], capacitive characterization [122–124], and a suite of "on-site" electrical-based non-destructive methods for evaluating durability [125].

Although there is uncertainty in this topic, much of the absence in ET literature from 1996-2008 probably results from three realizations, (a) ET was most rapidly developed within the medical imaging field, becoming more "mainstream" in biomedical imaging and geophysics in the mid-late 1990s [60], (b) in terms of computers available in the 1990s, ET was highly computationally demanding (imagine using a single central processing unit (CPU) clocked at 100-200 MHz for solving modern inverse problems today), and (c) the existence and uniqueness of highly-accurate ET forward models was not proven until 1992 [126].

From 2008 onward, there began a steady flow of research investigating moisture flow and other degradation mechanisms using ET. Although not initially characterizing transport properties, Finnish researchers at the University of Kuopio (now the University of Eastern Finland) began applying modern inverse problem solving methodologies for imaging concrete materials and structures [127]. From 2008 - 2010, the Kuopio group continued their work in ET imaging of concrete structures, including rebar and crack localization [50, 128, 129]. In doing this, the researchers were inadvertently making the most significant contributions to the field of ET characterization of transport properties in cement-based materials since its inception.

3.3. 2010 - present

Possibly owing to the increasing popularity of ERT and EIT as quantitative modality across engineering and increases in computational resources, the cumulative number of publications using ET for characterizing cement-based materials increased steadily from 2010 onward. To demonstrate this and the publishing trends of articles using ET for the characterization of cement-based materials between 1992 - 2018, Fig. 3 depicts the yearly and cumulative number of papers published in this area.

Many of the seminal works in this field were published between 2010 - 2015; particularly those of du Plooy and coauthors, who developed specialized ERT sensing protocols [31], imaged moisture ingress in concrete slabs [130], quantified chloride penetration into concrete [131], characterized moisture gradients in concrete [132], and assessed the state of cover concrete [31]. During this period, other researchers were also using ET for clarifying a large suite of different questions in concrete materials and structures. Some examples of additional works between 2010 and 2015 include localizing steel reinforcement using linear surface electrodes [133], conceptualizing the broad usage of ERT in NDT as a whole [134], and investigating ET with adaptive meshing for crack detection [135].

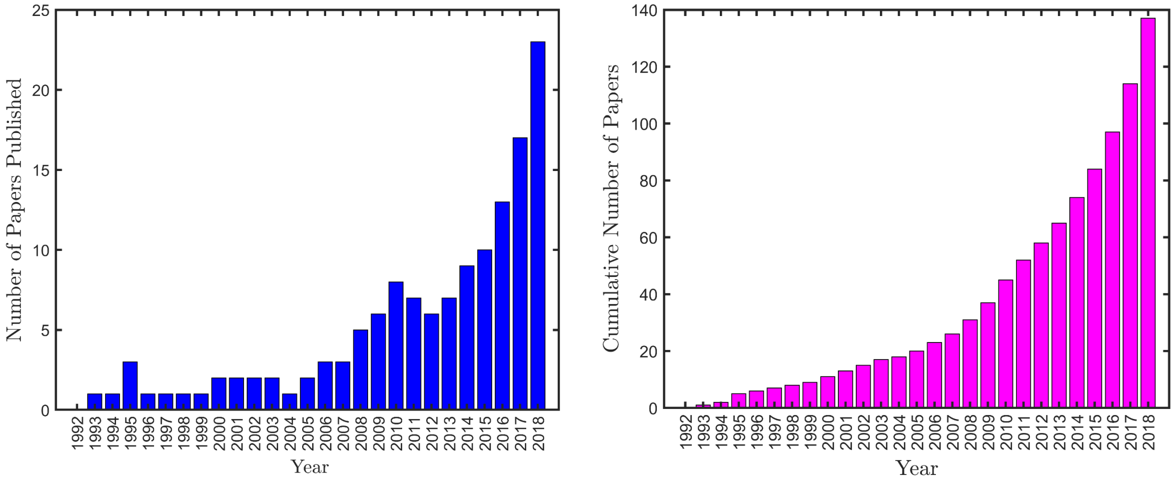


Figure 3: Bar graph depicting the yearly (left) and cumulative (right) number of papers published using ET to characterize cement-based materials from 1992 - 2018.

The specific usage of ET for characterizing transport properties in cement-based materials began to take hold in 2015 with the work published by Hallaji and coauthors [43], where the authors were the first to corroborate 2D unsaturated flow imaged with ERT with another 2D modality, neutron radiography. This work demonstrated that ET can accurately capture unsaturated moisture flow in undamaged cement-paste specimens, as shown in representative corroborated images in Fig. 4. Their work was of technical importance in the ET community since the effects of regularization, random noise, and other factors were uncertain in ET imaging of moisture flow in cement-based materials. However, by directly corroborating with a “gold standard” modality, many of these concerns were laid to rest.

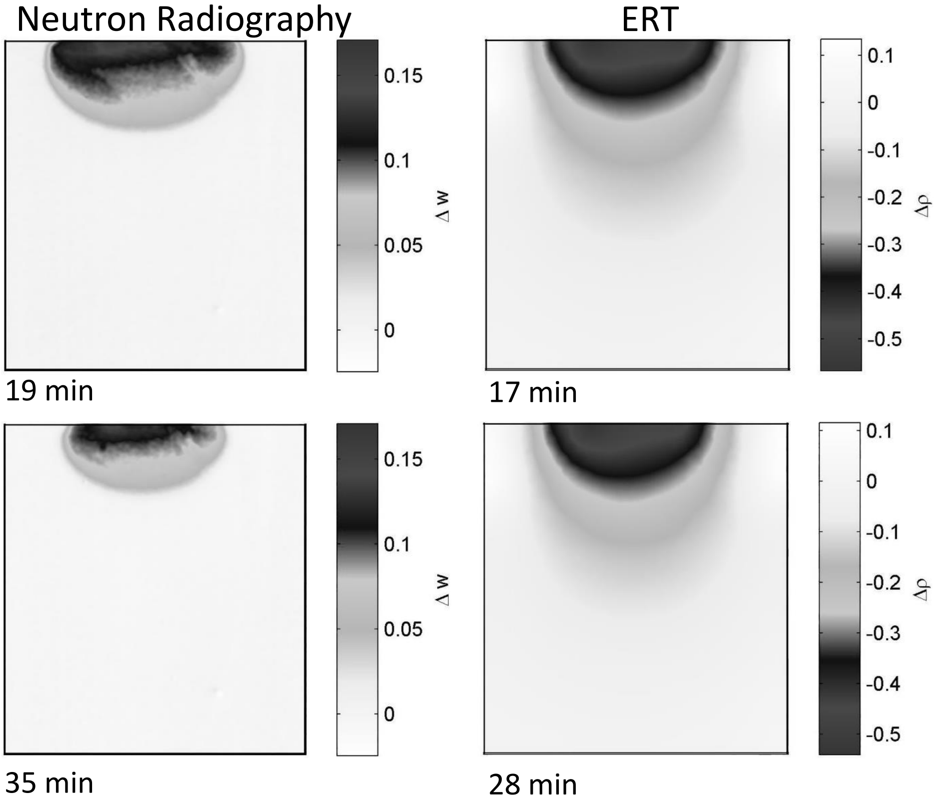
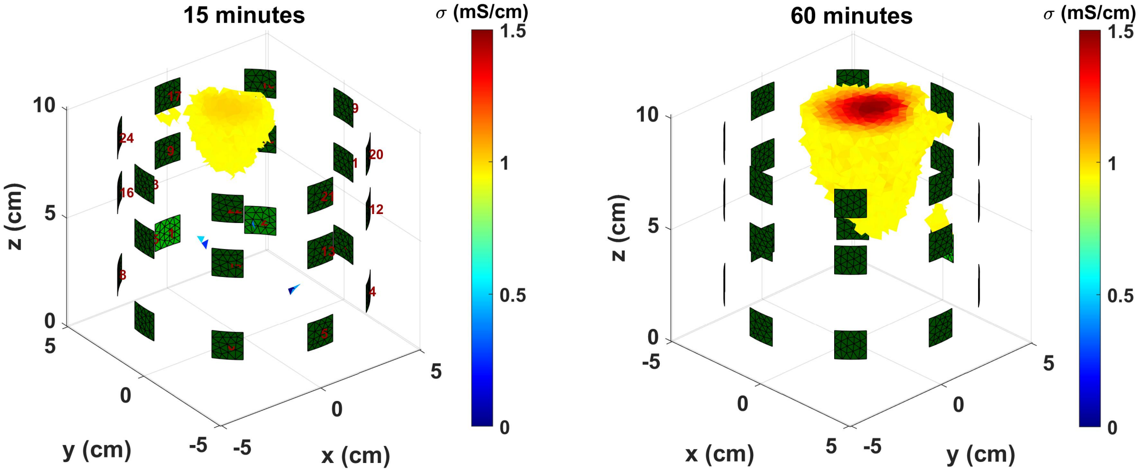


Figure 4: Neutron radiography images (left) and difference ERT reconstructions (right) of a square cement-paste specimen with two-dimensional (2D) water source located at the top-center of the specimen. The moisture ingress times of the neutron and ERT measurements are shown under the images. In the images Δw is change in volumetric water content relative to the initial condition and $\Delta\rho$ is the change in electrical resistivity. The images are from [43] and reported with permission from the article’s authors.

The 2015 Hallaji paper proved the effectiveness of 2D ET for transport characterization in cement-based materials. As authors have have noted, however, much more spatial information is gained by utilizing 3D ET as compared with 2D ET [136]. It was therefore obvious that researchers should extend 2D ET to 3D, thereby gaining information on transport processes not available using 2D ET. While 3D ET for visualizing moisture flow was qualitatively tested previously in [110], the use of 3D for characterizing flow rates, quantitative imaging, or imaging in damage material had not been evaluated.

These characterizations were first tested in 2016 using qualitative ERT difference imaging in a laboratory setting, where researchers successfully distinguished between flow rates of ingressing fluids with differing viscosity [59, 86]. In their work, the researchers found that when a sufficiently large volume of moisture had penetrated the specimens, significant reconstruction artifacts were present. They found that this resulted from the large global change in conductivity thereby violating the assumption of linearity in difference imaging. It was, however, concluded that difference imaging is suitable for imaging unsaturated flow at early states of ingress, which was also confirmed by Suryanto and coauthors shortly thereafter [137].

The same research group then extended their linearized ERT scheme to handle absolute imaging, which is not susceptible to artifacts resulting from linearization assumptions and is quantitative – as shown in the representative 3D ingress reconstructions shown in Fig. 5. In their work, they demonstrated the feasibility of quantitative 3D unsaturated flow imaging in small cylindrical mortar samples, by again distinguishing between ingressing fluids of differing viscosity and surface tension [22]. Once again, however, reconstructions computed at late stages of ingress suffered from reconstruction artifacts; this time however, large changes in the contact impedances were the likely culprit.



(a) (b)

Figure 5: ERT absolute imaging reconstructions of 3D moisture ingress in mortar cylindircal mortar specimens at (a) 15 minutes and (b) 60 minutes.

As of 2017, the question as to whether or not unsaturated moisture flow could be imaged in cement-based material with damage was unknown. Based on the common assumption in ET that the background is relatively homogeneous, the presence of e.g. discrete cracks clearly violates this assumption. In addressing this reality and to affirmatively answer the pervasive question, researchers utilized an approximative error estimate to subtract much of the background inhomogeneity from the ET data. In their study [138], the researchers found that ERT is capable of reconstructing progressive unsaturated moisture flow into discrete cracks, in the surrounding material, and between the cracks and surrounding material of the mechanically-damaged mortar samples[3]. Representative reconstructions from the work are shown in Fig. 6(f) alongside typical ERT experimental and numerical accompaniments, such as a raw concrete sample, prepared sample, discretized domain used in solving the inverse problem, etc.

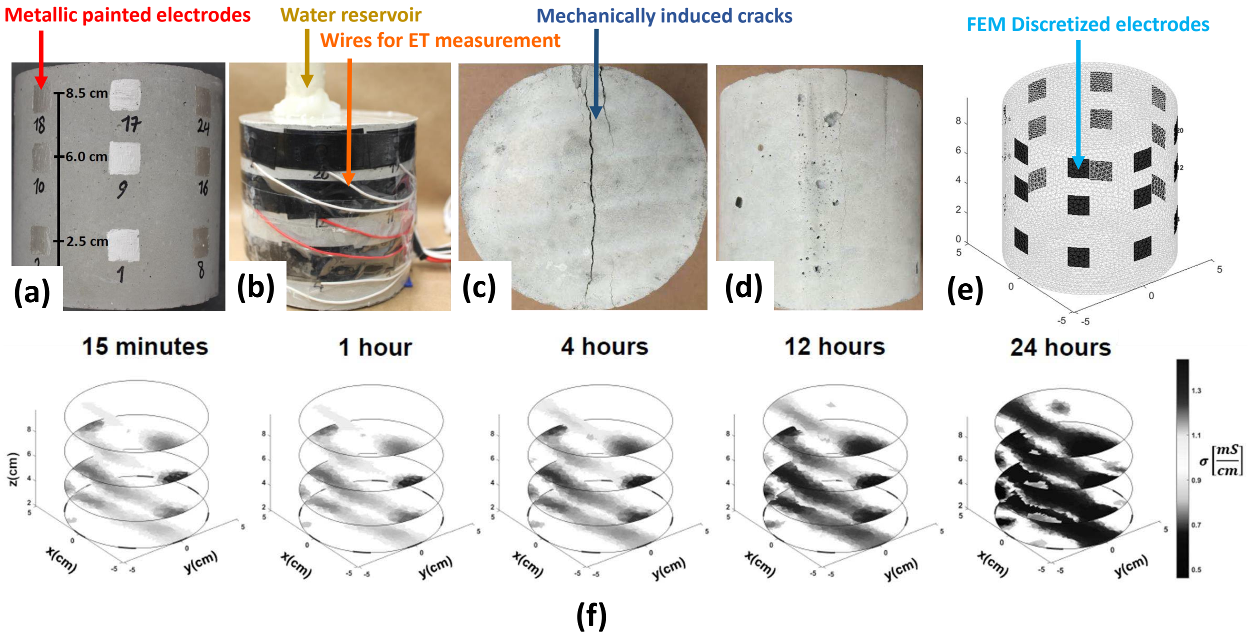


Figure 6: Typical ERT imaging accompaniments with descriptive labels including (a,b) prepared experimental sample with 24 painted on electrodes, (c,d) top and bottom of an unprepared (mechanically-cracked) sample, (e) FEM discretization of the physical domain using tetrahedral elements, and (f) horizontal "Frisbee" slices from 3D ERT reconstructions of progressive moisture flow in the damaged specimen at times of ingress ranging from 15 minutes - 24 hours. These images originate from [138].

Inventive researchers have also made significant strides in moisture flow monitoring by demonstrating the feasibility of ECT for related applications [139]. In doing so, they first utilized difference imaging for capturing 2D flow in undamaged specimens showing variable flow rates in materials with differing w/c ratios [64]. Following, the researchers successfully imaged transient flow in mortar specimens with discrete cracks in [92]. Other closely-related

---

[3] This type of unsaturated flow is often referred to as dual-permeability transport.

work in the area of capacitive measurement inversion has shown significant promise – in particular [123], where Fares and coauthors determined water saturation profiles by inverting experimentally-obtained capacitive data.

Recently, researchers have built upon the contemporary laboratory-scale research, investigating the use of ET for imaging moisture in large-scale applications. Notably, Rymarczyk and coauthors advanced the state-of-the art by applying machine learning to ET and moisture quantification in large walls [140] and historical buildings [141]. In this recent work, a series of feedforward neural networks were trained using finite elements simulations (via the forward model) mapping $\sigma \to V$. Using the trained networks, the authors bypassed the need for a traditional inverse solution using an optimization regime by directly computing σ from V. The obvious advantage of this method is its computational speedup; however, as with many deep-learning based approaches: (a) the applicability of the trained network in making predictions using data outside of the training data range, (b) the model's robustness to measurement noise, and (c) the influence of modeling errors intrinsic in the training data remain open questions. In addition to recent algorithmic advances, there has remained significant interest in quantifying fundamental transport properties in cement-based materials, such as moisture flow in cracked materials [142] and determining chloride content profiles in saturated slabs by combining ET and standard measurement devices, such as the Wenner device [143].

The latter work conducted by Fares and coauthors [143] presented a step-change in the capabilities of ET to image key concrete durability properties. In their work, an array of electrodes was affixed to small concrete slabs from which electric potentials were measured. Using these measurements and ERT resistivity images, experimentally-obtained chloride-resistivity curves were used to compute chloride concentration profiles. By corroborating the calibrated ERT results with destructively-obtained profiles, the feasibility of the method was demonstrated. The extension of this method to more general cases offers a tremendous opportunity to researchers interested in the durability of concrete; for example, determining chloride concentrations in the presence of moisture gradients. The challenge in this case would be the added non-uniqueness in determining resistivity and ion concentration distributions simultaneously – as opposed to just resistivity or conductivity. However, the use of deep learning to interpret complex ET results may offer a new means to deal with such challenges, among many others arising in this field.

To summarize the broad contributions made by numerous authors from 1993 – present, a timeline of major milestones is provided in Fig. 7. These activities are relevant to the use of ET for characterizing transport properties cement-based materials, and range from fundamental applications such as computing moisture distributions, monitoring 2D and 3D unsaturated flow, quantifying ions in pore solution, and visualizing dual-permeability flow in discrete cracks to very sophisticated applications incorporating machine learning and adaptive re-meshing. It is important to also keep in mind that the use of ET for characterizing transport properties in cement-based materials has also benefited from advances in the fields of inverse problems and computing. Some relevant contributions from these communities include the advent of Bayesian inversion regimes [82], modern regularization techniques [144], and (CPU) parallelism.

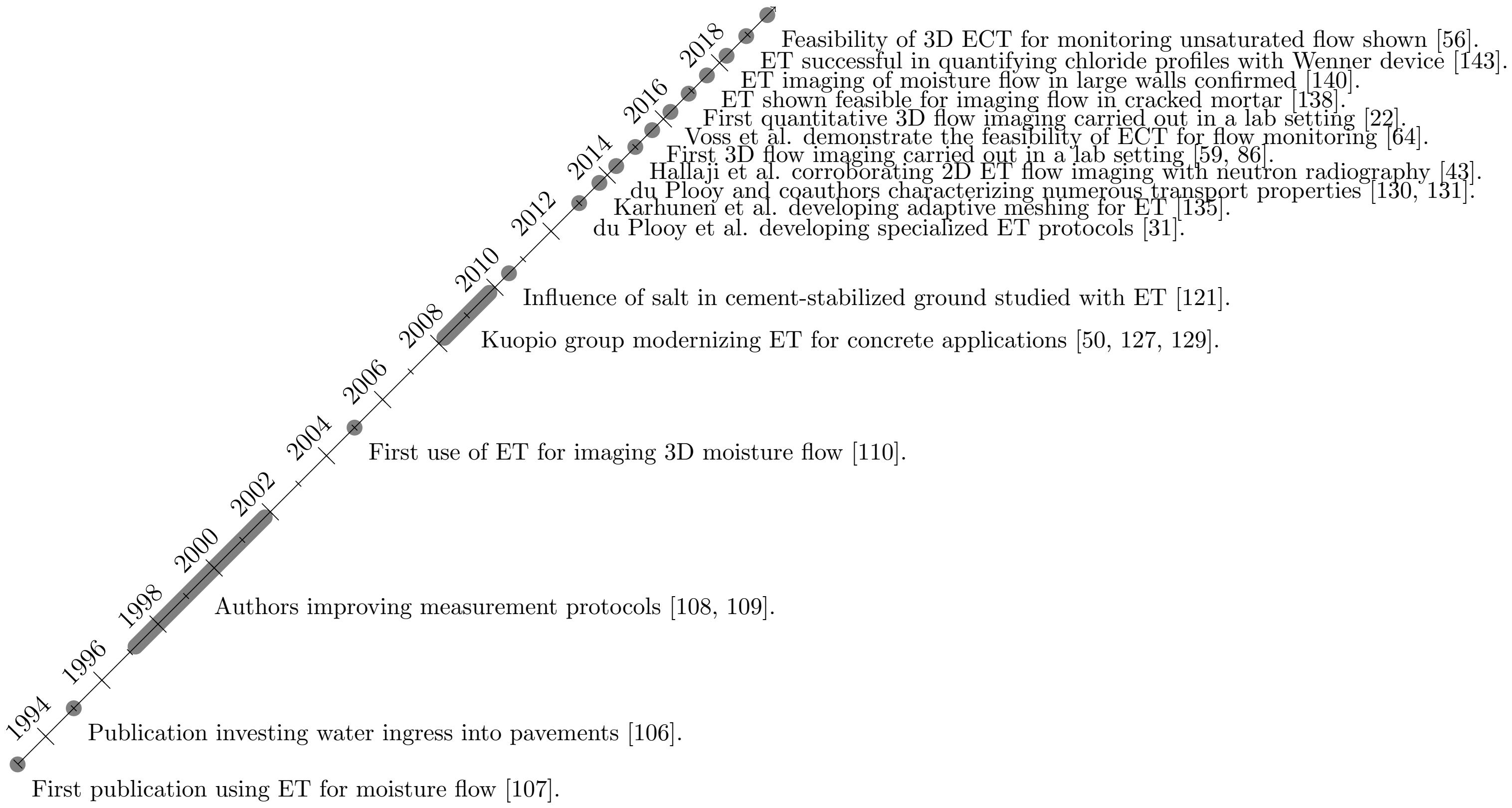


Figure 7: Timeline highlighting major milestones in the use of ET for characterizing transport properties in cement-based materials.

4. Discussion: opportunities and challenges

4.1. Some perspective

The use of electrical tomography for characterizing transport properties in cement-based materials is a new field. This is clear when contrasting ET to X-ray and neutron modalities, which have implemented tomography or radiography for characterizing cement-based materials since the 1970s [42]. Inasmuch, we are only beginning to realize the possibilities afforded by ET for characterizing fundamental transport properties in cement-based materials. On the flip side, ET is not as well technically established as e.g. X-ray tomography and also has notable limitations, such as low spatial resolution, a highly non-linear forward model, and an ill-posed nature. These realizations, among may others, will present both opportunities and challenges that will be concisely discussed in this section.

4.2. Opportunities for characterizing transport-related properties using electrical tomography

There exist a number of informal open opportunities as it relates to transport mechanisms in cement-based materials. Of course, populating such a list in its totality is infeasible. This is because it is often true that as soon as the scientific/engineering community makes a discovery regarding the transport behavior of a cement-based material, one or more additional unknowns/uncertainties is unveiled. However, we can envision problems that would be well-suited for ET by leverage the strengths of ET. Namely, these strengths are that (i) ET may be used for (theoretically) arbitrarily-large specimens, (ii) ET can be used quantitatively, and (iii) ET is a spatially-diffusive modality and moisture/ion diffusion is also spatially diffusive. Based on (i) – (iii), the following 10 transport-related research questions (opportunities) are deemed well-suited for ET:

1. Can we reliably image moisture gradients and chloride concentrations (and quantify their uncertainties) simultaneously for use in service-life predictions?
2. Are there situations where distributed cracking in cement-based materials results in a reduction in permeability/hydraulic conductivity relative to the undamaged state? (for example, when large discontinuous cracks are air filled).
3. At what distance from the heat source does moisture jamming occur in concrete exposed to fire?
4. For a given geometry and material, is there a critical degree of saturation above which spalling occurs and below which spalling does not occur in concrete walls exposed to elevated temperatures?
5. Are there additional fundamental insights to be gained by imaging 3D restrained shrinkage cracking at a large scale?
6. Can we quantitatively visualize 3D moisture movement, ion transport, and damage evolution in buried concrete members, such as foundations and footings?
7. How does sustained irradiation affect 3D transport in large reinforced concrete containment vessels?

8. Can we visualize and quantify percolation between ITZs of neighboring large aggregates in a mortar matrix?
9. Can 3D ET be used for quantifying corrosion in reinforced concrete members at the built scale?
10. Can 3D ET be used to quantify the matrix-fracture interaction factor in the dual-permeability model for various cement-based materials?

At present, the author is optimistic that ET may be used in answering questions 1-10. In addition, the opportunities made possible by the interface between deep learning and ET are essentially unknown. For example, by linking time-dependent moisture flow information provided by ET and learned relations with key transport properties, there may be significant opportunities in gaining deeper understanding on the underlying physics of multi-species flow and interaction. More importantly, it is hoped that by addressing these items with ET additional insights into the transport mechanisms of cement-based materials will be gained thus resulting in the design of more sustainable concrete infrastructure.

4.3. Challenges in characterizing transport-related properties using electrical tomography

Tomography is a technically challenging field to work in. This results from two main factors (a) many tomographic problems are ill-posed, non-linear, and require many degrees of freedom to achieve the desired resolution and (b) obtaining tomographic data usually requires sophisticated and numerous measurements. As such, there is never a "guarantee" that a tomographic image will come out "clean," that is to say, without artifacts. Worse yet, a process one is attempting to reconstruct may be invisible when data is not above some distinguishability threshold [145]. Owing to the relative infancy of ET for characterizing transport properties in cement-based materials, there remains much uncertainty resulting in fundamental challenges and hurdles. Since such challenges possibly outnumber the opportunities, we certainly will not populate all of them here. Rather, we enumerate 10 primary technical challenges that present barriers to ET characterization of transport in cement-based materials as follows.

1. General lower bounds or methods of computing the lower bounds for the distinguishability of ET transport measurements are not available.

2. The pervasive optimization regime in ET (Jacobian-based non-linear least squares optimization) does not handle many degree-of-freedom problems in a computationally-efficient manner.
3. Of present, the performance of only three prior models used in regularizing ET for characterizing cement-based materials is reported in the literature (Tikhonov, TV, and weighted smoothness).
4. Only single-state regimes have been studied in ET transport applications.
5. 3D electrode location optimization regimes are unavailable for concrete applications[4].
6. The feasibility of internal electrodes in 3D is unknown in ET transport applications.
7. Techniques for handling unknown and varying contact impedances are not reported in the context of ET for characterizing transport in cement-based materials.
8. The feasibility of "true EIT," reconstructing σ and ϵ simultaneously, in transport applications is unknown.
9. Only two methods for handling modeling and measurement errors have been reported in ET transport applications.
10. The use of state-estimation frameworks (Kalman filters, Gaussian processes, etc.) have yet to be evaluated.

The author acknowledges that a significant amount of work remains in this field. Pragmatically speaking, any individual enumeration in the above list would substantiate a PhD thesis in many institutions. Nonetheless, it is believed that by listing these challenges the readership will become more aware of these fundamental gaps in knowledge and application. As such, addressing these technical issues as a community may bring us closer to e.g. addressing the 10 challenges listed herein and other fundamental challenges in characterizing cement-based materials.

5. Summarizing remarks and paths forward

The use of electrical tomography for characterizing transport properties in cement-based materials has come a long way since its humble roots in 1993. Indeed, at that time, researchers

---

[4] cf. Fargier et al. (2010) [146] for inspiration on 3D electrode position optimization regimes for large structures (in this case, dykes).

were solving 2D ET inverse problems having only dozens of degrees of freedom, whereas today it is not uncommon to read an article reporting solutions to 3D problems with well over 10,000 degrees of freedom. Although the challenges in ET are not only computational, this fact among others provides an optimistic setting for researchers aiming to address ambitious transport problems using ET – such as the ones highlighted herein.

It is important to be optimistically realistic, which was a driving force behind including the "challenges" subsection. It is also important to note that solutions to the challenges posed by ET need not be addressed by the concrete community alone. Indeed, ET is but a mere subset of inverse problems as a whole, where creative researchers in the inverse problems community have been actively developing computationally efficient inversion regimes such as Krylov-based solvers [147], adjoint methods [148], D-Bar methods [149], and deep learning based regimes [150]. From a parameterization standpoint (how we choose to organize the problem), very few methods have been tried in ET for characterizing hydraulic properties. Indeed, such parameterizations may include already available regimes, such as stacking multiple states simultaneously [151] or joint parameterizations [152, 153]. From a measurement standpoint, it seems that every several months a new EIT measurement system emerges from the medical industry offering lower noise, faster measurements, etc. In summary, the author envisions a bright future for the theme of this article in the light of the opportunities presented, the development of new insights in transport as a result of pursuing such challenges, and the possibilities afforded by advancing our know-how in ET for characterizing transport properties in cement-based materials.

Acknowledgments

The author would like to thank the Dept. of Civil and Structural Engineering at the University of Sheffield for the continued support. The author would also like to thank Mohammad Pour-Ghaz (NC State), Milad Hallaji (Thornton Tomasetti), Dong Liu (University of Science and Technology of China), and Aku Seppänen (UEF) for the useful discussions and support leading up to the writing of this article.

References

[1] G. Habert, C. Ouellet-Plamondon, Recent update on the environmental impact of geopolymers, RILEM Technical Letters 1 (2016) 17–23.

[2] S. D. Palkovic, D. B. Brommer, K. Kupwade-Patil, A. Masic, M. J. Buehler, O. Büyüköztürk, Roadmap across the mesoscale for durable and sustainable cement paste–a bioinspired approach, Construction and Building Materials 115 (2016) 13–31.

[3] M. Frías, O. Rodríguez, M. S. De Rojas, Paper sludge, an environmentally sound alternative source of mk-based cementitious materials. a review, Construction and Building Materials 74 (2015) 37–48.

[4] E. M. Gartner, D. E. Macphee, A physico-chemical basis for novel cementitious binders, Cement and Concrete Research 41 (7) (2011) 736–749.

[5] M. Juenger, F. Winnefeld, J. L. Provis, J. Ideker, Advances in alternative cementitious binders, Cement and Concrete Research 41 (12) (2011) 1232–1243.

[6] P. Duxson, A. Fernández-Jiménez, J. L. Provis, G. C. Lukey, A. Palomo, J. S. van Deventer, Geopolymer technology: the current state of the art, Journal of Materials Science 42 (9) (2007) 2917–2933.

[7] A. Elahi, P. Basheer, S. Nanukuttan, Q. Khan, Mechanical and durability properties of high performance concretes containing supplementary cementitious materials, Construction and Building Materials 24 (3) (2010) 292–299.

[8] R. R. Hussain, T. Ishida, M. Wasim, Oxygen transport and corrosion of steel in concrete under varying concrete cover, w/c, and moisture, ACI Materials Journal 109 (2012) 1–8.

[9] S. Multon, F. Toutlemonde, Effect of moisture conditions and transfers on alkali silica reaction damaged structures, Cement and Concrete Research 40 (6) (2010) 924–934.

[10] K. Y. Ann, H.-W. Song, Chloride threshold level for corrosion of steel in concrete, Corrosion Science 49 (11) (2007) 4113–4133.

[11] W. D. Lindquist, D. Darwin, J. Browning, G. G. Miller, Effect of cracking on chloride content in concrete bridge decks, American Concrete Institute, 2006.

[12] J. Castro, D. Bentz, J. Weiss, Effect of sample conditioning on the water absorption of concrete, Cement and Concrete Composites 33 (8) (2011) 805–813.

[13] F. Ghasemzadeh, R. Rashetnia, D. Smyl, M. Pour-Ghaz, A comparison of methods to evaluate mass transport in damaged mortar, Cement and Concrete Composites 70 (2016) 119–129.

[14] S. Poyet, S. Charles, N. Honoré, V. L'hostis, Assessment of the unsaturated water transport properties of an old concrete: Determination of the pore-interaction factor, Cement and Concrete Research 41 (10) (2011) 1015–1023.

[15] R. Henkensiefken, J. Castro, D. Bentz, T. Nantung, J. Weiss, Water absorption in internally cured mortar made with water-filled lightweight aggregate, Cement and Concrete Research 39 (10) (2009) 883–892.

[16] A. Akhavan, F. Rajabipour, Quantifying permeability, electrical conductivity, and diffusion coefficient of rough parallel plates simulating cracks in concrete, Journal of Materials in Civil Engineering 29 (9) (2017) 04017119.

[17] Z. Yang, W. J. Weiss, J. Olek, Water transport in concrete damaged by tensile loading and freeze–thaw cycling, Journal of Materials in Civil Engineering 18 (3) (2006) 424–434.

[18] C. Leech, D. Lockington, P. Dux, Unsaturated diffusivity functions for concrete derived from nmr images, Materials and Structures 36 (6) (2003) 413.

[19] X. Li, S. Chen, Q. Xu, Y. Xu, Modeling the three-dimensional unsaturated water transport in concrete at the mesoscale, Computers & Structures 190 (2017) 61–74.

[20] D. Smyl, F. Ghasemzadeh, M. Pour-Ghaz, Modeling water absorption in concrete and mortar with distributed damage, Construction and Building Materials 125 (2016) 438–449.

[21] R. P. Spragg, J. Castro, T. Nantung, M. Paredes, J. Weiss, Variability analysis of the bulk resistivity measured using concrete cylinders, Advances in Civil Engineering Materials 1 (1) (2012) 1–17.

[22] D. Smyl, M. Hallaji, A. Seppänen, M. Pour-Ghaz, Quantitative electrical imaging of three-dimensional moisture flow in cement-based materials, International Journal of Heat and Mass Transfer 103 (2016) 1348–1358.

[23] J. Badr, Y. Fargier, S. Palma-Lopes, F. Deby, J.-P. Balayssac, S. Delepine-Lesoille, L.-M. Cottineau, G. Villain, Design and validation of a multi-electrode embedded sensor to monitor resistivity profiles over depth in concrete, Construction and Building Materials 223 (2019) 310–321.

[24] Y.-C. Lim, T. Noguchi, C.-G. Cho, A quantitative analysis of the geometric effects of reinforcement in concrete resistivity measurement above reinforcement, Construction and Building Materials 83 (2015) 189–193.

[25] F. Presuel-Moreno, Y. Liu, Y.-Y. Wu, Numerical modeling of the effects of rebar presence and/or multilayered concrete resistivity on the apparent resistivity measured via the wenner method, Construction and Building Materials 48 (2013) 16–25.

[26] R. B. Polder, Test methods for on site measurement of resistivity of concretea rilem tc-154 technical recommendation, Construction and building materials 15 (2-3) (2001) 125–131.

[27] R. Polder, C. Andrade, B. Elsener, Ø. Vennesland, J. Gulikers, R. Weidert, M. Raupach, Test methods for on site measurement of resistivity of concrete, Materials and Structures 33 (10) (2000) 603–611.

[28] C. Qiao, M. K. Moradllo, H. Hall, M. T. Ley, W. J. Weiss, Electrical resistivity and formation factor of air-entrained concrete, ACI Materials Journal 116 (3) (2019) 85–93.

[29] M. Tsui-Chang, A. N. Amirkhanian, P. Suraneni, R. P. Spragg, A. T. Coyle, W. J. Weiss, Activation energy of conduction for use in temperature corrections on electrical

measurements of concrete, Advances in Civil Engineering Materials 8 (1) (2019) 158–170.

[30] F. Presuel-Moreno, Y.-Y. Wu, Y. Liu, Effect of curing regime on concrete resistivity and aging factor over time, Construction and Building Materials 48 (2013) 874–882.

[31] R. L. Du Plooy, The development and combination of electromagnetic non-destructive evaluation techniques for the assesment of cover concrete condition prior to corrosion, Ph.D. thesis, Université Nantes Angers Le Mans (2013).

[32] I. Martínez, C. Andrade, Examples of reinforcement corrosion monitoring by embedded sensors in concrete structures, Cement and Concrete Composites 31 (8) (2009) 545–554.

[33] A. Norris, M. Saafi, P. Romine, Temperature and moisture monitoring in concrete structures using embedded nanotechnology/microelectromechanical systems (mems) sensors, Construction and Building Materials 22 (2) (2008) 111–120.

[34] W. McCarter, T. Chrisp, A. Butler, P. Basheer, Near–surface sensors for condition monitoring of cover-zone concrete, Construction and Building Materials 15 (2-3) (2001) 115–124.

[35] W. J. Weiss, R. P. Spragg, O. B. Isgor, M. T. Ley, T. Van Dam, Toward performance specifications for concrete: linking resistivity, rcpt and diffusion predictions using the formation factor for use in specifications, in: High tech concrete: Where technology and engineering meet, Springer, 2018, pp. 2057–2065.

[36] D. Smyl, M. Hallaji, A. Seppänen, M. Pour-Ghaz, Quantitative electrical imaging of three-dimensional moisture flow in cement-based materials, International Journal of Heat and Mass Transfer 103 (2016) 1348–1358.

[37] S. Lu, E. Landis, D. Keane, X-ray microtomographic studies of pore structure and permeability in portland cement concrete, Materials and Structures 39 (6) (2006) 611–620.

[38] H. Zelelew, A. Papagiannakis, A volumetrics thresholding algorithm for processing asphalt concrete x-ray CT images, International Journal of Pavement Engineering 12 (6) (2011) 543–551.

[39] P. H. Baker, D. Bailly, M. Campbell, G. H. Galbraith, R. C. McLean, N. Poffa, C. H. Sanders, The application of x-ray absorption to building moisture transport studies, Measurement 40 (9-10) (2007) 951–959.

[40] J. Carmeliet, J.-F. Delerue, K. Vandersteen, S. Roels, Three-dimensional liquid transport in concrete cracks, International Journal for Numerical and Analytical Methods in Geomechanics 28 (7-8) (2004) 671–687.

[41] S. Stanković, R. Ilić, K. Janković, D. Bojović, B. Lončar, Gamma radiation absorption characteristics of concrete with components of different type materials, Acta Physica Polonica A 117 (5) (2010) 812–816.

[42] P. Zhang, F. H. Wittmann, P. Lura, H. S. Müller, S. Han, T. Zhao, Application of neutron imaging to investigate fundamental aspects of durability of cement-based materials: a review, Cement and Concrete Research 108 (2018) 152–166.

[43] M. Hallaji, A. Seppänen, M. Pour-Ghaz, Electrical resistance tomography to monitor unsaturated moisture flow in cementitious materials, Cement and Concrete Research 69 (2015) 10–18.

[44] P. Trtik, B. Münch, W. Weiss, A. Kaestner, I. Jerjen, L. Josic, E. Lehmann, P. Lura, Release of internal curing water from lightweight aggregates in cement paste investigated by neutron and x-ray tomography, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 651 (1) (2011) 244–249.

[45] R. Enjilela, P. F. d. J. Cano-Barrita, A. Komar, A. J. Boyd, B. J. Balcom, Monitoring steady state moisture distribution during wick action in mortar by magnetic resonance imaging (mri), Materials and Structures 50 (2) (2017) 151.

[46] S. Beyea, B. Balcom, T. Bremner, P. Prado, D. Green, R. Armstrong, P. Grattan-Bellew, Magnetic resonance imaging and moisture content profiles of drying concrete, Cement and Concrete Research 28 (3) (1998) 453–463.

[47] D. J. Smyl, Electrical imaging and numerical simulation of unsaturated moisture flow in cement-based materials, Ph.D. thesis (2017).

[48] M. Yehya, E. Andò, F. Dufour, A. Tengattini, Fluid-flow measurements in low permeability media with high pressure gradients using neutron imaging: Application to concrete, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 890 (2018) 35–42.

[49] F. H. Kim, D. Penumadu, J. Gregor, N. Kardjilov, I. Manke, High-resolution neutron and x-ray imaging of granular materials, Journal of Geotechnical and Geoenvironmental Engineering 139 (5) (2012) 715–723.

[50] K. Karhunen, A. Seppänen, A. Lehikoinen, J. Blunt, J. P. Kaipio, P. J. Monteiro, Electrical resistance tomography for assessment of cracks in concrete, ACI Materials Journal 107 (5) (2010) 523–531.

[51] J. Mueller, S. Siltanen, Linear and Nonlinear Inverse Problems with Practical Applications, SIAM, Philadelphia, PA, USA, 2012.

[52] M. Kanematsu, I. Maruyama, T. Noguchi, H. Iikura, Visualization of water penetration into concrete through cracks by neutron radiography, in: Proc. Int. Seminar on Durability and Lifecycle Evaluation of Concrete Structures, R. Sato, editor, Higashi Hiroshima, Japan, 2006, pp. 69–76.

[53] D. P. Bentz, P. M. Halleck, A. S. Grader, J. W. Roberts, Four-dimensional x-ray microtomography study of water movement during internal curing, in: Proceedings of the International RILEM Conference-Volume Changes of Hardening Concrete: Testing and Mitigation, 2006, pp. 11–20.

[54] G. Villain, M. Thiery, Gammadensimetry: A method to determine drying and carbonation profiles in concrete, NDT & E International 39 (4) (2006) 328–337.

[55] D. Smyl, M. Hallaji, A. Seppänen, M. Pour-Ghaz, Three-dimensional electrical impedance tomography to monitor unsaturated moisture ingress in cement-based materials, Transport in Porous Media 115 (1) (2016) 101–124.

[56] A. Voss, P. Hosseini, M. Pour-Ghaz, M. Vauhkonen, A. Seppänen, Three-dimensional electrical capacitance tomography–a tool for characterizing moisture transport properties of cement-based materials, Materials & Design 181 (2019) 107967.

[57] A. Olaru, B. Blümich, A. Adams, Water transport in cement-in-polymer dispersions at variable temperature studied by magnetic resonance imaging, Cement and Concrete Research 44 (2013) 55–68.

[58] T. A. A. Junior, M. S. Nogueira, V. Vivolo, M. Potiens, L. Campos, Mass attenuation coefficients of x-rays in different barite concrete used in radiation protection as shielding against ionizing radiation, Radiation Physics and Chemistry 140 (2017) 349–354.

[59] D. Smyl, M. Hallaji, A. Seppänen, M. Pour-Ghaz, Three-dimensional electrical impedance tomography to monitor unsaturated moisture ingress in cement-based materials, Transport in Porous Media 115 (1) (2016) 101–124.

[60] L. Borcea, Electrical impedance tomography, Inverse Probl. 18 (2002) R99–R136.

[61] M. Soleimani, W. R. Lionheart, Nonlinear image reconstruction for electrical capacitance tomography using experimental data, Measurement Science and Technology 16 (10) (2005) 1987.

[62] T. Vilhunen, J. Kaipio, P. Vauhkonen, T. Savolainen, M. Vauhkonen, Simultaneous reconstruction of electrode contact impedances and internal electrical properties: I. theory, Measurement Science and Technology 13 (12) (2002) 1848.

[63] M. Vauhkonen, Electrical impedance tomography and prior information, Ph.D. thesis, University of Kuopio, Finland (1997).

[64] A. Voss, M. Pour-Ghaz, M. fonen, A. Seppänen, Electrical capacitance tomography to monitor unsaturated moisture ingress in cement-based materials, Cement and Concrete Research 89 (2016) 158–167.

[65] Q. Li, S. Xu, Q. Zeng, The effect of water saturation degree on the electrical properties of cement-based porous material, Cement and Concrete Composites 70 (2016) 35–47.

[66] W. J. Weiss, T. J. Barrett, C. Qiao, H. Todak, Toward a specification for transport properties of concrete based on the formation factor of a sealed specimen, Advances in Civil Engineering Materials 5 (1) (2016) 179–194.

[67] J. Weiss, K. Snyder, J. Bullard, D. Bentz, Using a saturation function to interpret the electrical properties of partially saturated concrete, Journal of Materials in Civil Engineering 25 (8) (2012) 1097–1106.

[68] G. Sant, D. Bentz, J. Weiss, Capillary porosity depercolation in cement-based materials: Measurement techniques and factors which influence their interpretation, Cement and Concrete Research 41 (8) (2011) 854–864.

[69] D. J. Smyl, Relating unsaturated electrical and hydraulic conductivity of cement-based materials, Australian Journal of Civil Engineering 16 (2) (2018) 129–142.

[70] L. M. Heikkinen, T. Vilhunen, R. M. West, M. Vauhkonen, Simultaneous reconstruction of electrode contact impedances and internal electrical properties: Ii. laboratory experiments, Measurement Science and Technology 13 (12) (2002) 1855.

[71] M. Vauhkonen, D. Vadasz, J. Kaipio, E. Somersalo, P. Karjalainen, Tikhonov regularization and prior information in electrical impedance tomography, IEEE Transactions in Medical Imaging 17 (2) (1998) 285–293.

[72] M. Hanke, B. Harrach, N. Hyvönen, Justification of point electrode models in electrical impedance tomography, Mathematical Models and Methods in Applied Sciences 21 (06) (2011) 1395–1413.

[73] M. Soleimani, C. Gómez-Laberge, A. Adler, Imaging of conductivity changes and electrode movement in EIT, Physiological Measurement 27 (5) (2006) S103.

[74] N. Hyvonen, L. Mustonen, Smoothened complete electrode model, SIAM Journal on Applied Mathematics 77 (6) (2017) 2250–2271.

[75] P. Ledger, hp-finite element discretisation of the electrical impedance tomography problem, Computer Methods in Applied Mechanics and Engineering 225 (2012) 154–176.

[76] L. Borcea, Electrical impedance tomography, Inverse Problems 18 (6) (2002) R99.

[77] W. Yang, L. Peng, Image reconstruction algorithms for electrical capacitance tomography, Measurement Science and Technology 14 (1) (2002) R1.

[78] J. Sarvas, Basic mathematical and electromagnetic concepts of the biomagnetic inverse problem, Physics in Medicine & Biology 32 (1) (1987) 11.

[79] J. Sylvester, G. Uhlmann, A global uniqueness theorem for an inverse boundary value problem, Annals of mathematics (1987) 153–169.

[80] J. Sylvester, G. Uhlmann, A uniqueness theorem for an inverse boundary value problem in electrical prospection, Communications on Pure and Applied Mathematics 39 (1) (1986) 91–112.

[81] D. Smyl, D. Liu, Less is often more: Applied inverse problems using hp-forward models, Journal of Computational Physics 399 (2019) 108949.

[82] J. Kaipio, V. Kolehmainen, M. Vauhkonen, E. Somersalo, Inverse problems with structural prior information, Inverse Problems 15 (1999) 713–729.

[83] B. Jin, T. Khan, P. Maass, A reconstruction algorithm for electrical impedance tomography based on sparsity regularization, International Journal for Numerical Methods in Engineering 89 (3) (2012) 337–353.

[84] J. Kaipio, E. Somersalo, Statistical and Computational Inverse Problems, Springer New York, 2005.

[85] D. Smyl, M. Pour-Ghaz, A. Seppänen, Detection and reconstruction of complex structural cracking patterns with electrical imaging, NDT & E International 99 (2018) 123–133.

[86] D. Smyl, M. Hallaji, A. Seppänen, M. Pour-Ghaz, Three dimensional electrical imaging of moisture ingress in mortar, ACI Special Publication.

[87] Y. C. Eldar, A. V. Oppenheim, Covariance shaping least-squares estimation, IEEE Transactions on Signal Processing 51 (3) (2003) 686–697.

[88] B. Letham, B. Karrer, G. Ottoni, E. Bakshy, et al., Constrained bayesian optimization with noisy experiments, Bayesian Analysis 14 (2) (2019) 495–519.

[89] D. Smyl, S. Bossuyt, W. Ahmad, A. Vavilov, D. Liu, An overview of 38 least squares-based frameworks for structural damage tomography, Structural Health Monitoring (in press).

[90] J. Nocedal, S. Wright, Numerical optimization, Springer Science & Business Media, 2006.

[91] S. Boyd, L. Vandenberghe, Convex optimization, Cambridge University Press, 2004.

[92] A. Voss, N. Hänninen, M. Pour-Ghaz, M. Vauhkonen, A. Seppänen, Imaging of two-dimensional unsaturated moisture flows in uncracked and cracked cement-based materials using electrical capacitance tomography, Materials and Structures 51 (3) (2018) 68.

[93] A. Fick, Ueber diffusion, Annalen der Physik 170 (1) (1855) 59–86.

[94] H. P. G. Darcy, Les Fontaines publiques de la ville de Dijon. Exposition et application des principes à suivre et des formules à employer dans les questions de distribution d'eau, etc, V. Dalamont, 1856.

[95] L. A. Richards, Capillary conduction of liquids through porous mediums, Physics 1 (5) (1931) 318–333.

[96] M. T. Van Genuchten, P. Wierenga, Mass transfer studies in sorbing porous media i. analytical solutions 1, Soil Science Society of America Journal 40 (4) (1976) 473–480.

[97] H. Gerke, M. T. Van Genuchten, A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media, Water Resources Research 29 (2) (1993) 305–319.

[98] N. Burdine, Relative permeability calculations from pore size distribution data, Journal of Petroleum Technology 5 (3) (1953) 71–78.

[99] R. H. Brooks, A. T. Corey, Properties of porous media affecting fluid flow, Journal of the Irrigation and Drainage Division 92 (2) (1966) 61–90.

[100] Y. Mualem, A new model for predicting the hydraulic conductivity of unsaturated porous media, Water Resources Research 12 (3) (1976) 513–522.

[101] M. T. Van Genuchten, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1, Soil Science Society of America Journal 44 (5) (1980) 892–898.

[102] K. Kosugi, Lognormal distribution model for unsaturated soil hydraulic properties, Water Resources Research 32 (9) (1996) 2697–2703.

[103] W. McCarter, S. Garvin, Dependence of electrical impedance of cement-based materials on their moisture condition, Journal of Physics D: Applied Physics 22 (11) (1989) 1773.

[104] A. Berg, G. Niklasson, K. Brantervik, B. Hedberg, L.-O. Nilsson, Dielectric properties of cement mortar as a function of water content, Journal of Applied Physics 71 (12) (1992) 5897–5903.

[105] S. Shimamura, C. Tashiro, Contribution of evaporable water to electrical conduction in porous hardened cements, Journal of Materials Science Letters 11 (7) (1992) 396–398.

[106] M. Buettner, A. Ramirez, W. Daily, Electrical resistance tomography for imaging the spatial distribution of moisture in pavement sections, Tech. rep., Lawrence Livermore National Lab., CA (United States) (1995).

[107] W. Daily, A. Ramirez, A. Binley, S. Henry-Poulter, Electrical resistance tomography of concrete structures, Tech. rep., Lawrence Livermore National Lab., CA (United States) (1993).

[108] M. Buettner, B. Daily, A. Ramirez, Electrical resistance tomography for monitoring the infiltration of water into a pavement section, Tech. rep., Lawrence Livermore National Lab., CA (United States) (1997).

[109] M. Chouteau, S. Beaulieu, An investigation on application of the electrical resistivity tomography method to concrete structures, Geophysics (2002) 15–19.

[110] P. Berowski, S. F. Filipowicz, J. Sikora, S. Wójtowicz, Determining location of moisture area of the wall by 3d electrical impedance tomography, in: 4th World Congress on Industrial Process Tomography, Aizu, Japonia, Vol. 5, 2005, pp. 214–219.

[111] W. Morris, E. Moreno, A. Sagüés, Practical evaluation of resistivity of concrete in test cylinders using a wenner array probe, Cement and Concrete Research 26 (12) (1996) 1779–1787.

[112] D. A. Whiting, M. A. Nagi, Electrical resistivity of concrete-a literature review, R&D Serial 2457.

[113] J.-P. Balayssac, V. Garnier, Non-destructive testing and evaluation of civil engineering structures, 1st Edition, Elsevier, Oxford, UK, 2017.

[114] D. Breysse, G. Klysz, X. Dérobert, C. Sirieix, J. Lataste, How to combine several non-destructive techniques for a better assessment of concrete structures, Cement and Concrete Research 38 (6) (2008) 783–793.

[115] M. Goueygou, O. Abraham, J.-F. Lataste, A comparative study of two non-destructive testing methods to assess near-surface mechanical damage in concrete structures, NDT & E International 41 (6) (2008) 448–456.

[116] J. Lataste, C. Sirieix, D. Breysse, M. Frappa, Electrical resistivity measurement applied to cracking assessment on reinforced concrete structures in civil engineering, NDT & E International 36 (6) (2003) 383–394.

[117] H. M. Jennings, J. W. Bullard, J. J. Thomas, J. E. Andrade, J. J. Chen, G. W. Scherer, Characterization and modeling of pores and surfaces in cement paste, Journal of Advanced Concrete Technology 6 (1) (2008) 5–29.

[118] G. Dotelli, C. Mari, The evolution of cement paste hydration process by impedance spectroscopy, Materials Science and Engineering: A 303 (1-2) (2001) 54–59.

[119] C. Andrade, V. Blanco, A. Collazo, M. Keddam, X. Novoa, H. Takenouti, Cement paste hardening process studied by impedance spectroscopy, Electrochimica Acta 44 (24) (1999) 4313–4318.

[120] D. Zhang, Z. Cao, L. Fan, S. Liu, W. Liu, Evaluation of the influence of salt concentration on cement stabilized clay by electrical resistivity measurement method, Engineering Geology 170 (2014) 80–88.

[121] L. Chen, Y.-J. Du, S.-Y. Liu, F. Jin, Evaluation of cement hydration properties of cement-stabilized lead-contaminated soils using electrical resistivity measurement, Journal of Hazardous, Toxic, and Radioactive Waste 15 (4) (2010) 312–320.

[122] G. Villain, A. Ihamouten, X. Derobert, Determination of concrete water content by coupling electromagnetic methods: Coaxial/cylindrical transition line with capacitive probes, NDT & E International 88 (2017) 59–70.

[123] M. Fares, Y. Fargier, G. Villain, X. Derobert, S. P. Lopes, Determining the permittivity profile inside reinforced concrete using capacitive probes, NDT & E International 79 (2016) 150–161.

[124] X. Yin, D. Hutchins, G. Diamond, P. Purnell, Non-destructive evaluation of concrete using a capacitive imaging technique: Preliminary modelling and experiments, Cement and Concrete Research 40 (12) (2010) 1734–1743.

[125] G. Villain, V. Garnier, Z. M. Sbartaï, X. Derobert, J.-P. Balayssac, Development of a calibration methodology to improve the on-site non-destructive evaluation of concrete durability indicators, Materials and Structures 51 (2) (2018) 40.

[126] E. Somersalo, M. Cheney, D. Isaacson, Existence and uniqueness for electrode models for electric current computed tomography, SIAM Journal on Applied Mathematics 52 (4) (1992) 1023–1040.

[127] K. Karhunen, A. Seppänen, A. Lehikoinen, J. Kaipio, P. Monteiro, Locating reinforcing bars in concrete with electrical resistance tomography, in: M. Alexander, Beushausen,

D. H.-D., P. Moyo (Eds.), Concrete Repair, Rehabilitation, and Retrofitting II, Taylor & Francis Group, Baton Rouge, FL, USA, 2008, Ch. 10, pp. 563–569.

[128] K. Karhunen, A. Seppänen, A. Lehikoinen, P. Monteiro, J. Kaipio, Electrical resistance tomography imaging of concrete, Cement Concrete Research 40 (2010) 137–145.

[129] K. Karhunen, A. Seppänen, A. Lehikoinen, J. Kaipio, J. Monteiro, Locating reinforcing bars in concrete with electrical resistance tomography, in: 2nd International conference on concrete repair, rehabilitation and retrofitting, Cape Town, South Africa, 2009.

[130] R. Du Plooy, G. Villain, S. P. Lopes, A. Ihamouten, X. Dérobert, B. Thauvin, Electromagnetic non-destructive evaluation techniques for the monitoring of water and chloride ingress into concrete: a comparative study, Materials and Structures 48 (1-2) (2015) 369–386.

[131] G. Villain, A. Ihamouten, R. Du Plooy, S. P. Lopes, X. Derobert, Use of electromagnetic non-destructive techniques for monitoring water and chloride ingress into concrete, Near Surface Geophysics 13 (3) (2015) 299–309.

[132] G. Villain, Z. M. Sbartaï, J.-F. Lataste, V. Garnier, X. Dérobert, O. Abraham, S. Bonnet, J.-P. Balayssac, N. T. Nguyen, M. Fares, Characterization of water gradients in concrete by complementary ndt methods, in: International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE 2015), 2015, p. 12p.

[133] K. Reichling, M. Raupach, N. Klitzsch, Determination of the distribution of electrical resistivity in reinforced concrete structures using electrical resistivity tomography, Materials and Corrosion 66 (8) (2015) 763–771.

[134] J.-F. Lataste, Electrical resistivity for the evaluation of reinforced concrete structures, in: Non-Destructive Evaluation of Reinforced Concrete Structures, Elsevier, 2010, pp. 243–275.

[135] K. Karhunen, A. Seppanen, J. P. Kaipio, Adaptive meshing approach to identification of cracks with electrical impedance tomography., Inverse Problems & Imaging 8 (1).

[136] P. J. Vauhkonen, M. Vauhkonen, T. Savolainen, J. P. Kaipio, Three-dimensional electrical impedance tomography based on the complete electrode model, IEEE Transactions on Biomedical Engineering 46 (9) (1999) 1150–1160.

[137] B. Suryanto, D. Saraireh, J. Kim, W. McCarter, G. Starrs, H. Taha, Imaging water ingress into concrete using electrical resistance tomography, International Journal of Advances in Engineering Sciences and Applied Mathematics 9 (2) (2017) 109–118.

[138] D. Smyl, R. Rashetnia, A. Seppänen, M. Pour-Ghaz, Can electrical resistance tomography be used for imaging unsaturated moisture flow in cement-based materials with discrete cracks?, Cement and Concrete Research 91 (2017) 61–72.

[139] A. Voss, M. Pour-Ghaz, M. Vauhkonen, A. Seppänen, Difference reconstruction methods for electrical capacitance tomography imaging of two-dimensional moisture flow in concrete, in: The 9th international conference on inverse problems in engineering (ICIPE), Waterloo, Canada, 2017.

[140] T. Rymarczyk, G. Kłosowski, E. Kozłowski, A non-destructive system based on electrical tomography and machine learning to analyze the moisture of buildings, Sensors 18 (7) (2018) 2285.

[141] T. Rymarczyk, P. Tchórzewski, Analysis of historical wall dampness using electrical tomography measuring system, International Journal of Applied Electromagnetics and Mechanics (Preprint) (2018) 1–9.

[142] K. Kawaai, I. Ujike, Electrical resistance tomography for assessing water movement in cracked cementitious mixtures, in: MATEC Web of Conferences, Vol. 199, EDP Sciences, 2018, p. 11016.

[143] M. Fares, G. Villain, S. Bonnet, S. P. Lopes, B. Thauvin, M. Thiery, Determining chloride content profiles in concrete using an electrical resistivity tomography device, Cement and Concrete Composites 94 (2018) 315–326.

[144] M. Benning, M. Burger, Modern regularization methods for inverse problems, Acta Numerica 27 (2018) 1–111.

[145] D. Isaacson, Distinguishability of conductivities by electric current computed tomography, IEEE Transactions on Medical Imaging 5 (2) (1986) 91–95.

[146] Y. Fargier, S. Palma-Lopes, D. François, C. Fauchard, P. Côte, Optimization of electrode layouts for 3d-resistivity imaging: application to water infiltrations in an experimental dike, in: Near Surface 2010-16th EAGE European Meeting of Environmental and Engineering Geophysics, 2010.

[147] A. K. Saibaba, T. Bakhos, P. K. Kitanidis, A flexible krylov solver for shifted systems with application to oscillatory hydraulic tomography, SIAM Journal on Scientific Computing 35 (6) (2013) A3001–A3023.

[148] A. A. Oberai, N. H. Gokhale, G. R. Feijóo, Solution of inverse problems in elasticity imaging using the adjoint method, Inverse Problems 19 (2) (2003) 297.

[149] S. J. Hamilton, A. Hauptmann, Deep d-bar: Real-time electrical impedance tomography imaging with deep neural networks, IEEE Transactions on Medical Imaging 37 (10) (2018) 2367–2377.

[150] J. Adler, O. Öktem, Solving ill-posed inverse problems using iterative deep neural networks, Inverse Problems 33 (12) (2017) 124007.

[151] D. Liu, V. Kolehmainen, S. Siltanen, A. Seppänen, A nonlinear approach to difference imaging in eit; assessment of the robustness in the presence of modelling errors, Inverse Problems 31 (3) (2015) 035012.

[152] E. Haber, D. Oldenburg, Joint inversion: a structural approach, Inverse Problems 13 (1) (1997) 63.

[153] K. Vozoff, D. Jupp, Joint inversion of geophysical data, Geophysical Journal International 42 (3) (1975) 977–991.